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Influence of butanol addition to diesel–biodiesel blend on engine performance and particulate emissions of a stationary diesel engine

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HIGHLIGHTS

- Effects of butanol addition to B20 on physicochemical and toxicological characteristics of PM were investigated.
- The butanol addition slightly increases BSFC and BTE.
- The $PM_{2.5}$, EC and particle-phase PAHs emissions decreased, with the increased OC fraction in PM.
- The total number of particles as well particle geometric mean diameter decreased.
- Reduction in the cytotoxicity of particle extracts was observed with butanol.

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ABSTRACT

There is a lack of detailed investigations on the effects of butanol addition to diesel/biodiesel blends on particulate emissions. This study represents the first attempt of its kind to fully evaluate the potential impact of diesel–biodiesel–butanol blends on engine performance, physical, chemical and toxicological properties of the particulates emitted by a single cylinder direct injection compression ignition engine with the engine working at a constant engine speed and at three engine loads. Ultralow sulfur diesel (ULSD) fuel blended with 20% palm oil methyl ester (PME) by volume was prepared (denoted as B20), and then blended with 5%, 10% and 15% of butanol by volume. The results indicated a marginal change in the brake specific fuel consumption (BSFC) up to 10% butanol addition, and an improvement in the brake thermal efficiency (BTE) at medium and high engine loads. Compared to B20, the particulate mass and element carbon (EC) concentrations, and the total number of particles were reduced significantly, whereas the proportion of organic carbon (OC) in the particles increased with an increase in butanol in the ternary fuel. Moreover, the geometric mean diameter (GMD) of the particles shifted towards smaller size. Butanol addition also showed a lower total particle-phase polycyclic aromatic hydrocarbons (PAHs) emission, lower carcinogenic potential and also lower cytotoxicity of particle extracts, compared to those of B20.

1. Introduction

Research on the use of sustainable and cleaner fuels in both mobile and stationary applications continues to receive considerable attention because of the motivation to reduce our dependence on fossil fuels and meet the increasingly stringent emission quality standards [1]. Biofuels, such as biodiesel and alcohols, have potential to partially or totally replace petroleum- based fuel in compression ignition (CI) engines for reducing diesel fuel consumption and toxic emissions, and more importantly restraining the life-cycle emission of CO_2 [2].

Biodiesel obtained via alcohol transesterification from vegetable oils is a promising alternative energy source. This biodiesel is renewable, nontoxic and readily biodegradable, is free of sulfur and aromatic compounds, and possesses a higher cetane number, higher flash point and better lubricity performance [2–4]. The most widely used vegetable oil-based biodiesels are rapeseed oil methyl ester (RME) in Europe and soybean methyl ester (SME) in the USA. Palm oil methyl ester (PME) is also considered a promising alternative fuel among biodiesels as it is the most produced feedstock and its yield is the highest among vegetable oil crops [4]. Many studies have been conducted on the use of these biodiesel blends in diesel engines to achieve both the environmental and energy benefits. B20 (a mixture of 20% biodiesel and 80% petroleum diesel) has become the most popular blend [2,5]. However, vegetable oil-based

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biodiesels have poor volatility and higher viscosity than those of diesel, which could lead to a poor atomization, carbon deposits or clogging of fuel lines, as well as thickening and gelling of the engine lubricating oil [2–4]. These major drawbacks of biodiesel limit their application in CI engines.

To extend the use of diesel/biodiesel blends in diesel engines, the addition of alcohols, mainly ethanol, to the blends has been considered [1,3,4,6,7]. The lower viscosity and higher volatility of alcohols compensates for these opposite properties in biodiesel [3,4]. Biodiesel in the blends acts as a co-solvent to improve the miscibility of alcohols with conventional diesel. With the increase in the percentage of renewable/oxygenated fuel in the blends, complete fuel combustion has been reported to be achieved [8]. In view of these technical merits, research on the simultaneous use of diesel, biodiesel and alcohols in the form of ternary blends is attracting more attention, with the beneficial effects of the blends being improved fuel properties, engine performance, combustion characteristics, and more importantly exhaust emissions [1,3–5,7–11].

Among alcohols, butanol has recently drawn particular attention as a renewable biofuel for diesel engines due to its higher heating value and cetane number, more miscibility with diesel, and less hydrophilic compared to methanol and ethanol [1,4,7]. Recent studies suggest that butanol can be a better alternative biofuel than ethanol for use in CI engines [11]. However, there is a lack of detailed investigations on the effects of butanol addition to diesel/biodiesel blends on engine performance and particulate emissions [1,4,6,7,11]. The mass emission rates of particulate emissions as well as the number concentration and size distribution of the particles are usually investigated in combustion studies. However, the combined physical and chemical properties of the particulate emissions, rather than the mass and size alone, determine their influence on the environment and human health. Very few investigations have been done till date on determining the physical and chemical properties of particles emitted from an engine fueled with diesel–biodiesel–alcohol blends [1,11]. The current study represents the first attempt of its kind to fully evaluate the potential impact of diesel–biodiesel–butanol blends on engine performance, physical, chemical and toxicological properties of the particulates emitted by a diesel engine, with the objective being to provide information for assessing if the ternary fuel blends help reducing health and environmental impacts or otherwise.

2. Experimental setup

2.1. Test engine and fuels

The schematic of the experimental system is shown in Supplementary Fig. 1. Experiments were carried out on a single cylinder, four-stroke, air-cooled, direct-injection, diesel back-up power generator (L70AE, Yanmar Corporation). The main specifications of the engine are shown in Supplementary Table 1. The fuels used include ULSD with less than 50-ppm (parts per million) by weight of sulfur, palm oil methyl ester (PME) as biodiesel, and anhydrous *n*-butanol of 99.8% purity (Sigma–Aldrich). The PME used in this study was obtained from palm oil-based biodiesel plant in Malaysia operated by Vance Bioenergy, and the fuel properties were provided by the biodiesel supplier. Major properties of the test fuels are shown in Table 1. Five fuels were prepared: ULSD, a 20 volume% PME and 80 volume% ULSD fuel blend known as B20; B20 blends contained 5%, 10%, and 15% by volume of butanol, and are identified as B20Bu5, B20Bu10, and B20Bu15 fuels, respectively.

2.2. Particulate sampling and testing

A two-stage Dekati mini-diluter (DI-2000, Dekati Ltd) was used for diluting the exhaust gas for sampling. The diluter provides primary dilution in the range of 8:1 to 6:1, depending on the engine operating conditions, while the secondary dilution system provides a further dilution of 8:1. The actual dilution ratio was evaluated based on measured CO_2 concentrations in the raw exhaust, in the background air and in the diluted exhaust. The CO_2 concentration was measured with a non-dispersive infra-red analyzer (MRU Vario Plus, Germany, ±0.5% accuracy). This measurement was done for every test, and all data presented in this article have been dilution-corrected to represent engine-out conditions.

Table 1
Properties of ultralow sulfur diesel (ULSD), biodiesel, and butanol [2,24].

Properties	ULSD	Biodiesel	Butanol
Cetane number	52	67	17
Lower heating value (MJ/kg)	42.5	40	34
Density (kg/m^3)@20 °C	830	875	810
Viscosity (mPa s)@40 °C	2.8	4.6	1.8
Boiling point (°C)	185–345	300–350	117.4
Heat of evaporation (kJ/kg)	270	300	585
Stoichiometric air/fuel ratio	14.7	11.3	11.2
Carbon content (% mass)	86.6	76.6	64.9
Hydrogen content (% mass)	13.4	12.2	13.5
Oxygen content (% mass)	–	11.2	21.6
Sulfur content (ppm)	<50	<10	–
Aromatic content (% mass)	0.6	–	–

Only the first stage diluter was used to cool the sampling gas temperature below 52 °C for particulate sampling. PM with aerodynamic diameter $\leqslant$2.5 μm ($PM_{2.5}$) was collected on pre-combusted (650 °C for 12 h) 47 mm quartz fiber filters (Whatman, USA) by using two Mini-Vol low volume particulate samplers (Air metrics Ltd.; 5 L min^{-1} flow rate). Before and after sampling, the filters were allowed to equilibrate in a humidity-controlled chamber at constant temperature and humidity (22 ± 3 °C, 35 ± 8% RH), and weighed using a microbalance (Sartorius MC5, accuracy of ±1 μg) for quantifying total $PM_{2.5}$ mass emissions.

After taking the weight, the filters were closed in glass petri dishes and stored under refrigeration at −20 °C for subsequent chemical analysis. A Sunset Labs (Forest Grove, OR) thermal/optical carbon aerosol analyzer was used to quantify EC and OC emissions according to the NIOSH 5040 reference method [12]. The particle number concentration and size distributions in the secondary dilution stage were measured by a Fast Mobility Particle Sizer (FMPS, Model 3091, TSI Incorporated, USA) for particles in the size range of 5.6–560 nm. In this setup, two diluters were used in series, with the first stage being heated to 190 °C in order to minimize thermophoretic deposition.

2.3. Particle-phase PAHs

Particle-phase PAHs were extracted from the quartz filter samples in 50/50 hexane/acetone (HPLC-grade, Fisher Scientific) mixture using a closed vessel microwave-assisted extraction system (MLS-1200 mega, Milestone, Italy) in accordance with the US EPA method 3546 [13]. Each of the eluents was divided into two equal parts, with one part for subsequent PAHs analysis, and the other part for toxicological analysis. More details of this method including the chemical analysis of 16 US priority PAHs by gas chromatography/mass spectrometry (GC/MS) have been discussed in our previous publication [14]. The 16 EPA PAHs are separated into three different molecular weight ranges: Low molecular weight (LMW) PAHs are two and three rings PAHs including naphthalene (Nap), acenaphthylene (AcPy), acenaphthene (AcP), fluorine (Flu), phenanthrene (PA) and anthracene (Ant). Middle molecular weight (MMW) PAHs are four rings PAHs including fluoranthene (FL), pyrene (Pyr), benzo[a]anthracene (BaA) and chrysene (CHR). High molecular weight (HMW) PAHs are five and six rings PAHs