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Blends of butanol and hydrotreated vegetable oils as drop-in replacement for diesel engines: Effects on combustion and emissions

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HIGHLIGHTS

- 30% n-butanol or isobutanol blended into HVO as economic oxygenated "extenders".
- No adverse effects on combustion, performance, efficiency, NO_x or other emissions.
- Butanol-HVO blends result in less particle mass, black soot, PAHs vs. diesel and vs. HVO.
- Biodiesel, HVO & blends lower emissions of EC, OC, PAHs and phytane vs. diesel.
- Butanol-HVO blends reduced carcinogenic PAHs by 75–78% and soot by 79–80% vs. diesel.

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ABSTRACT

This work investigates the performance of a mix of two emerging biofuels, butanol and hydrotreated vegetable oil (HVO), in an Iveco Tector diesel engine with no aftertreatment. HVO, a possible drop-in fuel for diesel engines, features excellent combustion and emissions characteristics yet is relatively expensive, while two isomers of butanol, n-butanol and isobutanol, are less expensive oxygenated fuels with a drawback to their use in diesel engines in the form of their increased ignition delay and, on some engines, higher emissions of nitrogen oxides.

Blends of 30% of either n-butanol or isobutanol into HVO had, compared to diesel fuel, resulted in a 70–80% decrease in the emissions of elemental carbon and carcinogenic polycyclic aromatic hydrocarbons (cPAHs) and a moderate decrease in the emissions of nitrogen oxides, without showing an adverse effect on combustion timing, heat release rates, engine maximum torque, thermal efficiency, and other measured pollutants.

Particulate matter from biodiesel, HVO, their blends with diesel fuel, and the above mentioned blends was also analysed for elemental carbon (EC) and organic carbon (OC), polycyclic aromatic hydrocarbons (PAHs), nitrated PAHs, n-alkanes and organic tracer compounds, including hopanes, steranes, and isoprenoids. n-Alkanes were the most abundant class among the analysed particulate organic compounds in emissions of all fuels. All biofuels exhibited, relative to diesel fuel, a decrease in the concentration of particulate PAHs and n-alkanes in emissions, while the concentrations of hopanes and steranes originated from lubricating oil were comparable across all fuels. Cold starts yielded about 15% higher concentrations of both particulate matter and particulate organic compounds in emissions than hot starts. The vast majority of EC and OC, studied organic compounds, and mass of $PM_{2.5}$ was included in the size fraction PM_1.

1. Introduction

Diesel engines have become a practical, efficient, reliable, and cost-effective prime mover of virtually all heavy vehicles and mobile machinery. The downsides of traditional petroleum diesel

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Nomenclature

ANOVA	analysis of variance
B0	neat diesel
B100	biodiesel
B30	blends by volume of 30% biodiesel with 70% of diesel fuel
CAD	crank angle degrees
cPAHs	carcinogenic polycyclic aromatic hydrocarbons
CPI	carbon preference index
EC	elemental carbon
HC	hydrocarbons
HVO	hydrotreated (hydrodeoxygenated) vegetable oil
HVO100	neat hydrotreated (hydrodeoxygenated) vegetable oil
HVO30	blends by volume of 30% hydrotreated vegetable oil blended with 70% of diesel fuel
iBu30	blends by volume of 30% iso-butanol with 70% hydrotreated vegetable oil
MFB	mass fraction burned
nBu30	blends by volume of 30% n-butanol with 70% hydrotreated vegetable oil
NExBTL30	blends by volume of 30% hydrotreated vegetable oil blended with 70% of diesel fuel
nitro-PAHs	nitrated polycyclic aromatic hydrocarbons
NO_X	nitrogen oxides
OC	organic carbon
PAHs	polycyclic aromatic hydrocarbons
PM	particulate matter
PM_1	particulate matter with aerodynamic diameter less then 1 μm
$PM_{2.5}$	particulate matter with aerodynamic diameter less then 2.5 μm
TC	total carbon
WHSC	World Harmonized Steady-State Cycle
WHTC	World Harmonized Transient Cycle

fuel are concerns about petroleum availability and cost, energy security and independence, international trade balance, and climatic changes arising out of fossil fuel combustion. Its current replacement, biodiesel (methylesters of mostly vegetable oils), is coming under scrutiny as according to some it is produced mostly from edible oils and hence competes with food production. This study investigates a blend of two candidate replacements, butanol and hydrotreated (hydrodeoxygenated) vegetable oil (HVO), as a drop-in fuel for existing diesel engines.

Hydrotreated vegetable oils, also termed “renewable diesel” are produced from biomass-based triacylglycerides (such as vegetable oils) through catalytic hydrodeoxygenation, resulting in mostly non-oxygenated aliphatic compounds (terminology and production reviewed by Knothe in [1]).

Traditionally, vegetable oils have been converted to biodiesel (n-alkyl-esters, typically methylesters, of fatty acids), and to a lesser extent used as fuel in their neat form. Biodiesel, both neat and in blends with diesel fuel, offers a substantial reduction of the emissions of particulate matter (PM) [1,2], with minor effect, typically but not always an increase, on the emissions of nitrogen oxides (NO_x) [2]. Biodiesel also tends to reduce the emissions of polycyclic aromatic hydrocarbons (PAHs) [3,4], although the effects on PAHs are not always consistent [4,5]. Possible downsides of biodiesel are cold flow properties and stability of the fuel.

HVO has higher cetane number and higher stability than methylesters of vegetable oils (biodiesel) produced by their transesterification. HVO has been reported to simultaneously reduce PM, NO_x, hydrocarbons (HC) and CO, with cold flow properties being its potential downside [6]. Westphal also claims reductions in NO_x, PAHs and PM, however, the PM reduction was not as high as that achieved with first-generation biodiesel [7,8]. Lapuerta recommends using HVO in a blend of up to 50%, due to lower lubricity, high cetane number and worse cold flow properties of HVO [9]. Aatola also recommends engine optimization for high-concentration blends to compensate for high cetane number and lower density of HVO, but confirms both NO_x and PM benefits even with original fuel injection timing [10]. Knothe [1] reports that cold flow properties can be improved by including branched chain alkanes and that cloud points comparable to diesel fuel were obtained with HVO. Nylund reports on a successful use of neat HVO in a bus fleet without any engine adjustments [11]. Two distinct disadvantages of HVO are that it uses similar feedstocks as biodiesel, and that its cost is presently much higher compared to diesel fuel and biodiesel.

Alcohols have been used primarily in spark ignition engines: Ethanol produced from biomass is blended in small concentration into gasoline as well as sold in high-concentration blends for flexible fuel vehicles. Ethanol and two isomers of butanol, n-butanol and isobutanol, can be produced from biomass at relatively comparable costs and energy inputs [12]. Alcohols, in general, have lower viscosity, higher volatility, and lower cetane number (ethanol 5–8, n-butanol 17 to around 25) than diesel fuel [13,14]. Two alcohols have been considered in diesel engines, ethanol and n-butanol, with n-butanol being more suitable than ethanol due to its (relative to ethanol) higher density, viscosity, lubricity, and cetane number. Butanol, unlike ethanol, is miscible with diesel fuel without additional co-solvents. The addition of alcohols into diesel fuel, in general, has been found to decrease the emissions of particulate matter [14,15], with the exception of cold start, where the observed outcomes are not consistent, due to the opposing effect of lower cetane number [14]. The emissions of PAHs were also reduced by addition of water-containing n-butanol [15]. Addition of 16% n-butanol into diesel fuel has been reported to delay the combustion by several crank angle degrees [16]. Addition of butanol into diesel fuel has lead to an increase [17], a decrease [18] or inconsistent effect [19] on the emissions of NO_x. Lin reported an increase in NO_x for smaller and decrease in NO_x for larger concentrations of water containing n-butanol in diesel fuel [15]. The addition of butanol to biodiesel or vegetable oil has increased the ignition delay and possibly the variability of combustion among individual engine working cycles [20]. Simultaneous addition of biodiesel and butanol to diesel fuel has reduced both NO_x and PM, shifting the smoke-NO_x curve towards lower levels [21].

Overall, HVO is a suitable but expensive fuel, and n-butanol is a cost-effective fuel with a high potential to reduce PM emissions, but has a low cetane number of around 25 [1] and may increase the emissions of NO_x. This study investigates the potential of a blend of HVO and butanol as a drop-in replacement for petroleum diesel fuel, or, the potential of butanol as an extender of the (currently costly) HVO.

Adding an oxygenate into HVO has been reported to reduce NO_x emissions by about 5% and PM emissions by 25–30% [22]. It is