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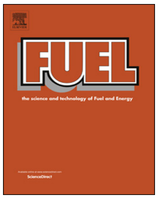

Influence of n-butanol-diesel-PODE$_{3-4}$ fuels coupled pilot injection strategy on combustion and emission characteristics of diesel engine

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ABSTRACT

Experiments in regard to influence of n-butanol, diesel and PODE$_{3-4}$ hybrid fuel coupled pre-injection strategy on combustion and emission characteristics of diesel engine were conducted at 20% EGR (exhaust gas recirculation) rates. BD20 that composed of 20% n-butanol and 80% conventional diesel (v/v), PD20 that composed of 20% PODE$_{3-4}$ and 80% conventional diesel (v/v), BDP20 that composed of 20% PODE$_{3-4}$ and 80% BD20 (v/v), and pure diesel fuel (D100) were tested. The results showed that compared to a single injection route, pilot injection route lowers the MPRR (Maximum Pressure Rise Rate). By decreasing pilot injection interval or increasing the pilot injection rate, MPRR is further reduced. MPRR can be reduced by blending PODE$_{3-4}$, and the descending sequence of MPRR for the four fuels is: BD20 > BDP20 > D100 > PD20. Moreover, adding the oxygenated fuel into diesel causes the NO$_x$ emission increase, and the change of pilot injection strategy impacts little on NO$_x$ emission of all the four fuels. The descending sequence of soot emission is: D100 > BD20 > PD20 > BDP20, where soot emission of D100 increases as pilot injection rate increases or decreases due to the increases of pilot injection interval, while emissions of other remaining three blends are insensitive to pilot injection strategy. The accretion of PODE$_{3-4}$ in the D100 or BD20 shows a significant downtrend in CO emission, where that of BDP20 is the lowest; CO and HC emissions of the four fuels increase due to the increases of pilot injection interval, and enhancing the pilot rate results in reduction in HC emissions of PD20 and BDP20, but the change of CO emission is not obvious. By introducing the pilot injection, the total particle number concentration of pure diesel increases, but with modest effect on those of the blends. Regardless of single injection or pilot injection, total particle number concentrations of multi-fuels are significantly lowered compared with that of D100.

1. Introduction

With increasingly stringent regulations on engine-out emissions, many advanced combustion technologies have been proposed and developed to reduce soot and NO$_x$ simultaneously. As a promising combustion model, low-temperature combustion (LTC) has demonstrated its advantages in soot and NO$_x$ reduction [1,2].

For improving emissions from diesel engines, application of advanced injection strategies has obtained extensive attention [3,4]. As one of the effective measures to optimize combustion process and reduce emissions, the pilot injection has shown enormous advantages [5,6], and the trade-off relationship between engine emissions, combustion stability, and fuel economy improved with its application [7,8]. Compared to the single injection route, CO, soot and HC emissions of the pre-injection strategy reduce [9] and it achieves significant improvements in emissions and combustion noise level [10–12]. Many scholars discovered that pre-injection strategies were effective in NO$_x$ emissions reduction [13–14]. An experiment carried out using a Euro V diesel engine with double pilot injection strategies highlighted significant improvements in CO and HC emissions [15]. Moreover, the particle number and mass concentrations reduced dramatically with advanced pilot injection [16]. Therefore, it is essential to study the influence of pilot injection strategies on the diesel engine performance.

Due to the increased serious energy crisis and environment deterioration, exploring renewable alternative fuels for engines has emerged. Due to its significant advantages as an oxygenated fuel, characterized by higher cetane number and heating value, easier vaporization, and a larger air-fuel ratio range compared to low carbon alcohols, i.e., methanol and ethanol, thus n-butanol as a diesel alternative is extensively investigated [17–19]. Many kinds of literature

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Nomenclature

PODEn	polyoxymethylene dimethyl ethers
D100	pure diesel
BD20	20% n-butanol + 80% pure diesel
PD20	20% PODE$_{3-4}$ + 80% pure diesel
BDP20	20% PODE$_{3-4}$ + 80% BD20
MPRR	maximum pressure rise rate
HCCI	homogeneous charge compression ignition
LTC	low-temperature combustion
RCCI	reactivity controlled compression ignition
CA	crank angle
EGR	exhaust gas recirculation
PM	particle matters
MPCI	multiple premixed compression ignition
BTDC	before top dead center
LD engine	light duty engine

dealing with the influences of n-butanol and diesel hybrid fuels on the diesel engine performance and emissions have been published, demonstrating n-butanol is promising as a diesel additive [20–22]. For example, Işık et al. [23] investigated how could the properties of n-butanol-diesel–biodiesel hybrid fuels affect the diesel engine performance. Illustrated that the thermal efficiency rose, meanwhile, CO and NO$_x$ emissions dropped off because of the n-butanol additive at relatively low loads. Scholars illustrated that a multi-cylinder LD engine performed great cold start characteristics, PM emission reduced while NO$_x$ generation increased by using n-butanol and diesel multi-fuels [24]. Cheng, Huang, and Zheng et al. [25–27] all experimentally investigated how could the injection strategies affect the diesel engine performance and the fuel is n-butanol and diesel hybrid fuel. Many consequence indicated that adding n-butanol into diesel could conspicuously reduce soot emission, meanwhile, performance of diesel engine was also improved. However, the application of adding a high proportion n-butanol into diesel sacrificed the combustion performance, conspicuously increased the consumption of fuel and caused a depressed thermal efficiency due to n-butanol's low caloricity and cetane number [28].

PODEn(Polyoxymethylene Dimethyl Ethers) is an excellent renewable additive, characterized by high volatility, high cetane number, and rich in oxygen [29–30]. Experiment about the effects of PODE HCCI combustion on the engine performance was conducted by Wang et al. [31] in a single-cylinder engine varied the charge mass equivalence ratio and EGR rate. The results showed that PODE HCCI combustion mode produced extremely low soot and NO$_x$ emissions. Other scholars investigated the compatibility between PODE$_{3-4}$ and diesel at varying ratios, found that a stratification occurs when the proportion of PODE$_{3-4}$ exceeds 40% at 5 °C [32]. Experiment conducted by Liu et al. [33] showed that the multiple premixed compression ignition (MPCI) mode of gasoline/diesel/PODE blends can break the NO$_x$ and soot trade-off relationship, and reduce the maximum HC and CO emissions by 59% and 44%. In 2016, Liu et al. [34] also concluded that the gasoline/diesel blends can reduce the soot emission, and the additive of PODE$_{3-4}$ in gasoline/diesel blends can further decrease the soot emission, increase the combustion efficiency and thermal efficiency. An RCCI (defined as reactivity Controlled Compression Ignition) experiment that the fuels were the gasoline and PODE hybrid fuels had been conducted by Tong et al. [35], and it turned out that PODE stabilized the operation, improved the thermal efficiency, and even lowered the soot emissions.

In summary, n-butanol has a low cetane number, low oxygen content, limited ability to reduce soot, CO, HC, etc., while high cetane number, high oxygenated PODE has the potential to further reduce soot, CO, HC. The study with respect to the influences of PODE, n-butanol, and diesel ternary hybrid fuel coupled with pre-injection strategies on the diesel engine performances is still rare. To our knowledge, only few literatures focusing on PODE additive into the n-butanol and diesel mixtures. In this essay, PODE$_{3-4}$ is used as an effective component of ternary hybrid fuel that optimized the performance of diesel/n-butanol hybrid fuels. Moreover, the optimal pilot injection strategies characterized by high efficiency but low emissions of blended fuels are recommended.

2. Experimental device and scheme

2.1. Facilities and fuels of the experiment

The physicochemical properties to the test fuels are exhibited in Table 1. Mixture ratios of fuel during this investigation were selected as follows: (D100)100% conventional diesel, (BD20) a mixture of 20% n-butanol and 80% conventional diesel (bulk factor), (PD20) a mixture of 20% PODE$_{3-4}$ and 80% diesel fuel (bulk factor), (BDP20) a mixture of 20% PODE$_{3-4}$ and 80% BD20 blends (bulk factor). The main physicochemical properties and the mixing ratio of the blend fuels are exhibited in Table 2. The experimental facilities included a YUCHAI four-cylinder diesel engine, an eddy current dynamometer and its control system, and exhaust analyzers. The main engine parameters are exhibited in Table 3. Fig. 1 shows the experimental devices.

During the test, a constant 1600 rpm engine speed is selected to ensure that the engine can output maximum torque. The cylinder pressure inside the diesel engine was measured with a pressure sensor (Kistler 6052CU20) for each crank angle increment, and the cylinder pressure was saved for 200 cycles and then averaged at each operating point. The turbocharged engine's intake temperature was kept at 30 ± 2 °C by an inlet cooling equipment, and operating parameters such as intake pressure (0.15 MPa) and injection pressure (120 MPa) were maintained at constant values by the commercial software INCA. The EGR rate which was measured by Horiba MEXA 7100DEGR was also controlled by the INCA and EGR value. Soot and particle emissions were measured by AVL 415S and Cambustion DMS500, respectively. Table 4 lists the uncertainties of the experiment.

2.2. Operating conditions and methods

The torque of each cycle for each of the four fuels was kept at 138 N.m (0.8 MPa), about 60% engine load. At each operating point, the engine performance and emissions of fuels D100, BD20, PD20, and BDP20 were analyzed. The EGR ratio was a constant value of 20%; based on a comparative trial, this 20% EGR value could achieve a low NO$_x$ emission and avoid vigorous growth of soot emissions. The injection timing of single strategy for comparison and the timing of main injection were kept at 3°CA BTDC, and the injection pressure was 120 MPa. During the experiment, four different pilot injection rates

Table 1
The nature of fuels.

	Diesel[a]	PODE$_{3-4}$[b]	n-Butanol[c]
Chemical formula	C_{12}-C_{25}	$CH_3O(CH_2O)nCH_3$	$C_4H_{10}O$
Cetane number	54	78.4	17
Density (g/mL)	0.82	1.019	0.81
Oxygen content (%)	–	46.98	21.58
Low heating value (MJ/kg)	42.8	19.05	33.10
Latent heat of evaporation (kJ/kg)	260	300	585
Kinematic viscosity (m^2 /s@20 °C)	4.8	1.05	3.64

[a] Nature of diesel, from ASTM D975.
[b] Nature of PODE$_{3-4}$, from Ref. [33].
[c] Nature of n-butanol, from Refs. [37–40].