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Experimental study on diesel conventional and low temperature combustion by fueling four isomers of butanol

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HIGHLIGHTS

- Blended fuels show later ignition timing and higher premixed heat release than diesel.
- Ignition of *iso*-butanol/diesel is the latest and *tert*-butanol/diesel is the earliest.
- Butanol/diesel blends exhibit higher thermal efficiencies than diesel.
- Soot of *iso*-butanol/diesel is the lowest and *tert*-butanol/diesel is the highest.
- Gaseous emissions are not obviously affected by adding butanol isomers.

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ABSTRACT

Effects of butanol on conventional and low temperature combustion were investigated on a single-cylinder diesel engine. Four butanol isomers, *n*-butanol, *sec*-butanol, *iso*-butanol and *tert*-butanol were added into diesel by volume ratios of 20% and 40%, referred to as N20/N40, S20/S40, I20/I40 and T20/T40, respectively. Experiments were conducted over a wide range of EGR from 0% to ~65%. Results indicate that butanol/diesel blends show the retarded combustion phasing and higher premixed heat release compared with pure diesel. Differences in cylinder pressures and heat release rates among different butanol/diesel blends get larger as EGR rate and blending ratio increases. Ignition delays from the longest to shortest are in the sequence of *iso*-butanol/diesel, *sec*-butanol/diesel, *n*-butanol/diesel and *tert*-butanol/diesel. Butanol/diesel blends exhibit higher thermal efficiencies compared with diesel in a certain EGR region. The addition of butanol isomers can significantly reduce soot emission and a higher blending ratio results in greater soot reduction. And the soot emissions, from the highest to lowest, are in the order of *tert*-butanol/diesel, *n*-butanol/diesel, *sec*-butanol/diesel, and *iso*-butanol/diesel, which is consistent with the commonly recognized view that a lower soot emission accompanies with a longer ignition delay. The difference in soot emission among different butanol/diesel blends is predominantly determined by fuel's cetane number, meanwhile physical properties such as volatility can also influence soot emissions to some extent. Regulated gaseous emissions are not significantly affected by addition of butanol isomers.

1. Introduction

Diesel engines are widely used for their high thermal efficiency, high power output and good reliability. However, diesel engines also exhibit the propensity of high soot and NO_x emissions. With the increasingly stringent emission regulations and the urgent demand on increasing thermal efficiency, some new combustion concepts have been proposed and widely investigated, such as homogenous charge compression ignition (HCCI) [1–4] and low temperature combustion (LTC) [5–8]. These new combustion concepts have showed the potential to achieve ultra-low emissions and high efficiency.

It is very hard for diesel fuel to achieve HCCI operation by port-injection due to its inherent fuel properties [9–11]. The higher viscosity, lower volatility of diesel fuel makes the preparation of homogeneous mixture very hard and the higher cetane number results in quite high combustion rates and overly advanced combustion phasing. Therefore, LTC is more feasible for diesel engines due to the fact that diesel fuel is directly injected into the in-cylinder and the combustion phasing can be effectively controlled by the injection timing. Akihama et al. [12] investigated the mechanism of smokeless rich diesel combustion by high levels of EGR dilution, which was viewed as the earliest study on LTC. They

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Notation

ATDC	after top dead center	IMEP	indicated mean effective pressure
BTDC	before top dead center	ITE	indicated thermal efficiency
CA5	crank angle at 5% of total heat release	LTC	low temperature combustion
CA50	crank angle at 50% of total heat release	I20/I40	addition 20% or 40% (v/v) *iso*-butanol into diesel fuel
CA90	crank angle at 90% of total heat release	N20/N40	addition 20% or 40% (v/v) *n*-butanol into diesel fuel
DCN	derived cetane number	R_b	blending ratio
EGR	exhaust gas recirculation	S20/S20	addition 20% or 40% (v/v) *sec*-butanol into diesel fuel
HCCI	homogenous charge compression ignition	T20/T20	addition 20% or 40% (v/v) *tert*-butanol into diesel fuel
HRR	heat release rate		

concluded that temperature reduction was sufficient to avoid the soot and NO formation region on the Φ–T map without changing fuel spray system in LTC mode. Alriksson et al. [13] researched LTC at 25% and 50% engine load under two EGR strategies. They found at 25% load, high levels of EGR resulted in low soot and NO_x emissions. But at 50% load, the high EGR dilution resulted in the increase of soot emissions. In fact, many previous studies [12–15] have shown that soot emission presented a rapid increase with the increment of EGR rate once the EGR rate exceeded a specific value. Then, after the soot peak, soot emissions began to reduce sharply with further increase of EGR rates and the low temperature combustion was achieved at quite high EGR rates. Therefore, a soot-bump region exists in a specific EGR range when EGR rate is varied from low to quite high level. In this soot-bump region soot emission is very sensitive to the variation in EGR rates, which makes the combustion control very hard. In addition, in the region of high EGR rates, HC and CO emissions as well as the fuel consumption are very high, which is also the main barrier for the high EGR diluted low temperature combustion [16–18].

In order to solve the problems in LTC engines above mentioned, some advanced technologies have been employed and investigated, such as advanced injection strategies, higher boost pressures, lower compression ratio, and EGR control strategy [18–22]. Among these technologies, the change of fuel properties is one of important and effective methods to realize low temperature combustion. Butts et al. [23] found that increasing cetane number could reduce CO and UHC, improve fuel consumption and reduce combustion noise due to more favorable combustion phasing in LTC mode. Han et al. [24] found that the changes of fuel composition such as using the blend of gasoline and diesel could impact the ignition delay and global equivalence ratio and resulted in different HC and CO emissions. Further, by using the blend of gasoline and diesel fuel, soot and NO_x emissions were simultaneously decreased without significantly reducing local combustion temperatures which is essentially necessary in conventional LTC strategies [25]. Liu et al. [14] found that as 20% of 2,5-dimethylfuran (DMF) was blended with diesel fuel, soot emissions were reduce at conventional diesel combustion and LTC mode and the most important reason on soot reduction was the longer ignition delay of DMF. Han [26] found that the cetane number, 90% distillation temperature and aromatic content could affect the ignition delay of LTC and cetane number is the most dominant factor. Further, particulate matter emissions were strongly dependent on the ignition delay time regardless of fuel types. Han et al. [27] investigated the effects of different fuel properties and injection strategies on LTC and found that *n*-butanol was more suitable to enable LTC than diesel fuel as using the high-pressure direct injection strategy. Liu et al. [28,29] investigated flame structure and soot quantitative distribution by using *n*-butanol and soybean biodiesel on a constant volume chamber and found that *n*-butanol presented more benefits than soybean biodiesel in LTC mode. This is because *n*-butanol has lower boiling point and viscosity, higher vaporization heat and these fuel properties can improve the mixing process and results in lower flame luminosity and soot concentrations.

Recently, the application of *n*-butanol on diesel engines has been widely researched in both conventional diesel combustion and LTC mode because *n*-butanol has more advantages than ethanol as a transportation fuel, such as higher heating value and better intermiscibility with diesel fuel. Chen et al. [30] investigated the effects of different *n*-butanol blending ratios on combustion and emissions on a passenger-car diesel engine and found that *n*-butanol–diesel blends could increase the burning rate and the maximum power output could not be reduced up to 40% *n*-butanol addition. In their further study on a heavy-duty diesel engine [31], they found that as 40% *n*-butanol was blended into diesel fuel, it could simultaneously achieve ultra-low soot and NO_x emissions while maintaining high thermal efficiency level at medium EGR region. Rakopoulos et al. [32] investigated the effects of ethanol and *n*-butanol addition on combustion and emissions and found that the thermal efficiency as fueling *n*-butanol/diesel blends was a little higher than that of ethanol/diesel blends at the same oxygen content. NO_x emissions of *n*-butanol/diesel blends were a little lower than that of ethanol/diesel, but soot emissions of *n*-butanol/diesel blends were higher. Armas et al. [33] investigated pollutant emissions of ethanol/diesel and butanol/diesel blends at the same oxygen content in New European Driving Cycle and found that NO_x and THC emissions were slightly increased with alcohol blends, while CO and soot emissions were reduced with these fuels. Giakoumis [34] reviewed literatures on emissions of ethanol/diesel or *n*-butanol/diesel blends during transient conditions on diesel engines and found that PM and CO emissions were reduced, while HC emissions were increased as fueling ethanol/diesel or *n*-butanol/diesel blends. NO_x emissions would be increased or decreased depending on the alcohol blending ratios and the engine calibration strategies. Valentino et al. [35] investigated the engine performance and emissions as fueling *n*-butanol/diesel blends under LTC mode and found that the combined influence of lower cetane number and higher volatility of *n*-butanol blends improved emissions compared with neat diesel fuel with a slight penalty on fuel consumption. Liu et al. [36] compared the spray, combustion flame propagation and soot quantitative distribution as ethanol and butanol were added into soybean biodiesel on a constant volume combustion chamber. They found that the volatility difference between alcohols and biodiesel resulted in the occurrence of micro-explosion at some specific ambient temperature ranges which could improve the mixing process. The addition of ethanol resulted in lower soot mass compared with *n*-butanol addition. In addition, some other studies on *n*-butanol/diesel blends have also shown similar results as aforementioned reviews [37–43]. Therefore, *n*-butanol, as a potentially promising renewable alternative fuel, can be used in diesel engines without the penalty of engine power and can also reduce soot emissions in both conventional combustion and low temperature combustion modes.