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Comparative evaluation of the effect of butanol–diesel and pentanol–diesel blends on carbonaceous particulate composition and particle number emissions from a diesel engine

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HIGHLIGHTS

- Blending of butanol or pentanol with diesel fuel changed the DPM characteristics.
- The blended fuels reduced particulate mass, EC and total counts of particles.
- Butanol was more effective than pentanol for the above reductions.
- The blended fuels increased both OC and WSOC in particles.
- They showed different effects on counts of nanoparticles and lager particles.

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ABSTRACT

This study was undertaken to comparatively evaluate the effects of blending butanol and pentanol with ultralow sulfur diesel (ULSD) at 10% and 20% by volume on engine performance, emissions of particulate mass and counts, and carbonaceous particulate components from a single cylinder, direct injection diesel engine. The engine was operated at a constant engine speed and at three engine loads. The results indicate a marginal change in the brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE). Compared to diesel fuel, both the blended fuels can effectively reduce the particulate mass and elemental carbon (EC) emissions, and also total counts of volatile and solid particles. Moreover, with the same proportion of butanol or pentanol in the blended fuels, the butanol–diesel blend shows a higher potential to inhibit EC formation and a higher emission reduction in solid and volatile particles in terms of their counts than that of the pentanol–diesel blend. However, both of the blended fuels show a slight decrease in organic carbon (OC) emissions, a significant increase in water-soluble organic carbon (WSOC) emissions and therefore high OC/EC and WSOC/OC ratios. In addition, the reduction of total particle number emissions with the addition of both butanol and pentanol is a result of a significant reduction in the number of particles larger than 50 nm. However, the blended fuels show a slight increase in or no significant change in particles of less than 50 nm while the number of particles with diameter less than 20 nm increases for 20% butanol and pentanol blends at low engine load.

1. Introduction

The short-chain alcohols, namely methanol and ethanol, in combination with diesel fuel, have been widely studied as fuels for use in diesel engines because these alcohols can be readily converted from renewable bio-based resources, and have high oxygen contents and high H/C ratios, thereby providing the potential to reduce soot and diesel particulate matter (DPM) emissions [1–3]. Despite their advantages, the short-chain alcohols have lower heating value (LHV) compared to diesel fuel, miscibility and stability problems when blended with diesel fuel, low cetane number, high auto-ignition temperature and poor lubricating characteristics [4–7]. Although several approaches have been adopted to try to solve or alleviate the problems, there are still some challenges during their practical applications. For example, on the one hand, immiscibility can be overcome by using emulsifiers to form a micro-emulsion with methanol or ethanol [5], or by directly injecting them into the air intake [3,8], both of which could be combined with the preheating of intake air to improve ignition

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and vaporization [5]. However, these processes require either complex engine hardware modifications or skilled technical expertise, making it unattractive for applications. On the other hand, blending methanol or ethanol with diesel with certain stabilization additives and cetane enhancers seems to be preferred because of its simplicity with no need to modify the engine. However, the percentage of alcohols in the blended fuels can be limited, e.g. 5–10%, and additives could be costly [2,5].

The use of long-chain alcohols such as butanol and pentanol blended with diesel fuel has recently received considerable research attention as alternative fuels for diesel engines [4,6,7,9–15]. They provide advantages over short-chain alcohols as they provide higher LHV, higher energy density and cetane number, better miscibility with diesel, and have less hygroscopic (i.e., less-corrosive problems), while keeping lower self-ignition temperature, vaporization latent heat and knock tendency [4,6]. These fuels can thus be blended with diesel fuel in a higher fraction. An additional attractive advantage of butanol and pentanol is that they could be produced from biological pathways such as natural microbial fermentation of engineered micro-organisms and biosynthesis from glucose, with the production of these higher alcohols consumes less energy due to their longer carbon chains when compared to methanol and ethanol [16,17]. However, the mass availability of long-chain alcohols is currently far from the well-established commercial ethanol production, and novel cost-efficient synthesis of these alcohols from biological sources is currently under investigation [16,17]. In recent years, an extensive research has been carried out on the use of various butanol–diesel blends in diesel engines, and the effects of the butanol–diesel blends on the engine performance, engine combustion, and exhaust emissions with the engine operating under steady and transient conditions are identified [11–15]. Apart from butanol, pentanol is a second-generation fuel, 5-carbon structure alcohol, and a more attractive additive to diesel than butanol because its fuel properties are closer to those of petroleum diesel compared with butanol. A few recent studies have been conducted to explore the use of pentanol–diesel blends in diesel engines [6,7,9,10]. These studies found that pentanol–diesel blends have no solubility or stability problems with up to 30% pentanol by volume in the blended fuels [6], show better combustion characteristics, better engine performance, and lower soot and particulate emissions [7,9,10].

It is known that apart from the DPM mass, other physical characteristics of DPM and also its chemical composition determine its potential influence on the environment and human health. We have recently conducted experiments to evaluate the influence of butanol–diesel blends on carbonaceous composition and particle number size distributions [18]. However, no studies have been reported to date on determining the physical and chemical properties of particles emitted from an engine fueled with pentanol–diesel blends. This knowledge is needed in order to improve our understanding of the environmental and health benefits associated with the use of long-chain alcohol–diesel blends. The current work is among the first study of its kind to characterize and compare the effects of blending butanol and pentanol with diesel fuel on DPM emission characteristics under different engine operating conditions. The objective is to provide insights into the potential advantages and disadvantage of using both butanol–diesel and pentanol–diesel blends for controlling the emissions of carbonaceous particulates from diesel engines. Specifically, the influence of blending 10% and 20% of butanol or pentanol (by volume) with ultralow sulfur diesel on engine performance, particulate mass, volatile and solid particle number emissions and their size distributions was investigated and compared. This work further examined the effects of these blended fuels on the composition of carbonaceous particulates including EC (elemental carbon), OC (organic carbon) and WSOC (water-soluble organic carbon). We selected a non-road diesel engine for this study as such engines are widely used and emit a substantial fraction of DPM on a global level because they have limited emission control measures. For example, the U.S. Environmental Protection Agency (EPA) estimates that non-road diesel engines contribute to about 44% of the DPM emissions nationwide [19].

2. Experimental setup

2.1. Test engine and fuels

The schematic of the experimental system employed in this study is shown in elsewhere [20]. Experiments were carried out on a single cylinder, naturally aspirated, four-stroke, direct-injection diesel engine (L70AE, Yanmar Corporation) connected to a 4.5 kW generator. The diesel engine has a displacement of 296 cm^3 (cc) with bore and stroke of 78 and 62 mm, respectively and a fixed speed of 3000 rpm (revolutions per min). The main specifications of the engine are shown in elsewhere [20]. The generator was connected with several resistance heaters, and the engine load was adjusted by the variation of the total resistance. Other similar diesel engines have been used in other studies for investigating the influence of long-chain alcohols–diesel blends on engine exhaust emissions [7,13].

ULSD with less than 10 ppm by weight of sulfur was used as the baseline fuel. Anhydrous n-butanol and n-pentanol with the purity of 99.8% and 99% were purchased from Sigma–Aldrich as the long-chain alcohols, respectively. In this study, two kinds of blended fuels were prepared by the volume proportion of 10% and 20% of each alcohol in the ULSD, and are identified as D90B10, D80B20 for the butanol–diesel blends and D90P10, D80P20 for the pentanol–diesel blends, respectively. The major properties of each fuel are provided in Table 1.

2.2. Particulate sampling and testing

A two-stage Dekati mini-diluter (DI-1000, Dekati Ltd.) was used for diluting the engine exhaust for sampling and online evaluation. The diluter provides primary dilution in the range of 8:1–6:1, depending on the engine operating conditions, while the secondary dilution system provides a further dilution of 8:1. The actual dilution ratio for each stage was determined by simultaneously measuring CO_2 concentrations in the raw exhaust, in the background air and in the diluted exhaust, using a non-dispersive infrared analyzer (MRU VarioPlus, Germany, ±0.5% accuracy). This measurement was done for every test, and all data presented in this

Table 1
Properties[a] of ultralow sulfur diesel (ULSD), butanol and pentanol.

Properties	ULSD	n-Butanol	n-Pentanol
Chemical formula	–	C_4H_9OH	$C_5H_{11}OH$
C (wt.%)	86.6	64.9	68.2
H (wt.%)	13.4	13.5	13.6
O (wt.%)	–	21.6	18.2
Sulfur content (mg/kg)	<10	–	–
Lower heating value (MJ/kg)	42.5	33.1	34.7
Heat of evaporation (kJ/kg)	250–290	585	308
Density (kg/m^3)@20 °C	827	810	814
Viscosity (mPa s)@40 °C	2.86	2.22	2.88
Cetane number	52	17	20
Flash point (°C)	71	35	49
Boiling point (°C)	210–235	117	138
Ignition temperature (°C)	200–220	343	300
Stoichiometric air–fuel ratio	14.7	11.2	11.8

[a] Data have been taken from Refs. [7,9,14].