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Effects of *iso*-butanol/diesel and *n*-pentanol/diesel blends on performance and emissions of a DI diesel engine under premixed LTC (low temperature combustion) mode

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HIGHLIGHTS

- *Iso*-butanol and *n*-pentanol were used to enable a partially premixed LTC in a diesel engine.
- Combustion-phasing and charge-dilution were controlled by EGR and injection timing.
- Test fuels presented enhanced premixed combustion with high peak pressures and HRR.
- Simultaneous reduction of NO_x/PM was realized with test fuels under moderate EGR & late injection.
- *Iso*-butanol blends offered better EGR tolerance than *n*-pentanol blends.

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ABSTRACT

This study attempts to achieve simultaneous reduction of smoke and NOx emissions using a combination of low EGR, retarded injection timing and diesel fuel reformulation (with low cetane number alcohols) to enable a partially premixed low temperature combustion (LTC) mode in DI diesel engine. Two higher alcohol/diesel blends, B40 (40% *iso*-butanol–60% diesel) and P40 (40% *n*-pentanol–60% diesel) blends were prepared and tested under the combination of three EGR rates (10%, 20% and 30%) and two injection timings (23° and 21° CA bTDC) at high loads and constant engine speed. The performance and emission characteristics of the engine under these conditions are investigated. Results indicate that B40 gives a longer ignition delay, higher peak pressure and higher premixed heat release rate than P40. B40 has superior EGR tolerance and better influence on NOx-smoke trade-off when compared to P40. At retarded injection timing (21° CA bTDC) and 30% EGR, B40 presented simultaneous reduction of NOx (↓ 41.7%) and smoke (↓ 90.8%) emissions with diesel-like performance while P40 presented simultaneous reduction of NOx (↓ 39.3%) and smoke (↓ 15%) emissions with a small drop in performance. It was found that B40 presented better smoke suppression characteristics than P40. Smoke emissions of both blends increased drastically beyond 30% EGR. HC emissions increased and CO emissions remained low for both blends at all EGR rates. The combination of low EGR, late injection and higher alcohol/diesel blends can achieve partially premixed LTC and reduce smoke and NOx emissions simultaneously.

1. Introduction

Diesel engines are indispensable equipment in transport, agriculture and power generation sectors because of their higher fuel conversion efficiency, higher power output and higher torque capability compared to gasoline engines. Fossil fuels like diesel oil are fast depleting and their usage in diesel engine causes emissions that affect both environment [1] and human health [2,3]. In the year 2012–13, India consumed 69 million tons of diesel oil for transportation, agriculture and power generation purposes which is four times than that of gasoline [4]. This indicates that a huge population is constantly exposed to hazardous gaseous emissions from diesel engines. Over the last decade, India had to rely heavily on imports to meet its increasing fuel demands. High crude-oil imports suggest payments in dollars and depletion of foreign reserves which affects economy [5]. Hence there is an

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Nomenclature

ASTM	American Society for Testing and Materials
aBDC	above bottom dead center
aTDC	above top dead center
B40	40% isobutanol + 60% ULSD by volume
bmep	brake mean effective pressure
bBDC	before bottom dead center
BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
CA	crank angle
CAS	chemical abstracts service
CO	carbon monoxide
DI	direct injection
EGR	exhaust gas circulation
HC	hydrocarbons
NOx	nitrogen oxides
P40	40% pentanol + 60% ULSD by volume
PLTC	pre-mixed low temperature combustion
Ret	retarded injection timing (21° CA bTDC)
Std	engine's standard injection timing (23° CA bTDC)
SOI	start of injection
ULSD	ultra low sulfur diesel

increasing pressure on scientific community to address the global concerns of environmental pollution and energy insecurity. Several attempts have been made by researchers to reduce diesel emissions that contain harmful NOx and smoke components by reformulating diesel fuel with renewable biofuels and by designing new combustion strategies to utilize those fuels within the existing engine infrastructure.

Simultaneous reduction of smoke and NOx emissions is very difficult to achieve in diesel engines due to the inherent trade-off relation between them. Pre-mixed low temperature combustion (LTC) is a combustion strategy that offers promising solution to this problem [6]. Exhaust gas recirculation (EGR) and retardation of injection timing are considered to be the most effective approaches to achieve LTC mode [7]. Modulated kinetics (MK) was a type of LTC discovered by Nissan [8,9] that uses medium EGR levels and retarded injection timing to prolong the ignition delay [10]. Introducing high EGR can suppress smoke and NOx formation by extending the ignition delay (for effective pre-mixing) and reducing the overall combustion temperature respectively [6]. But it can deteriorate combustion and eventually decrease the performance of the engine due to high levels of HC and CO emissions. Retarding the injection timing also extends the ignition delay and provides ample time for fuel/air mixing but results in reduction of brake thermal efficiency (BTE) and increased smoke density [11]. Therefore to mitigate the detrimental effects of high EGR rates and retarded of injection timing, a fuel with lower cetane number and higher volatility can be utilized. In this way, a partially premixed LTC mode with low rates of soot and NOx formation may be realized without the use of high EGR rates [12,13]. The key characteristic of premixed LTC is a thoroughly mixed fuel/air mixture that burns at low temperature following a long ignition delay period [10]. Alcohols are suitable candidates for achieving LTC because they can provide (a) high resistance to auto-ignition (b) long ignition delay period (due to low cetane number) for sufficient mixing (c) faster vaporization (due to high volatility) for increasing the mixing rate.

Besides being suitable fuels for LTC mode, alcohols are oxygenated with a hydroxyl group that can increase oxygen availability during combustion and reduce smoke emissions in diesel engines especially at high engine loads [14]. Alcohols also present no serious penalties in NOx emissions due to their higher latent heat of vaporization and lower energy content when compared to diesel [15]. Bio-derived alcohols, as blending components can increase the renewable fraction in diesel and reduce fossil fuel dependence concurrently. For a country like India with vast availability of arable land, use of alcohol is a viable and sustainable option because they can be produced by fermentation and gasification of renewable feedstocks that include sugarcane, corn, wheat and even waste biomass [16].

Alcohols cannot be used in its neat form in conventional diesel engine due to their low cetane number. Several techniques like alcohol fumigation, dual-injection, alcohol–diesel blends and alcohol–diesel emulsions can be utilized to make diesel technology compatible with alcohol-based fuels [17]. Previous researches have employed several methods to utilize alcohols and to reduce emissions in diesel engines. They include using (a) alcohol fumigation [18,19], (b) combination of alcohol/diesel blends and EGR [20,21], (c) combination of alcohol fumigation and injection timing modification [22] and (d) combination of EGR and alcohol fumigation [23]. The present study utilizes two renewable higher alcohols; *iso*-butanol and *n*-pentanol as blending components with diesel in the existing diesel engine infrastructure. This is possible due to their higher energy density, higher cetane number, better blend stability and less hygroscopic nature when compared to other widely-studied lower alcohols like ethanol and methanol [16,24]. Table 1 presents the physical and chemical properties of some alcohols.

Iso-butanol is a naturally occurring 4-carbon alcohol that can be produced by fermentation of cellulose [25] and biosynthesis from glucose using genetically engineered micro-organisms like *Escherichia coli*, cyanobacteria and *Saccharomyces cerevisiae* [26–28]. Proprietary biochemical pathways are being developed by bio-fuel producers for large scale commercial production of *iso*-butanol in-order to reduce the high costs involved [29]. Efforts like conversion of algae to *iso*-butanol [30] and direct electro-microbial conversion of carbon-dioxide [31] can reduce the dependency on food crops. There are few studies on *iso*-butanol usage in diesel engines. Karabektas and Hosoz [24] used up to 20% *iso*-butanol in a DI diesel engine and reported a decrease in brake power and a slight decrease in BTE. NOx emissions reduced with increase in *iso*-butanol content. HC emissions increased while CO emissions decreased slightly. Ozsezen et al. [17] used up to 15% *iso*-butanol/diesel blends in a turbo-charged six-cylinder diesel engine and have shown similar results. Smoke emission decreased with increasing blend proportions of *iso*-butanol. Gu et al. [21] concluded that a combination of medium EGR, retarded injection timing and butanol addition up to 30% can reduce NOx and soot emissions simultaneously at light/medium loads. Recently, Zheng et al. [32] studied the effects of four butanol isomers blends in diesel on performance and emissions in a single-cylinder diesel engine under EGR rates up to 65% and found that *iso*-butanol presented longest ignition delay and lowest smoke emissions among the isomers. This is the motivation behind choosing *iso*-butanol over *n*-butanol in the current investigation.

n-Pentanol is a 5-carbon straight-chain alcohol that is recently gathering attention because of its advantages over other butanol isomers [33]. It is an excellent biofuel that can be produced from biological pathways like natural microbial fermentation of