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Combustion and emission characteristics of diesel engine fueled with diesel/biodiesel/pentanol fuel blends

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HIGHLIGHTS

- First study on combustion characteristic of diesel/biodiesel/pentanol with CI mode.
- Pentanol addition with diesel/biodiesel shows improved fuel/air mixing.
- Pentanol blends shows advanced CA50 and shorter combustion duration.
- Pentanol blends presents low emissions while maintaining higher ITE.

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ABSTRACT

Pentanol is one of the next generation biofuels that could potentially help relieve the energy crisis and environmental problems. The objective of this study is to reveal the effects of pentanol addition to diesel and biodiesel fuels in different ratios on the combustion and emission of a single-cylinder direct-injection diesel engine. The tests were conducted at a constant speed (1600 r/min) under different engine loads without exhaust gas recirculation. The indicated thermal efficiency using pentanol blends was found to be higher than that of using pure diesel for all of tested loads from 0.5 to 1.0 MPa indicated mean effective pressure at the test conditions, which is due to its higher maximum heat release rate and shorter combustion duration. An obvious decrease in soot emissions was attained with the addition of pentanol. Moreover, emissions of nitrogen oxides (NO_x) were simultaneously reduced compared with using pure diesel fuel at low to middle loads. Furthermore, diesel engine fueled with oxygenated fuel blends can reduce the carbon monoxide and unburnt total hydrocarbons emissions except for the diesel–pentanol blends at low engine load. Finally, the strategy with 40% diesel–30% biodiesel–30% pentanol showed better combustion, emission characteristics as well as economy performance among all the fuels.

1. Introduction

Increasingly stringent emission regulations and concerns over energy security have recently led to extensive increasing interest in alternative renewable fuels. Except for advanced combustion modes, the idea of using oxygenated fuels as alternatives to reduce diesel emissions has been studied for many year. Recently, many researchers focused their attention on fuel design for low emissions and better combustion control [1,2]. Among all oxygenated biofuels, alcohols have been widely investigated in the past decades, especially methanol [3–6] and ethanol [7–11]. However, in recent years, a strong interest in alcohols with longer carbon chain, such as butanol, whose molecule containing four carbons, has emerged because of their favorable physical and thermodynamic properties [12]. For example, higher alcohols have the potential to overcome the drawback of low energy density of small-molecule alcohols and can achieve better miscibility with diesel fuel [13]. Meanwhile, higher alcohols offer benefits in reducing soot and carbon monoxide (CO) emissions at constant specific nitrogen oxides (NO_x) emission in a diesel engine [14].

Recent studies found that the properties of oxygenated fuels, such as volatility, oxygen content, latent evaporation heat and cetane number (CN) do impact the combustion and emission characteristics significantly. Wang et al. [15] proposed a fuel design scheme including diesel, biodiesel and dimethyl carbonate (DMC) to meet the Euro IV emission regulation without using any after-treatment device. Yilmaz et al. [16] conducted experiments with different types of blended fuels with diesel, biodiesel, alcohols and vegetable oil in a two-cylinder diesel engine. They observed

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decreased NO_x emissions and increased CO, total hydrocarbon (THC) emissions by adding alcohols. Sharon et al. [17] compared the effects of different blended fuels of diesel, used palm oil and butanol on a DI diesel engine. Results showed that a reduction of smoke opacity, NO_x emissions and an improvement on brake thermal efficiency (BTE) were achieved with butanol addition. Hulwan et al. [18] found an obvious reduction in smoke for diesel–ethanol–biodiesel blends, where biodiesel was used as a co-solvent for diesel–ethanol blends of high ethanol content. Engine tests using diesel–biodiesel–butanol blends were carried out by Zhang et al. [19] on a single cylinder engine and results showed that the addition of butanol could effectively reduce both particulate mass and total particle number concentrations. Tüccar et al. [20] concluded that engine emissions of NO_x, CO and smoke opacity were improved with butanol addition.

Similar to butanol, pentanol is one of the next-generation biofuels with a five-carbon molecular structure, which can be produced from renewable feedstock [21,22]. Pentanol has an even higher energy density compared to butanol, which could further improve the fuel economy. In addition, compared to small-molecule alcohols, pentanol has higher cetane number and is thus easier to auto-ignite. These properties provide better compatibility with conventional diesel engines and existing fuel distribution infrastructure. However, few studies on the use of pentanol as an alternative fuel or fuel additive have been reported in compression ignition engines. Yang and Dec [23] studied the fundamental combustion characteristics of iso-pentanol in homogeneous charge compression ignition (HCCI) engines, and found that iso-pentanol has higher HCCI reactivity than gasoline and ethanol. Wei et al. [24], Campos-Fernandez et al. [25] found that diesel–pentanol blends could significantly reduce both the mass and number concentrations of particulate matter, and improve the brake thermal efficiency without adverse influences on combustion with respect to the diesel fuel. Besides, several fundamental experimental [26,27] and modeling studies [28] for pentanol combustion also drew many researchers' attention recently.

The objective of this research is to evaluate the potential of adding pentanol to different diesel–biodiesel blended fuels in order to improve the overall fuel performance and thus attain an overall good engine performance. On one hand, the addition of pentanol with lower viscosity and high volatility could improve the atomization quality of diesel–biodiesel blends, and the higher oxygen content in pentanol could reduce soot emission. On the other hand, biodiesel's higher cetane number could maintain the ignition quality for the blended fuels. Finally, a promising multi-component blending strategy is determined to attain the higher percentage of oxygen content but at the same time keeping important fuel properties such as density, viscosity, volatility and cetane number within acceptable limits.

2. Experimental setup and test procedure

2.1. Test engine

In this work, a single cylinder, four-stroke diesel engine retrofitted from a four-cylinder engine was employed. The main engine specifications are listed in Table 1.

The engine is connected to an electric dynamometer, which is capable of producing 110 kW and rated at a maximum speed of 4000 rpm. The engine electronic control unit (ECU) is modified into an open module, which allowed us to flexibly control the injection parameters, such as injection pressure, number of injection events, and injection timing. The tests were carried out after the temperature of the lubricating oil and cooling water have reached 85 °C to ensure that the engine was at its steady condition.

Table 1
Engine specifications.

Compression ratio	16.7
Bore (mm)	83.1
Stroke (mm)	92
Connecting rod length (mm)	145.8
Number of valves	4
Displacement (*L*)	0.5
Injector	7 holes, 0.136 mm diameter
Injection system	Common rail
Intake valve open (°CA BTDC)	24
Intake valve close (°CA ABDC)	50
Exhaust valve open (°CA BBDC)	86
Exhaust valve close (°CA ATDC)	16

2.2. Test fuel

Table 2 lists the main properties of diesel, biodiesel, pentanol and test fuels used in the study. The commercial 0# diesel with the cetane number of 56.5 is used as the baseline fuel. It is seen that pentanol has a lower CN, surface tension, density and boiling point compared to the diesel fuel. Biodiesel, on the other hand, has the highest CN, surface tension, density and boiling point among the three neat fuels. Meanwhile, due to higher viscosity, biodiesel has poor atomization property compared with diesel [29].which could be improved with the addition of pentanol. In this study, three different blended fuels, D70P30 (70% diesel, 30% pentanol), D70B30 (70% diesel, 30% biodiesel) and D40B30P30 (40% diesel, 30% biodiesel and 30% pentanol) were prepared at the mixing ratio of volume. Because of the relatively low boiling point of pentanol, addition of pentanol into the blended fuels could lead to rapid vaporization and thus improve atomization efficiency. Since mixing of the higher volatility with the lower one could promote the evaporation of lower one [30], this presents a fuel design approach to optimize the spray characteristic of the fuel blends. On the other hand, the addition of biodiesel with higher ignitability can enhance the ignition characteristic of the blends.

2.3. Test facilities and methods

The schematic of the experimental set-up is shown in Fig. 1. In this test, the cylinder pressure was sampled with an AVL GH14P transducer and recorded with the data acquisition system (AVL Indimodul 621) at a resolution of 0.5°CA. Heat release and other combustion analysis parameters were calculated from the averaged cylinder pressure of 200 consecutive cycles. Turbocharger was removed from the engine and an external air compressor was used to supply intake air. The AVL 439 opacimeter was employed to measure smoke, and the light absorption coefficient k is used for the soot scale. The gaseous emissions, including NO_x, CO, CO_2 and HC, were measured by the AVL CEB-II exhaust gas analyzer. The fuel consumption was measured by an FCM-D digital fuel meter with a resolution of 0.1 g.

Engine tests were carried out at six steady loads and the constant speed of 1600 rpm and no exhaust gas recirculation (EGR) was used. Engine load was swept from Indicated Mean Effective Pressure (IMEP) of 0.5–1.0 MPa. All test data was acquired with constant intake pressure of 0.12 MPa. The same double injection strategies were implemented for all fuels. For pilot injection, 10% of total fuel amount was delivered at the 17°crank angle (CA) before top dead center (BTDC), and the main injection timing was 1° CA BTDC. Meanwhile, the injection pressure was maintained at 80 MPa.

Considering the lower heating value (LHV) difference between the oxygenate fuel blends and diesel, the fuel consumption for oxygenate fuel blends was scaled with the same LHV of diesel for a fair comparison, according to the following equation: