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Combustion and emissions of compression ignition in a direct injection diesel engine fueled with pentanol

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A B S T R A C T

Pentanol is a new generation bio-fuel that could help relieve the energy crisis and environmental problems. The objective of this study is to reveal the combustion and emission characteristics of pentanol in a single-cylinder direct-injection diesel engine. In the present investigation, experimental data for pentanol in conventional diesel combustion mode were presented. The emissions, combustion characteristics and thermal efficiency for pentanol and diesel fuel were obtained under the same operating conditions. Results show that NO_x and soot emissions decrease significantly for pentanol with comparable efficiencies under single injection strategy without EGR (exhaust gas recirculation). Especially, the lowest NO_x emission is 0.23 g/kW h while the soot is negligible for pentanol at 1600 rpm and 0.6 MPa IMEP (Indicated Mean Effective Pressure). Pentanol fuel offers obvious characteristics to achieve a smoother heat release rate with reduced peak pressure-rise rate in contrast to the diesel fuel.

1. Introduction

Renewable fuels are being embraced throughout the world as a source of alternatives to fossil fuels due to their potential of improving energy security and reducing pollutant emissions for transportation vehicles. In addition, the biofuels could also balance the greenhouse gas emissions which are considered as the main factor for global warming. In the past decades, an extensive amount of studies on the short chain alcohols, especially methanol and ethanol, have been conducted, including those on performances and emission characteristics in diesel engines [1–3].

However, in recent years, a strong interest in higher alcohols, containing four or more carbons, as a renewable bio-based resource has emerged because of their favorable physical and thermodynamic properties [4]. Thus, higher alcohols can be used as fuel additives to improve the low temperature fluidity of palm oil [5]. Further, higher alcohols have the potential to overcome the drawback of lower alcohols due to the higher cetane number and better miscibility in diesel fuel [6].

Butanol is a higher alcohol with a 4 carbon structure and it has been widely investigated as a fuel or fuel additive recently [7]. Butanol can be used safely in diesel engines with favorable exhaust emissions [8]. Valentino et al. [9] found that a noticeable decrease in soot emissions was achieved because of the longer ignition delay of butanol blends. Moreover, Yao et al. [10] concluded that the butanol addition can reduce the regular emissions without an adverse influence on brake specific fuel consumption and NO_x emissions.

Pentanol is an attractive next-generation bio-fuels with 5-carbon structure, which can be produced from renewable feedstock [11,12]. Compared to the more frequently investigated short chain alcohols, pentanol has the advantage of having higher energy density, higher heating value, higher viscosity, lower hygroscopicity and lower volatility. These properties provide better compatibility with conventional diesel engines and existing fuel distribution infrastructure. However, significantly less work on pentanol have been reported in compression ignition engines. It is imperative to understand the basic combustion properties of pentanol in the modern CI (compression ignition) engines.

Yang et al. [13] studied the fundamental combustion characteristics of iso-pentanol in HCCI (homogeneous charge compression ignition) engines, in which the intake charge of iso-pentanol was fully premixed. The results indicated that iso-pentanol had higher HCCI reactions than gasoline, and showed high ITHR (intermediate-temperature heat release), which was important for extending HCCI to high-load operation without knock. Javier Campos-Fernandez et al. [14] investigated the power and fuel economy performance of diesel/pentanol fuel blends (in a range

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between 10% and 25% volume pentanol) on a direct-injection Perkins diesel engine, and the results showed that a slight power reduction and an improvement on brake thermal efficiency was achieved with low volume ratio of pentanol addition. Wei et al. [15] evaluated the effects of different pentanol–diesel blends (10, 20 and 30% by volume) in a naturally-aspirated direct injection diesel engine. Engine tests showed that the n-pentanol addition could significantly reduce both the mass concentration and number concentration of particulate matter, while NO_x increased slightly.

Furthermore, fundamental experiments and detailed kinetic modeling studies for pentanol/iso-pentanol combustion had also attractived many researchers' attention recently. Tsujimura et al. [16] developed a detailed chemical kinetic model for isopentanol and used to simulate HCCI combustion. Dayma et al. [17] measured the concentration of stable species in a JSR (jet stirred reactor) over a range of equivalence ratios and temperatures at 10 atm, and proposed a detailed chemical kinetic model of isopentanol. More recently, a detailed reaction mechanism of iso-pentanol including a wide range of temperature, pressures and equivalence ratios was developed by Sarathy et al. [18], and validated against the previous and new experimental data. Their results show that 1-pentanol is more reactive than iso-pentanol. Heufer et al. [19] reported a detailed kinetic model for n-pentanol based on modeling rules of C4-alcohols. The proposed model shows good agreement with the ignition delay time data [20], species concentration data of JSR and laminar flame velocity [21]. All these studies revealed the beneficial effects of the pentanol as a diesel blend.

Growing attention is being converged on the oxygenated pentanol as an alternative fuel or additives for fossil fuels, and more experimental data was needed urgently to obtain an in-depth understanding for the influence of the pentanol parameters on engine performance. In particular, there is no experimental investigation on effects of neat pentanol in direct injection compression ignition diesel. The aim of the present study is to evaluate the emission performance, fuel economy and combustion characteristic of neat pentanol in a modern diesel engine. The combustion type of pentanol is a typical spray-diffusion combustion, and the results are compared with the baseline diesel data.

2. Experimental setup and test procedure

2.1. Test engine

The experiments were performed in a single cylinder, four-stroke, water-cooled, direct injection diesel engine, which is retrofitted from a Euro 4 light-duty four-cylinder engine by deactivating cylinders 2–4. The engine with a common rail injection system was connected to an electric dynamometer, which was capable of producing 110 kW and was rated at a maximum speed of 4000 rpm. The engine was controlled by an open ECU (electronic control unit), which could control injection parameters flexibly, such as injection pressure, number of injection events and injection timing. In the experiment, lubricating oil and cooling water were maintained at 85 °C to ensure that the engine was at best condition. Table 1 gives the main engine specifications and Fig. 1 shows a schematic of the experimental set-up.

2.2. Test fuel

Table 2 lists the main properties of diesel and pentanol used in the study, and the properties of butanol are also provided in Table 2 for comparison. The commercial 0# diesel with the cetane number of 56.5 is used as the baseline fuel. The pentanol used in this study was neat fuel which was obtained from Tianjing Fucheng chemical reagent factory (purity > 98.5%). Compared to diesel fuel, pentanol has a lower CN (cetane number) and is less prone to auto-ignition. However, the characteristics of relatively long ignition delay may be beneficial for improving local mixing and forming more premixed combustion. Kalghatgi et al. [22–24] found that the autoignition resistance of the fuel is the most important property to achieve low emissions for PPCI (partially premixed compression ignition) mode. The gasoline-like fuel were studied subsequently by Manente et al. [25], Shi et al. [26], Zhang et al. [27], and Yang et al. [28] under different operating conditions for CI engine. Similar to the gasoline-like fuel, pentanol is more resistant to auto-ignition than diesel fuel. Meanwhile, due to lower viscosity and lower boiling point, pentanol has better evaporation property than diesel, which could improve atomization efficiency. When compared to diesel, the in-cylinder combustion temperature of pentanol is lower due to its higher heat of evaporation, resulting in less NO-formation [29]. Pentanol is an oxygenated fuel, thereby providing the potential to reduce soot emissions in diesel engines. Two fuels have similar density. Pentanol has a greater similarity to diesel fuels in physiochemical properties and better water tolerance than C_1–C_4 alcohols.

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,0.19 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

2.3. Test facilities and methods

Cylinder pressure was measured with an AVL GH14P transducer and recorded with the data acquisition system (AVL Indimodul 621) at a resolution of 0.5 deg CA. Heat release and other combustion analysis parameters were calculated from the averaged cylinder pressure of 200 consecutive cycles. Fuel consumption was measured by an FCM-D digital fuel meter with a resolution of 0.1 g.

The AVL 439 opacimeter was employed to measure soot in the exhaust gas. The gaseous emissions, including NO_x, CO (carbon monoxide), CO_2 and THC (total hydrocarbon), were measured by the AVL CEB-II exhaust gas analyzer. The entire engine-out emissions were averaged over 60s under steady state conditions. Table 3 reports the accuracy of the main acquired data.

The experiments were conducted by sweeping the injection timing at constant engine speed of 1600 rpm and constant load of IMEP (Indicated Mean Effective Pressure) 0.6 MPa while no EGR was used. All test data was acquired with constant intake pressure of 1.2 bar, and constant IP (injection pressure) of 80 MPa for both fuels. For the diesel, single and double injection (a pilot injection and a main injection) strategies are both implemented in this investigation. For the double injection strategies, 10% of total fuel amount was delivered during pilot injection, the dwell between pilot and main injection was fixed at 16°CA while the main injection timing varies. The pentanol was also tested under the same condition with single injection strategy.

After each fuel test, the previous fuel was flushed out from the fuel lines and injection system and the engine was running with the new fuel for at least 10 min before the next test.

Considering the LHV (lower heating value) difference between pentanol and diesel, the fuel consumption for pentanol was scaled