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Effect of EGR dilution on combustion, performance and emission characteristics of a diesel engine fueled with *n*-pentanol and 2-ethylhexyl nitrate additive

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ABSTRACT

The *n*-pentanol/diesel dual-fuel coupled with EGR (exhaust gas recirculation) technology could simultaneously reduce soot and nitrogen oxide (NO_X) emissions discharged from the compression ignition engine. However, under high EGR rates, the low cetane number of the *n*-pentanol/diesel dual fuel resulted to combustion deceleration behavior. Because the combustion rate has a significant influence on the thermal efficiency of the engine, it was necessary to add 2-ethylhexyl nitrate (EHN) as a cetane improver to fuel mixtures to ensure that the *n*-pentanol/diesel fuel has appropriate combustion characteristics. In this study, it was attempted to investigate the performance and emission of a four-cylinder, turbocharged diesel engine with EHN fueled with *n*-pentanol/diesel blends at varying EGR rates. The five tested fuels included pure diesel (P0), and a mixture of 50% *n*-pentanol and 50% diesel (P50). Moreover, EHN was added to P50 at ratios of 0.5, 1, and 2%. The results showed that P50 could reduce soot emission, nucleation and accumulation mode particles. However, the burning speed and brake thermal efficiency (BTE) were notably reduced, and emissions of hydrocarbon (HC) and carbon monoxide (CO) significantly increased. With the EGR technology, NO_X emission was significantly reduced. When EHN was added to P50, engine ignition delay was shortened, BTE increased, and HC and CO emissions were substantially reduced. The use EGR technology combined with *n*-pentanol and EHN simultaneously reduced soot and NO_X emissions, and only slightly reduced BTE.

1. Introduction

Because of their high output power and thermal efficiency, diesel engines are widely applied in engineering machinery. Nevertheless, the uncontrolled soot–nitrogen oxide (NO_X) trade-off relationship seriously threaten the development of diesel engines. In order to satisfy the increasingly strict emission regulation and achieve energy saving objectives, numerous advanced combustion technologies and strategies have been applied [1], such as homogeneous charge compression ignition (HCCI) [2,3], premixed charge compression ignition (PCCI) [4–6], reactivity controlled compression ignition (RCCI) [7,8], and low temperature combustion (LTC) [9–12]. Because of the superiority and complexity of LTC, its effect in terms of engine performance and emission characteristics is certainly worth a systematic investigation.

In recent years, with the energy crisis and environment deterioration becoming more critical, finding renewable alternative engine fuels has gained widespread interest. Eco-friendly oxygenated fuels and renewable biofuels, such as alcohols, can be transformed from various non-food biomass, including agricultural residuals, forest wood, and marine algae [13,14]. Moreover, alcohols have the potential of simultaneously reducing particulate matter (PM) and NO_X emissions [15,16]. The use of C1–C3 alcohols (methanol, ethanol and propanol) have also been studied as diesel fuel blends [17–19]. However, several feedbacks in the use of lower-chain alcohol diesel blends report that these have poor miscibility, lower heat value, and inferior stability during blending. In addition, the cetane number (CN) of lower-alcohols are considerably lower than that of diesel fuel. Therefore, recently, studies of higher-chain alcohols, such as butanol (C4 alcohol), have gained considerable attention. Compared with lower-chain alcohols, butanol can mix well with diesel fuel [20,21]. Moreover, the viscosity, energy density, CN, flashpoint, and boiling point of butanol are all higher than those of lower-chain alcohols. Thus, numerous studies on butanol have been conducted through comprehensive experimental and modeling investigations [22–27]. However, a numerical and

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Nomenclature

HCCI	homogeneous charge compression ignition
PCCI	premixed charge compression ignition
RCCI	reactivity controlled compression ignition
LTC	low temperature combustion
PM	particulate matter
ID	Ignition delay
CN	cetane number
CA	crank angle
CA50	crank angle corresponding to the 50% of the total heat release
EHN	2-ethylhexyl nitrate
P50	50% *n*-pentanol + 50% diesel
P50 + 0.5%EHN	50% *n*-pentanol + 50% diesel + 0.5% EHN
P50 + 1%EHN	50% *n*-pentanol + 50% diesel + 1% EHN
P50 + 2%EHN	50% *n*-pentanol + 50% diesel + 2% EHN
T_{max}	maximum in-cylinder temperature
EGR	exhaust gas recirculation
BTE	brake thermal efficiency
MPRR	maximum pressure rise rate
NO_X	nitrogen oxides
HC	hydrocarbons
CO	carbon monoxide
ATDC	after top dead center

experimental study by Yanai et al. [28] on the combustion and ignition characteristics of a direct injection engine fueled with *n*-butanol at low load showed that neat *n*-butanol exhibited poorer combustion performance compared with pure diesel fuel.

As the carbon chain length of alcohol increases, ignition properties are generally improved. The alcohol *n*-pentanol, which has a five-carbon straight-chain in its molecule, has an even higher CN and energy density (about 80% of diesel) and less hygroscopic nature compared with methanol, ethanol, propanol and butanol [29]. In addition, *n*-pentanol has higher lubricity and viscosity, which may be beneficial to some engine components (such as fuel rails, fuel pumps, and oil injectors). Apart from these, its closer chemically correct air/fuel ratio and low heating value to diesel made *n*-pentanol more suitable for blending with diesel in compression ignition engine [30]. Compare with the preparation of lower-chain alcohols, *n*-pentanol preparation involves less energy. The preparation of *n*-pentanol mainly includes both biosynthesis from glucose and nature microbial fermentation of engineered micro-organisms [31]. The properties of *n*-pentanol and lower-chain alcohols are summarized in Table 3. From this table, it can be noted that the physical properties of *n*-pentanol are similar to those of diesel. Thus, among all alcohols, it is apparently the most attractive additive to diesel fuel. In recent years, a number of scholars have focused their attention to the research of *n*-pentanol. Wei et al. [32] investigated the influences of *n*-pentanol addition on the emission and combustion characteristics in a diesel engine. The results showed that brake specific fuel consumption (BSFC), carbon monoxide (CO), and hydrocarbon (HC) emissions increased, whereas both particulate number and mass concentration simultaneously decreased. The same conclusions were obtained by Zhu et al. [33]. Babu et al. [34], Yilmaz et al. [35], and Dhanasekaran et al. [36] focused their investigations on engine emission fueled with *n*-pentanol-biodiesel-diesel blends and found that soot and NO_X emissions decreased; however, HC and CO emissions increased. To gain deeper insight into the fundamentals of pentanol isomer combustion, especially regarding the chemical kinetic aspect, a number of modeling studies have recently been conducted [37–40]. Consequently, *n*-pentanol was proven better than butanol and other lower-chain alcohols. However, because of its lower CN, the ignition delay (ID) of *n*-pentanol is longer than diesel fuel, and has resulted to poor engine combustion performance, limiting its use in commercial diesel engines.

There are several methods for improving fuel ID, including increasing the compression ratio, installing an extra spark plug and redesigning the combustion chamber. However, there is an effective method that requires the least effort—the addition of CN improvers into fuels. Among the widely used ignition assisting additives, 2-ethylhexyl nitrate (EHN) is a commercial CN improver, which offers the best behavior in the most competitive way. It provides free radicals into the combustion chamber, accelerates oxidation process, which improves combustion characteristics, and lowers burning point and shortens ID [41–43]. Atmanli et al. [44] and Imdadul et al. [45] explored the addition of EHN to *n*-butanol/diesel mixtures in a turbocharged diesel engine, and demonstrated that EHN significantly decreased BSFC but slightly increased CO emission. Li et al. [46] and Ileri et al. [47] obtained similar results in their works. Zhang et al. [48] experimentally investigated the combustion and emission of 2,5-dimethylfuranblends with EHN addition in a compression ignition (CI) engine. The results showed that EHN addition slightly increased NO_X emission, decreased the total hydrocarbon emission notably at high EGR rates, whereas has insignificant influences on CO emissions. Ickes et al. [49] found that the addition of EHN increased the engine-out NO_X under the LTC condition tested. However, the studies on the EHN additive to *n*-pentanol/diesel blends on combustion and emission performance are limited, particularly higher blending ratio (up to 50%) of *n*-pentanol with diesel fuel.

Exhaust gas recirculation (EGR) technology is a widely used and effective way to reduce the NO_X emissions emitted from diesel engine, however, it has negative influence on soot emissions. Shi et al. [50] carried out an experiment on combined effect of EGR and biodiesel on emission characteristics of a diesel engine, and found that soot of 30% EGR rate was highest at medium load. He et al. [51] investigated the influence of alcohol additives and EGR on the emission and combustion performance of diesel engine, concluded that at high-load condition, the distributions shift toward larger particle size with increase EGR rates. Huang et al. [52] studied the effects of EGR rates and diesel/gasoline/*n*-butanol blends on particle emissions of a diesel engine. They demonstrated that the particulate mass concentrations of tested fuels increased with the increase of EGR rate. Kumar et al. [53] further explored the effect of reformed EGR on performance and emissions of a diesel engine and demonstrated that soot emissions for all reformed exhaust gas recirculation (REGR) were lower than that of corresponding EGR levels.

Based on these presented literature reviews, it could be concluded that adding EHN to *n*-pentanol/diesel results to high combustion efficiency and reduction of pollutant emissions. However, investigations on engine performance and exhaust emissions with the addition of EHN to *n*-pentanol/diesel blends coupled with EGR rates are limited, especially concerning the particle size distribution at low-load condition. Therefore, the work of which remains meaningful and important because commercial diesel engine are widely used at low-medium loads, and neat alcohols exhibit poorer combustion performance compare to pure diesel in low engine load. Accordingly, in this study, EHN was chosen to be added to 50% pure diesel and 50% *n*-pentanol in volume (P50) with concentrations of 0.5, 1, and 2%. All tested fuels combined with EGR rates were systematically investigated on a four-cylinder diesel engine at low-load condition.

2. Experimental details

2.1. Test engine

The experiment was conducted on a four-cylinder, turbocharged