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Ignition and combustion characteristics of *n*-pentanol–diesel blends in a constant volume chamber

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HIGHLIGHTS

- Fuel's ignition and combustion characteristics are measured by different method.
- Diesel blends containing 20% and 40% *n*-pentanol are examined.
- D60P40 advances ignition phase over D80P20 under low oxygen content conditions.
- Flame luminosity is reduced with the increase of pentanol ratio in most conditions.
- Pentanol could significantly accelerate soot oxidation under all conditions.

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ABSTRACT

Pentanol is considered as one of the most promising alternative biofuels due to its excellent physicochemical properties. The objective of this work was to compare the ignition and combustion characteristics of different *n*-pentanol/diesel blends in an optical constant volume combustion chamber. The tested fuels included 20% (D80P20) and 40% (D60P40) of *n*-pentanol blended with diesel in volume, and pure diesel (D100). Broadband chemiluminescence technique was used to measure the timing and location of spray ignition. A high-speed CCD camera with two ND8 dimmer lenses was used to capture the incandescence radiated from the soot particles during combustion. A wide range of experimental conditions was investigated. The ambient temperature ranged from 800 K to 1200 K and the oxygen concentration ranging from 10% to 21%, covering both the conventional and low temperature combustion regimes. The results show that pure diesel has shorter ignition delay and distance comparing to pentanol blends. A larger blending proportion of pentanol D60P40 advances the ignition phase more than the D80P20 in low oxygen concentration conditions. Due to the fuel-borne oxygen and the dilution effect, the natural flame luminosity is reduced significantly with the increase of pentanol ratio in most conditions except under the intermediate temperature region of 1000 K. In that condition, the shorter ignition delay and flame lift-off length of pentanol blends cause a slightly increase in the natural flame luminosity. The natural flame luminosity images showed that the oxygen-contained structure of pentanol could accelerate soot oxidation under all conditions. This indicates that pentanol blends could decrease final soot emissions in internal combustion engines.

1. Introduction

Diesel engines are widely used in modern transport, power generation, agriculture and irrigation systems due to their high thermal efficiency [1–6]. However, the high NOx and soot emissions and the fast depletion of fossil fuel resource greatly limit the development of diesel engines due to the recent rigorous regulations on pollutant emissions and fuel consumption. In the last two decades, biofuels have obtained growing interest worldwidely as alternatives or supplements in mobile vehicles due to their potential of improving energy security and reducing pollutant emissions [7,8]. Biofuels are composed of or produced from biological raw materials, and mostly environment-friendly. Besides, biofuels also help reduce the carbon dioxide emissions [9], which can contribute to the domestic and international targets of greenhouse gas reduction. Therefore, many countries have established corresponding policies to advocate the use of renewable biofuels for petroleum-based ones. For example, Renewable Fuel Standard (RFS) program [10] was proposed by the U.S. government and the 2030 Frame-

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work for climate and energy [11] was put forward by the EU Commission.

Among all the alternative fuels, short-chain alcohol-based biofuels, such as methanol and ethanol, have received significant attention due to their mature production technology and high oxygen content [12,13], which could effectively improve the combustion characteristics and reduce the soot emissions [14]. However, the low cetane number, high latent heat of vaporization, miscibility and stability problems when blended with diesel fuel greatly limit the application of short-chain alcohols as alternative fuels for diesel engines [15]. Long-chain alcohols containing four or more carbons have significant advantages over short-chain alcohols when using in diesel engines. Long-chain alcohols have higher energy density and higher cetane number than short-chain alcohols. They also present better blend stability and could be blended with diesel in large blend ratios. Moreover, less hygroscopic nature of higher alcohols makes it easier to store and transport [16]. Butanol is a four-carbon alcohol and has been widely investigated as an alternative fuel or fuel additive in recent years [17,18]. Experimental studies on the engines fueled with butanol-diesel blends showed that lower exhaust emissions could be achieved with slight impact on engine performance [19–21]. Butanol also showed a good exhaust gas recirculation (EGR) tolerance due to its oxygen-containing structure, and a simultaneous reduction of smoke and NOx emissions could be achieved while combining with the proper EGR ratio and injection strategy [22,23].

Pentanol, a long-chain alcohol with five-carbon structure, has attracted much attention recently and is regarded as a most potential next-generation biofuel. Pentanol can be produced from biological pathways like natural microbial fermentation of engineered micro-organisms [24] and biosynthesis from glucose [25]. Compared to butanol and other short-chain alcohols, pentanol has higher energy density higher, larger cetane number, better blend stability and less hygroscopic nature. These advantages make pentanol very competitive as an alternative fuel in diesel engines. By now, a few works on pentanol have been carried out in compression ignition engines [22,26–32]. It was found that *n*-pentanol blends had an obvious advantage over neat diesel fuel in reducing the nitrogen oxides emissions, particulate mass and number concentration, and increasing the brake thermal efficiency [21,30,32]. Li et al. [31] used pure pentanol in a single-cylinder direct-injection diesel engine. The results showed that NOx and soot emissions decrease significantly for pentanol with comparable efficiencies under single injection strategy without EGR. Kumar et al. [22,29] recently applied the combination of pentanol/diesel blends and a medium EGR rate (20–30%) to achieve simultaneous reduction of NOx and smoke emissions. The results showed that 45% pentanol/diesel blends could be used in diesel engines without any modifications, and would not cause any visible damage to the engine parts subject in long-term durability tests. Fundamental experimental [33–35] and kinetic modeling studies [36–38] for pentanol combustion were conducted to help understand and improve the efficient and clean application in diesel engines in the view of combustion chemistry.

The "diesel conceptual model" presented by Dec [39] and Musculus [40] shows that the combustion process in diesel engine is a complex process involving fuel atomization, vaporization, fuel-air mixing, ignition and combustion. They also confirmed that ignition and combustion characteristics of fuel spray are the key factors influencing the working performance and pollutant emission of diesel engines. Moreover, the experimental data on the ignition and combustion processes are indispensable to develop the combustion mechanism of fuels and validate the simulation results of computational fluid dynamic models. However, since it is difficult to control the environment and make observations due to the cycle-by-cycle variations and the complex engine geometry, investigating the ignition and combustion characteristics of fuels using engine experiments may be not a good choice. Out-of-engine optical experiments can provide valuable information for understanding combustion process [41–43]. Optically accessible constant volume chamber is a powerful tool to reproduce the ambient conditions relevant to thermal engines with good repeatability [44]. The main parameters such as temperature, gas density and oxygen contents can be adjusted easily. With corresponding visualization techniques such as high-speed schlieren imaging [45] and PLIF [46], the ignition and combustion processes of fuel sprays into engine-likes conditions could be recorded. A few works were conducted to investigate the effect of alcohol addiction on the ignition and combustion characteristics of diesel spray in engine-like conditions. Liu [47] investigated the flame propagation and soot formation of *n*-butanol/biodiesel/diesel blends in a constant volume combustion chamber. The results showed that low *n*-butanol addition had limited or no effect on the auto-ignition timing. Wu [48] investigated the combustion characteristics of acetone-butanol-ethanol (ABE) – diesel blends and found that the natural flame luminosity was reduced significantly with the increase of ABE ratio and ABE50 achieved a shorter ignition delay. However, to the best of the authors' knowledge, there are still lack of reports on the ignition and combustion characteristics of pentanol-diesel blends. Since the physical and chemical properties of long-chain alcohols are quite different from that of neat diesel and other shorter alcohols, it is worthwhile to understand how the long-chain alcohol influences the ignition and combustion process of blends.

In the present paper, an extensive investigation was conducted on the ignition and combustion characteristics of higher alcohol pentanol/diesel blends and conventional diesel fuel. The constant volume chamber was used to simulate the in-cylinder condition prior to injection in a real diesel engine. A wide range of experimental conditions was investigated. The ambient temperature ranged from 800 K to 1200 K and the oxygen concentration ranged from 10% to 21%. The different ambient temperature represents different operating conditions of a real engine, while the different oxygen level represents different EGR ratios were adopted. At the instant prior to injection, 800 K is the typical in-cylinder temperature in the low temperature combustion (LTC) engine while 1200 K stands for the highest in-cylinder temperature in a traditional heavy duty diesel engine. 10% oxygen content is roughly equivalent to the oxygen content in the cylinder of diesel engines with 50% EGR rate, while 21% oxygen content is equivalent to the oxygen content in the cylinder of diesel engines without EGR. These conditions represent the in-cylinder conditions prior to injection in a real diesel engine with both traditional and LTC technology. By using two target-oriented optical techniques, the detailed ignition and combustion information were systematically analyzed for pentanol blends and pure diesel, such as ignition time, ignition position, flame luminosity and flame lift-off length. Compared to the short-chain alcohol blends, the results revealed a more complex influence mechanism of ignition and combustion for higher alcohol pentanol/diesel blends, which is highly depended on the ambient conditions. The reported work expanded the understanding of high pentanol/diesel blends combustion and provided detailed experimental data to promote the application of the new-generation biofuel in diesel engines.

2. Experimental setup

2.1. High pressure chamber and injection system

A premixed combustion heated constant volume combustion bomb (CVCB) was used to simulate the in-cylinder conditions of a diesel engine at the time of injection. The schematic of the exper-