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Investigation of particulate emission characteristics of a diesel engine fueled with higher alcohols/biodiesel blends

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HIGHLIGHTS

- Blending butanol or pentanol with biodiesel changed the DPM characteristics.
- The blends reduced EC and DPM emissions, but increased WSOC and OC fractions.
- They reduced emissions of total particle-phase PAHs and also carcinogenic potential.
- They showed different effects on counts of nanoparticles and lager particles.

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ABSTRACT

A systematic study was conducted to make a comparative evaluation of the effects of blending n-butanol and n-pentanol with biodiesel at 10% and 20% by volume on engine performance and on the physico-chemical characteristics of particulate emissions from a single cylinder, direct injection diesel engine. The engine was operated at a constant engine speed and at three engine loads. Compared to biodiesel, butanol–biodiesel blends lead to a maximum of 1.6% increase in the brake thermal efficiency (BTE) and an increase in the brake specific fuel consumption (BSFC) by 1.9–3.9% at low and medium engine loads. Pentanol–biodiesel blends result in an improvement in the BTE and a maximum of 2% increase in the BSFC. Compared to biodiesel, both the blended fuels can reduce the particulate mass and elemental carbon (EC) emissions, with butanol being more effective than pentanol. The blended fuels also show a lower emission of total particle-phase polycyclic aromatic hydrocarbons (PAHs) and also a lower carcinogenic potential. However, the proportion of particulate-bound organic carbon (OC) and water-soluble organic carbon (WSOC) are increased for the both blended fuels, especially for 20% butanol in blends. The emissions of volatile and solid particles are reduced significantly in terms of their counts for both kinds of blended fuels at medium and high engine loads, whereas the total particle counts for both 10% and 20% butanol in blended fuels are increased at low engine load due to a significant increase in particles with diameter less than 15 nm.

1. Introduction

Research on the use of sustainable and cleaner fuels in internal combustion (IC) engines for both mobile and stationary applications continues to receive considerable attention because of the motivation to reduce our dependence on conventional fossil fuels and to mitigate environmental and health impacts [1]. Among the proposed alternative fuels, biodiesel and alcohols are the most widely investigated ones in diesel engines for reducing diesel fuel consumption and toxic emissions [2–4]. Biodiesel is renewable, nontoxic and readily biodegradable, has no aromatic compounds, and possesses a high cetane number, high flash point and also excellent lubricity performance [5–7]. It has been widely reported that substantial reduction in hydrocarbon (HC), carbon monoxide (CO) and diesel particulate matter (DPM) emissions can be achieved through the application of biodiesel from various feedstocks in diesel engines [2–6]. Despite its many advantages, the direct application of pure biodiesel, or the use of high percentage of biodiesel in diesel blends may cause a poor atomization and incomplete combustion, carbon deposits or clogging of fuel lines, as well as thickening and gelling of the engine lubricating oil due to its poor volatility and high viscosity [6,8–10]. These major drawbacks of biodiesel limit its proportion in diesel blends, typically about 20% [10]. Apart from biodiesel, lower alcohols, mainly methanol and ethanol, in combination with diesel fuel, have been

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widely investigated for reducing the NO_x and the particulate emissions [3,4]. However, some practical difficulties prevent their use as fuels in diesel engines, such as reduced 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 properties [8–10].

Although several approaches have been attempted to resolve or alleviate the problems, there are still some challenges when applying these lower alcohols into practical applications. For example, on the one hand, immiscibility can be overcome by using emulsifiers to form a micro-emulsion with methanol or ethanol [9,10], or by directly injecting them into the air intake [11]; both of these alcohols could be combined with the preheating of intake air to improve ignition and vaporization [9,10]. However, these processes require either skilled technical expertise, or complex engine hardware modifications making these options unattractive for practical applications. On the other hand, blending diesel with methanol or ethanol with certain stabilization additives and cetane enhancers seems to be preferred because of its simplicity with no need to modify the existing engine. However, the percentage of alcohols in diesel blends is usually restricted to 5–10%, and additives could be costly [9]. The use of higher alcohols such as butanol and pentanol blended with diesel fuel in diesel engines has recently drawn considerable research attention due to higher miscibility with diesel [12–17]. However, the fuel properties such as lubricity, viscosity, and cetane number of higher alcohols–diesel blends still need to be improved [12].

Blending of biodiesel with both lower and higher alcohols can simultaneously overcome the above-mentioned disadvantages of biodiesel and alcohols and has therefore been extended to their application in diesel engines [5,7–10,18–21]. For example, biodiesel and alcohols are miscible to some extent without any need for an emulsifier or a co-solvent. In the blended fuels, the lower viscosity and higher volatility of alcohols compensates for these opposite properties in biodiesel. Likewise, the lower cetane number of alcohols could be improved with the simultaneous use of the higher cetane value of biodiesel. Meanwhile, with the increased amount of oxygen content in blends, complete fuel combustion can be achieved. Extensive research has recently been carried out on the use of various methanol–biodiesel and ethanol–biodiesel blends in diesel engines [5,7,9,21]. From those previous studies, it has become clear that methanol and/or ethanol blended with biodiesel decreases NO_x and DPM emissions while there are mixed results in terms of CO and HC emissions depending on the relative proportion of methanol or ethanol used as well as the engine operating conditions. Recently, Laza et al. [8] and Kumar et al. [18] revealed that fuel properties such as lubricity, viscosity and cetane number can also be improved by blending higher alcohols with biodiesel. These blended fuels were more suitable for applications in diesel engines than methanol–biodiesel or ethanol–biodiesel blends. Subsequently, Tosun et al. [19] compared the effects of blending 20% methanol, ethanol and butanol by volume with peanut methyl ester on fuel properties, engine performance, and exhaust emissions. They concluded that butanol–biodiesel blends showed higher engine power and torque, higher reductions of CO emissions than both methanol–biodiesel blends and ethanol–biodiesel blends. Meanwhile, Yilmaz et al. [10], Kumar et al. [18] and Rakopoulos [20] explored the effects of butanol–biodiesel blends on diesel engine performance and exhaust emissions, respectively. These studies revealed the beneficial effects of using various blends of butanol with diesel fuel on CO, smoke and DPM emissions at various engine loads.

There has been no systematic investigation on the quality of engine emissions when being fueled with pentanol–biodiesel blends, to the best of our knowledge. Meanwhile, the effect of blending biodiesel with both butanol and pentanol on the physical and chemical characteristics of diesel particulate emissions remains unknown. This knowledge is needed in order to improve our understanding of the environmental and health benefits associated with the use of biodiesel and higher alcohols blends. The aim of this study was to make a comparative evaluation of the impact of butanol–biodiesel and pentanol–biodiesel blends on the performance of diesel engines and on the physico-chemical characteristics of particulates emitted under different operating conditions. Specifically, the influence of pure biodiesel, and biodiesel blended with 10% and 20% of butanol or pentanol (by volume) on particulate mass, volatile and solid particle number concentrations and their size distributions were investigated. This work further examined the effects of these fuel blends on the composition of carbonaceous particulates including EC (elemental carbon), OC (organic carbon), WSOC (water-soluble organic carbon), and the toxic polycyclic aromatic hydrocarbons (PAHs). 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 [22]. Similar diesel engines have been used in other studies for investigating the influence of higher alcohols/biodiesel blends on engine exhaust emissions [18,20]. However, these engines are different from those used in on-road vehicles, equipped with modern technology. The outcome of the current study may offer insights into the effect of biodiesel blended with higher alcohols on the quality of particulate emissions from non-road diesel engines, and prove to be useful for future assessments of environmental and health benefits of these fuel blends.

2. Experimental setup

2.1. Test engine and fuels

The schematic of the experimental system employed in this study is shown in our previous publication [23]. 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 with bore and stroke of 78 and 62 mm, a fixed speed of 3000 rpm (revolutions per min). The main specifications of the engine are shown in [23]. The fuels used include ultralow sulfur diesel (ULSD) with less than 10 ppm (parts per million) by weight of sulfur, methyl esters of waste cooking oil (WCO) as biodiesel, n-butanol (Sigma–Aldrich, 99.8%, anhydrous), and n-pentanol (Sigma–Aldrich, 99%, anhydrous). The biodiesel used in this study was obtained from Alpha Biodiesel Pte Ltd in Singapore, and the fuel properties are provided by the biodiesel supplier. The two kinds of blended fuels were prepared by the volume proportion of 10% and 20% of each alcohol in biodiesel, and are identified as B90Bu10, B80Bu20 for the butanol–biodiesel blends and B90P10, B80P20 for the pentanol–biodiesel blends, respectively. Pure diesel fuel and biodiesel are identified as D100 and B100, 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-2000, Dekati Ltd) was used for diluting the exhaust gas for particulate sampling and online testing. 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