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Full Length Article

Effect of using butanol and octanol isomers on engine performance of steady state and cold start ability in different types of Diesel engines

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HIGHLIGHTS

- Tested fuels with similar cetane number were conducted in production setting engines.
- Butanol and octanol isomers blends and Diesel offer coincident heat release profiles.
- Alcohols addition to Diesel in blends seems promote the combustion.
- The oxygen content of the blends sharply reduce particulate emissions.
- Tested blends have excellent cold start performance.

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ABSTRACT

To reduce greenhouse gas (GHG) emissions and fossil fuel consumption, addition of renewable alcohols to Diesel fuel may offer a potential solution. However, use of such alcohol/Diesel blends in existing Diesel engines is not yet fully understood. In the present study, alcohol/Diesel blends were tested by examining engine performance and emissions in both a light duty (LD) engine and a heavy duty (HD) engine with settings typical of those used in production engines. In addition, cold start tests of the blends were performed in a multi-cylinder LD Diesel engine. Four different alcohols were selected to mix with Diesel, i.e. *n*-butanol, isobutanol, 2-ethylhexanol and *n*-octanol. These alcohols were blended separately with either hydrotreated vegetable oil (HVO) or di-tertiary-butyl peroxide (DTBP), acting as cetane number (CN) improvers, in Diesel fuel. The mixtures were prepared to have the same CN as Diesel fuel.

The results indicated that with similar CN and the same engine settings, the alcohol/Diesel blends and Diesel fuel exhibited the same start of combustion and almost identical heat release processes. The blends generated slightly faster combustion and a higher indicated thermal efficiency than Diesel fuel under most of the tested conditions and in both engines. Diesel blends of *n*-butanol and 2-ethylhexanol showed good cold start performance in the multi-cylinder LD engine. Results regarding emissions demonstrated that the total particulate matter (PM) number was reduced when using alcohol/Diesel blends and the PM diameter seems to decrease as the amount of oxygen in the fuel was increased in the LD engine. It was concluded that alcohol/Diesel blends produce much less soot than Diesel fuel in both types of engine owing to the higher oxygen content in the blends but cause slightly increased NO formation.

1. Introduction

Internal combustion engines are widely employed in transportation because of their high efficiency and reliability. However, greenhouse gas (GHG) emissions from fossil fuel burning are currently one of the most urgent concerns globally owing to their effects on health and the climate. In the EU, 19.2% of GHG emissions was generated from the transport sector in 2013 [1]. In the US, transport contributed 27% of all GHG emissions in 2013 [2]. Furthermore, the share of GHG emissions from transport in both the EU and US is still rising.

Vegetable oil and bio-Diesel are widely investigated as alternative fuels in Diesel engines to reduce GHG emissions as their sustainable production process and relative similar properties with fossil Diesel. Rakopoulos et al. [3] have reported the differences

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of heat release of burning vegetable oil and bio-Diesel in Diesel engines and the potential of using them to suppress the smoke, NO_x and CO emissions.

The use of bio-alcohols as alternative fuels is attracting increasing attention, especially as alcohols can be derived from non-food biomass [4]. Replacing fossil fuels with ethanol produced from wheat straw or waste wood has been shown to reduce well-to-wheels (WTW) typical GHG emissions by 80–87% [5]. Methanol and butanol produced from inedible feedstocks can also be used as fuels, allowing a dramatic reduction of 94% [5] and 70–90% [6], respectively, in life cycle GHG emissions.

Compared with methanol and ethanol, longer carbon chain alcohols, such as butanol and octanol, have higher cetane number (CN), heating values, flash point and density values closer to those of Diesel, as shown in Table 1. Furthermore, butanol and octanol isomers have excellent solubility in Diesel, making it easy to prepare blends.

Larger molecule alcohol Diesel blends have been investigated in Diesel engines. Rakopoulos et al. [7–9] studied the combustion of *n*-butanol/Diesel blends in HD Diesel engines and demonstrated that using such blends can suppress soot formation without a significant increase in NO_x emissions under both of steady and transient conditions and therefore the smoke-NOx trade-off is defeated. Yao et al. [10] investigated the effect of *n*-butanol and pilot and post injection on engine performance and emissions in a HD Diesel engine. Use of multi-injection strategies and butanol/ Diesel blends were shown to efficiently reduce soot emissions. However, their individual impact on soot reduction was reduced when used together. Furthermore, another study [11] from the same group showed that high EGR together with use of an oxygenated additive (butanol) is an effective method to reduce soot and NO_x emissions.

Alcohols normally have a lower CN than Diesel fuel, resulting in a longer ignition delay, which in turn influences the combustion behaviour and emissions. To raise the CN of the blends, a CN improver can be added into the mixtures. Michikawauchi et al. [12] added 1% and 2% CN improver (DTBP) in Diesel fuel with 30% butanol to investigate NO_x and soot emissions. It was found that soot emissions can be reduced as a result of using the oxygenated alcohol and improved mixing whilst at the same time increasing the CN.

Previous studies have mainly focused on using alcohol/Diesel blends without any CN improver or with a fixed quantity of CN improver for all blends. Therefore, it is difficult to assess whether the observed differences in results obtained with Diesel and blends are due to changes in ignition delay or oxygen content in the fuel. In the present study, the CN of the tested alcohol/Diesel blends was the same as that of Diesel fuel, removing the effect of ignition delay. In addition, the CN of Diesel fuel is an important parameter specified in the EN590 standard. Meeting this limit should facilitate the launch of alcohol Diesel blends in the market.

This study investigated the possibility of using alcohol/Diesel blends in production setting engines by comparing the engine performance, cold start behaviour and emissions when using blends and Diesel fuel. Information on the potential of using renewable alcohols as drop-in fuels in Diesel fuel in production vehicles is valuable because changing the fuel may be the easiest and fastest way to increase renewable fuel use and reduce GHG emissions. This study found that in the presence of a CN improver, alcohol (*n*-butanol, isobutanol, *n*-octanol and 2-ethylhexanol) Diesel blends showed very good engine performance akin to that obtained with fossil Diesel fuel, as well as acceptable emissions and cold start behaviour.

2. Materials and methods

2.1. Fuel properties

Diesel fuel, *n*-butanol, isobutanol, 2-ethylhexanol and *n*-octanol were used as the main components in the fuel mixtures. HVO and DTBP were added into the mixtures as CN improvers to compensate for the low CN of the alcohols. Tested Diesel fuel meeting the EN590 standard but containing no biofuel (FAME) was used as the reference fuel. Longer carbon chain alcohols, such as butanol and octanol isomers, have higher CN, heating value, flash point and density, lower vaporization latent heat and better lubricity and solubility in Diesel fuel than methanol and ethanol (shorter carbon chain alcohols), see Table 1. These properties of larger molecule alcohols are closer to those of Diesel fuel, making them easier to blend with Diesel. HVO is a high CN biofuel. Therefore, it can be added to Diesel/alcohol blends to increase the CN to the same value as that of Diesel. HVO is refined from vegetable oils and animal fats and completely devoid of aromatics and sulphur, which helps reduce emissions [16,17]. DTBP is a widely used ignition improver that increases a blend's CN even when added in very small volumes [18].

The CN of the different blends was determined using a cooperative fuel research (CFR) engine complying with the ASTM D-613 standard. CN values for the blends used in this work are shown in Table 2.

To match the CN of Diesel (52), various amounts of DTBP or HVO were added to the alcohol/Diesel blends. For fuels with CN values between 48 and 52, the reproducibility of the CFR engine test results is 3.8–4.3, and all the tested blends lay within this range. The blends used in the study were named systematically as follows: the first part denoted the alcohol used (isoBu = isobutanol, nBu = *n*-butanol, 2EH = 2-ethylhexanol and nOc = *n*-octanol), the second part (numbers) denoted the percentage of alcohol in the blend (10, 20, or 30 for 10%, 20%, and 30%, respectively) and the last letter denoted the additive used (H for HVO, D for DTBP).

Table 1
Properties of alcohols and Diesel [4,13–15].

	Methanol	Ethanol	Isobutanol	*n*-Butanol	2-Ethylhexanol	*n*-Octanol	Diesel
Oxygen content (wt.%)	49.93	34.73	21.62	21.62	12.31	12.31	0
Density (g/ml)	0.787	0.785	0.802	0.810	0.836	0.830	0.837
Heating value (MJ/kg)	20.1	26.9	33.17	33.21	34.7	38.4	42.8
Cetane number	3.8	5–8	<15	17–25	23.2	37.5	52
Flash point (°C)	12	13	28	35	81	81	82
Viscosity @ 40 °C (mm^2/s)	0.58	1.13	2.62	2.63	5.2	5.5	3.04
Boiling point (°C)	65	79	108	118	184	195	193–357
Lubricity (μm)	1100	1057	–	590	–	236	315
Vaporization latent heat (kJ/kg)	1109	904	566	582	–	562	270
Solubility in water	Miscible	Miscible	Immiscible	Immiscible	Immiscible	Immiscible	Immiscible