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Experimental investigation on performance, combustion and emission characteristics of a common-rail diesel engine fueled with polyoxymethylene dimethyl ethers-diesel blends

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HIGHLIGHTS

- PODE-diesel blends have high oxygen content, cetane number and good stability.
- The volatility and oxidation characteristics of PODE-blends are investigated.
- PODE-diesel blends can reduce smoke, CO and HC emissions.
- The addition of PODE can improve combustion process and brake thermal efficiency.
- PODE-diesel blends decrease particle number concentration and mass concentration.

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ABSTRACT

Polyoxymethylene dimethyl ethers (PODE) was blended with diesel fuel at volume ratio of 10%, 20% and 30% in the preparation of PODE-diesel blend fuels (marked as P10, P20 and P30). The volatility and oxidation characteristics of blend fuels, and the thermal parameters were analyzed using thermogravimetric method and Coast-Redfern integral method respectively. Also, the effects of PODE-diesel blends on the performance, combustion and emission characteristics were carried out on a 4-cylinder turbocharged intercooled common-rail diesel engine. The results show that P10, P20 and P30 have good stability at room temperature, and also the kinematic viscosity of PODE-diesel blends gradually decreases with increasing PODE blending ratio and temperature. Also with the increase of the blending ratio of PODE, the activation energy of blend fuels decreases and the comprehensive combustion index improves. When the diesel engine is fueled with PODE-diesel blends, the ignition delay period is shortened, shifting the rate of heat release and the rate of pressure rise curves forward. This increment in PODE blending ratio increases the maximum in-cylinder pressure and improves the brake thermal efficiency. The blend fuel has little impact on NO_X emissions, however, it can significantly improve HC, CO and smoke emissions. Compared with pure diesel fuel, the smoke emissions of P10, P20 and P30 at full load are reduced by 27.6%, 41.5% and 47.6%, respectively. PODE-diesel blends therefore could reduce particle number concentration and particle mass concentration in diesel exhausts, shifting the distribution peak to small particle sizes. Compared with pure diesel fuel, the peak number concentration of accumulation-mode particles (50 nm < Dp < 1000 nm) of P10, P20 and P30 decrease by 15.97%, 32.28% and 43.79%, respectively. This indicates that PODE as one of the emerging alternative fuels has the potential to achieve high efficient and clean combustion for diesel engines.

1. Introduction

Diesel engines, due to their high power performance, efficiency and durability, are widely applied in various fields, such as transportation, engineering machinery and agricultural power [1–2]. However, the emissions of nitrogen oxides (NO_X) and particulate matters (PM) from diesel engines have caused serious environmental pollution. Nowadays, governments and emission regulators enact stringent emissions laws and regulations to protect the environment [3–5]. In addition, internal combustion engines consume 70% of petroleum fuel per day, which makes the energy crisis more serious [6]. Alternative fuel and fuel modification are considered to be the effective ways to alleviate oil crisis and to achieve high

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efficient and clean combustion. Experimental research indicates that fuel properties like oxygen content [7], cetane number [8] and volatility [9] have great influence on combustion and emission. Yilmaz et al. [10] showed that the higher oxygen content of pentanol increased brake specific fuel consumption (BSFC) and NO_X emissions and the higher latent heat of evaporation of pentanol increased HC and CO emissions. Atmanli [11] reported that the addition of EHN cetane improver notably decreased BSFC and NO_X and increased CO emissions, but had the opposite effects on HC emissions for DnBH and DPnH microemulsions. Moreover, research showed that the high viscosity and poor volatility of blended fuels affect the air-fuel mixing process and atomization rate, resulting in lower in-cylinder pressure and heat release rate [12].

At present, a variety of oxygenated fuels represented by methanol [13], ethanol [14], biodiesel [15,16], dimethyl ether [17] and dimethyl carbonate [18] have been widely studied because the oxygen in the fuel molecules plays the role of oxygen self-supported in the combustion process. These fuels can improve the combustion and emission characteristics of diesel engines. Polyoxymethylene dimethyl ethers (PODE) has been perceived as an emerging alternative fuel for diesel, because it can significantly reduce soot emissions from diesel engines [19]. Methylal is synthesized from formaldehyde solution and methanol over heterogeneous acid catalyst. Methylal then reacts with paraformaldehyde forming PODE components [20]. Since all these reactants can be produced from methanol which is in turn produced from coal or biomass through syngas, the synthesis of PODE does not depend on the resources of petroleum [21]. PODE has various advantages, for instance, its auto-ignition capability is better than alcohols, its chemical stability is superior to biodiesel, and its volatility is more suitable for diesel than dimethyl ether and dimethoxymethane [6]. Previous studies [22,23] indicated that PODE as an alternative fuel has the potential to achieve high efficient and clean combustion and can be applied practically in engines without changing their mechanical structure or with only slight optimization of the baseline engine. Li et al. [24] investigated the effects of PODE addition on the spray and atomization of diesel spray by using a high pressure common-rail system. The research showed that as PODE was added into diesel, the spray tip penetration was slightly decreased, however the average spray cone angle and projected area were slightly increased. In addition, the droplets number tended to be uniformly distributed around 12–20 μm range and smaller characteristic diameters were observed and the relative size range kept constant. Liu et al. [25] employed PODE as an additive to optimize gasoline partially premixed combustion in a multi-cylinder heavy-duty diesel engine. Results showed that the NO_X-soot trade off relationship in conventional diesel engine could be dramatically improved using gasoline/POED blends without the drawback of fuel economy. Song et al. [22] conveyed a comparative study of using diesel and PODEn as pilot fuels for natural gas dual-fuel combustion. Due to its higher oxygen, higher ignitability and higher volatility, PODEn achieved lower HC, CO, NO_X, soot emissions and higher efficiency compared to diesel fuel. The characteristics of PODE homogenous charge compression ignition (HCCI) combustion were investigated by Wang et al. [23]. They reported that PODE HCCI exhibited two-stage ignition with a strong low temperature heat release (LTHR) before the high temperature heat release (HTHR). Also HTHR changed from one-stage to two-stage with an increase of charge mass equivalence ratio, and ultra-low NO_X emissions and soot-free combustion were achieved under lean mixture conditions. However, PODE lean HCCI combustion generated high levels of CO and HC emissions. Tong et al. [26] explored the influence of PODE as the direct-injection high reactivity fuel in dual-fuel reactivity controlled compression ignition (RCCI) operation on a single-cylinder diesel engine, and found that improved indicated thermal efficiency and ultra-low smoke could be achieved with PODE. The effects of PODE blend on combustion and emissions in a heavy-duty diesel engine were investigated by Liu et al. [6]. The results indicated that using 15–25% PODE as a component in diesel can decrease combustion duration, reduce 73–94% soot emissions and 25% PODE can satisfy the Euro VI soot limit with the weighted NO_X emissions controlled at about 2.7 g/kWh. Wang et al. [27,28] studied the effects of $PODE_{3\text{-}4}$-diesel blends on PM emissions in the European Stationary Cycle (ESC), and their results showed that adding 20% $PODE_{3\text{-}4}$ reduced PM by 36.2% and its break thermal efficiency (BTE) was slightly higher than that of diesel fuel. Pellegrini et al. [29] also found that PODE-diesel blends reduced PM emission in a light-duty diesel engine and 50% PODE could meet the Euro VI NO_X limit at the same PM emission level of neat diesel. However, the thermostability and oxidation characteristics of PODE-diesel blends, and the effects of blend fuels on particle size distribution and number concentration of diesel exhaust still lack a deep investigation.

In current study, PODE is used as a component to optimize the properties of diesel fuel. Firstly, the viscosity-temperature characteristics of PODE-diesel blends with different volume blending ratios (0, 10%, 20% and 30%) are investigated. Secondly, the evaporation and oxidation characteristics of blend fuel are studied with thermogravimetric analysis method. Finally, the effects of blend fuel on the engine performance and emission characteristics are investigated on a 4-cylinder turbocharged intercooled common-rail diesel engine. Particle properties, such as size distribution, number concentration and mass concentration are also analyzed. The purpose of this research is to limit particulate emission for the application of PODE in multi-cylinder diesel engines.

2. Experimental fuels and methodology

2.1. Test engine and apparatus

The experimental prototype is an inline, 4-cylinder, turbocharged, water-cooled, electronic controlled common-rail diesel engine with the displacement of 4.09L and compression ratio of 17.5. Table 1 lists the main technical specifications of the engine and Fig. 1 shows schematic diagram of the experimental setup. The engine speed and torque were controlled automatically by an electrical dynamometer (AVL 504/4.6 SL). The specific fuel consumption rate was measured by an instantaneous fuel consumption monitor (AVL 735S). The in-cylinder combustion pressure was measured by a piezo-electric pressure sensor (Kistler 6052C) coupled with a combustion analyzer (Dewetron M0391E) while the pressure data were recorded with the resolution of 0.5°CA. The smoke emission was measured by a filter-type smoke meter (AVL 415S) and gaseous emissions including CO, HC and NO_X were measured using an emission analyzer (Horiba MEXA 7200D). Where CO was measured with a non-dispersive infrared (NDIR) analyzer, while NO_X was detected using a chemiluminescent

Table 1
Specifications of the test engine.

Item	Specification
Engine type	4-cylinder, in-line, turbocharged, intercooling
Fuel injection system	Common rail
Bore × stroke (mm)	105 × 118
Displacement (L)	4.09
Compression ratio	17.5
Combustion chamber	Direct injection ω type
Rated power (kW / r/min)	95/2600
Maximum torque (N m/r/min)	400/1500