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Improvement of combustion performance and emissions in diesel engines by fueling *n*-butanol/diesel/$PODE_{3-4}$ mixtures

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HIGHLIGHTS

- The effects of loads in CI engine fueled with *n*-butanol/diesel/$PODE_{3-4}$ were studied.
- The effects of $PODE_{3-4}$ on particulate emission were studied for the first time.
- $PODE_{3-4}$ can improve efficiency and reduce emissions significantly.
- The addition of $PODE_{3-4}$ in *n*-butanol/diesel blend reduces CO and THC.
- $PODE_{3-4}$ can improve the accumulated particulate matters emission.

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ABSTRACT

Polyoxymethylene dimethyl ethers ($PODE_n$) are an excellent biofuel with no C—C bond and substantial soot-reduction potential. The effects of BMEPs on the characteristics of combustion performance and emissions in a four-cylinder direct injection diesel engine with *n*-butanol/diesel/$PODE_{3-4}$ blends were investigated. Mechanism of the PODE blends on soot reduction is discussed. The experimental results indicate that upon adding $PODE_{3-4}$ to the blend of *n*-butanol with diesel can improve the thermal efficiency and combustion efficiency with an increment in the brake specific fuel consumption (BSFC). As the BMEP increased, a decreasing trend was observed in the emissions of soot, CO, and THC, while increasing NO_x formation. Under a BMEP of 1.2 MPa, the soot emissions from the combustion of BD20, BDP10, and BDP20 reduced by 61.5%, 80.7, and 91.1%, respectively, compared to that from pure diesel. Under equal BMEP value, adding $PODE_{3-4}$ to *n*-butanol/diesel blend reduced the soot, CO and THC emissions, and the lowest soot and THC emissions were found for BDP20, followed by BDP10, BD20, and D100. The number concentration of the accumulated particulate matter as well as the mass concentration of total particulate matters can be decreased by adding $PODE_{3-4}$. The chemical kinetics simulation results reveal that C—O bonds break and CH_2O is first produced in the pyrolysis of $PODE_n$; as the value of n increases, more CH_2O is produced and further oxidized to form HCO, which is finally transformed into CO and CO_2, avoiding the production of soot precursors.

1. Introduction

At present, controlling the emission from diesel engines is a matter of primary importance for environmental reasons. An effective way to pursue this goal is to add oxygen-containing compounds to the diesel fuel [1,2]. With the aggravation of the global energy crisis, the world is experiencing a change in energy-related structures. Energy is no longer associated with petroleum resources only, but it tends to be diversified. By changing the physical and chemical characteristics of fuels, the combustion performance can be improved, promoting complete combustion and reducing the pollutant emissions of diesel engines without great modifications of their structure [3]. The component to be added should not only have a high cetane number value, but also show good mutual solubility with diesel, easy degradation and low cost; in addition, the raw materials should be easily accessible.

Recently, a number of alternative fuels have been studied, including natural gas [4–7], alcohol fuels [8–10], dimethyl ether [11–13] and biodiesel [14–16]. Biodiesel, as a diesel engine fuel, has many advantages [17]. First, it is a non-toxic biodegradable alternative fuel, which can be obtained from renewable sources. Second, it has been reported that diesel–oxygenate blends can yield lower exhaust emissions, especially in terms of particle emission. Third, the addition of

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oxygenates in the mixture can decrease the amount of aromatic hydrocarbons and sulfur in the fuel. Therefore, it is essential to investigate the effect of the content of oxygenates on the emission and combustion performance of the fuel in a diesel engine.

Among oxygenated fuels, *n*-butanol has a higher calorific value, cetane number and flash point with respect to methanol and ethanol, but a lower evaporation pressure and combustion temperature. In addition, it is more easily vaporized and is compatible with a larger range of air-fuel ratio values. It can also overcome the shortcomings of low-carbon-content alcohols applied to diesel engines [18]. In recent years, a great deal of research has been conducted on the effects of the addition of *n*-butanol to diesel, in terms of combustion performance and exhaust emissions [19–24]. These studies indicated that *n*-butanol is a promising additive for diesel. Zheng et al. [25] experimentally studied the effects of blending *n*-butanol into diesel fuels on the combustion performance and emissions characteristics in a modified single-cylinder diesel engine under two-stage injection and high EGR rate conditions. Their results showed that *n*-butanol/diesel blended fuels can reduce soot emissions compared to diesel, at the expense of increasing the NO_x emissions and the maximum pressure rise rate. Gerardo et al. found that the addition of *n*-butanol to diesel fuels improved soot and NO_x emissions because of decreasing cetane number and increasing oxygen content [26]. In addition, with increasing amount of *n*-butanol in the fuel, the soot and CO emissions decreased, while the HC emissions increased [27]. However, other studies have demonstrated that a large amount of *n*-butanol is detrimental to the combustion performance, leading to a higher specific fuel consumption and a lower thermal efficiency because of the low cetane number and heat value of *n*-butanol [28].

Polyoxymethylene dimethyl ethers (PODEn), $CH_3O(CH_2O)nCH_3$, are a new type of additive for diesel fuels. PODEn molecules show a favorable mutual solubility with diesel. In particular, $PODE_{3–4}$, with an oxygen content of 46.98%, has a higher cetane number than diesel [29], exhibits good ignitability and high volatility, which can improve the formation of the mixture between fuel and air in the cylinder and promote complete combustion. The high cetane number of $PODE_{3–4}$ can help overcome the low ignitability of *n*-butanol caused by its low cetane number. Previous research results indicate that $PODE_{3–4}$ is, in fact, a promising additive in diesel fuel [29].

In recent years, some researchers have paid close attention to the application of $PODE_{3–4}$ as an additive for diesel [30–33]. Xiao et al. [34] investigated the compatibility of $PODE_{3–4}$/diesel mixtures with different proportions, finding that the mixtures with a content of $PODE_{3–4}$ over 40% exhibited density stratification. Liu et al. [29] studied the effect of the addition of 10–20% $PODE_{3–4}$ (in volume) to diesel on combustion performance and exhaust composition. Their results show that blending $PODE_{3–4}$ with diesel can improve the engine efficiency and significantly reduce the emissions of harmful substances, especially soot. In 2016, Liu et al. [35] also studied the emission characteristics and thermal efficiency of diesel engines fueled with different mixtures of gasoline, diesel, and $PODE_{3–4}$. Their results demonstrate that soot emissions are lower in the case of gasoline/diesel blends, and the addition of $PODE_{3–4}$ can further decrease soot emissions, also increasing the combustion efficiency and thermal efficiency. Tong et al. [36] experimentally investigated the combustion characteristics of a gasoline/PODE mixture in a Reactivity Controlled Compression Ignition (RCCI) diesel engine. Their results indicate that the addition of PODE can improve thermal efficiency, decrease soot emission, and improve engine stability. A few studies concerning the addition of PODE into *n*-butanol/diesel blends are available [29].

From the detailed discussion above-mentioned, it is evident that $PODE_{3–4}$ demonstrates a significant potential as an additive component for the optimization of the properties of *n*-butanol/diesel mixtures. In this study, D100 (pure diesel fuel), BD20 (with 20% *n*-butanol in diesel), BDP10 (obtained by adding 10% of $PODE_{3–4}$ to BD20) and BDP20 (20% of $PODE_{3–4}$ added to BD20) were prepared, and their combustion performance was compared in a four-cylinder direction injection diesel engine. This study aims to explore the potential advantages of obtaining high combustion efficiency and emission reduction by adding $PODE_{3–4}$ to *n*-butanol/diesel blends, especially the effects of $PODE_{3–4}$ addition on the particle characteristics (including PM size distribution, PM number concentration, and PM mass concentration), and the pyrolysis mechanisms of PODEn for soot reduction are also discussed in this study.

Table 1
Technical specification of test engine.

Model	Specification
Number of cylinders	4
Cylinder diameter (mm)	85
Number of valves	16
Stroke (mm)	88.1
Displacement (L)	1.99
Maximum torque (Nm)	286
Compression ratio	16.5
Rated power (kW)/Speed (r/min)	100/4000

2. Experimental apparatus and procedures

2.1. Test engine and apparatus

The test was conducted on a four-cylinder diesel engine. Table 1 lists the major parameters of the engine, and Fig. 1 illustrates the whole test system.

The engine speed was maintained at 1600 rpm (corresponding to the maximum brake torque conditions) in this test. A pressure sensor (Kistler 6052CU20) was used to measure the cylinder pressure. The pressure was recorded for every increment of the crank angle, and 200 consecutive pressure cycles were measured and stored at each operating point. The INCA software was applied to control the fuel injection system. The engine intake pressure was 0.15 MPa, and the intake temperature was (30 ± 2) °C. The Exhaust Gas Recirculation (EGR) rate was controlled by the EGR valve; the EGR rate and exhaust gas emission were measured using a Horiba MEXA 7500DEGR; soot emission was measured using an AVL 415S system; and the particle emission was measured using a Cambustion DMS500. Table 2 lists the experimental uncertainties of the instruments.

2.2. Test fuels

Diesel, purchased from the market in Nanning, China, *n*-butanol, and $PODE_{3–4}$ were used as the base fuels. The detailed properties of the three base fuels are listed in Table 3. Four fuels were tested in this work. Pure diesel (denoted as D100) was used as a baseline comparison, and the other three fuels were obtained by blending diesel, *n*-butanol and $PODE_{3–4}$ at different volume ratios. Specifically, for BD20, 20% of *n*-butanol was added to pure diesel; for BDP10, 10% of $PODE_{3–4}$ was added to BD20; for BDP20, 20% of $PODE_{3–4}$ was added to BD20. The fuel compatibility test results of BDP20 reveal that 20% $PODE_{3–4}$ is successfully soluble in the BD blend fuel at 20 °C, without stratification occurring. The composition and cetane number value of these mixed fuels are listed in Table 4. D100 has the highest cetane number of 54, whereas BD20 has the lowest cetane number of 45.4. The addition of $PODE_{3–4}$ significantly improves the cetane number, the values for BDP10 and BDP20 being 48.7 and 52, respectively, both of which are higher than that of BD20 and slightly lower than that of D100.

2.3. Operating conditions and test procedure

Table 5 lists the engine operating conditions. Four loads were tested at an engine speed of 1600 rpm. The engine was operated in the mode