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Full Length Article

A comparative analysis of n-butanol/diesel and 1-pentanol/diesel blends in a compression ignition engine

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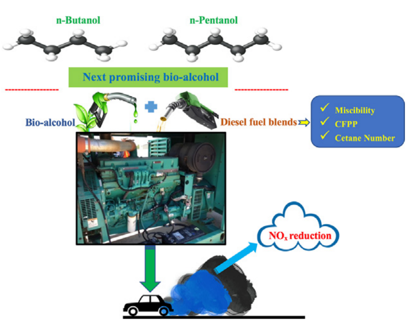
GRAPHICAL ABSTRACT



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ABSTRACT

The use of alcohols in diesel engines is an alternative way of reducing dependence on diesel fuel. Specifically, higher alcohols such as n-butanol (nB) and 1-pentanol (Pn), which consist of high carbons and can be produced from mainly non-edible sources, can directly be mixed with diesel fuel which in return provides significant promise from economic and environmental stand points. For this reason, the examination of the use of such high-carbon alcohols in diesel engines has become significantly important in recent years. In this work, six different binary (D-nB and D-Pn) fuel mixtures were obtained by mixing the diesel fuel with n-butanol and 1-pentanol at low and high mixing ratios (5%, 25% and 35% alcohol by volume) and basic fuel properties were examined. The test fuels were tested at four different loads (0, 3, 6 and 9 kW) at a constant engine speed (1800 rpm) in a direct injection diesel engine with diesel as the reference fuel. Fuel properties of the binary fuels were in compliance with the European Norm (EN590) and all of the fuels exhibit a steady phase without any indication of phase separation. Compared to diesel fuel's engine characteristics, brake specific fuel consumption (BSFC) increased by 14.02% in binary blends, resulting in a 7.36% reduction in brake thermal efficiency (BTE). However, exhaust gas temperature (EGT) increased by an average of 47.55%. The addition of 1-pentanol to diesel had a significant impact on the decrease of oxides of nitrogen (NO_x) emissions as an average decrease of 14.27% was observed. On the other hand, the higher latent heat of evaporation (LHE) of n-butanol and 1-pentanol had multiple disadvantageous outcomes such as a cooling effect in-cylinder, lower combustion efficiency and slightly higher carbon monoxide (CO) and hydrocarbon (HC) emissions as compared to diesel. The results indicated that the binary blends with 35% alcohol content happened to be a promising alternative for lower NO_x emissions at the expense of increasing CO and HC emissions. Overall, it is concluded that n-butanol and 1-pentanol blends can be safely used in diesel engines without any engine modification or any additive.

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1. Introduction

Diesel engines produce higher NO_x and particulate matter (PM) emissions than gasoline engines, while emitting less HC, CO and carbon dioxide (CO_2) [1]. However, diesel engine vehicles have a wide range of use in the transportation sector and the industry despite these pollutants. This trend will continue in the future due to the increasing population worldwide. However, due to the uncertainty of oil prices and the lack of new reserves and tight emission regulations, it is inevitable to use alternative fuels in lieu of fossil fuels in diesel engines. The European Union transportation sector aims for 10% renewable fuel use in the transportation sector [2–4]. This target is to be accomplished by gasoline-alcohol and diesel–biodiesel blends in gasoline and diesel engines, respectively. Extensive and effective production and consumption of biofuels have numerous social, environmental and health benefits. For this reason, developing countries are increasingly focusing on the fuel supply and the use of alternative fuel resources to provide economic and social benefits [5].

Among these resources, bio-alcohols, which can be produced from non-edible vegetable waste oils, promise a good future. Thus, bio-alcohols for diesel engines have a potential from an environmental perspective because they are produced from renewable resources and have the life cycle (CO_2) [6–8].

The most important point in the combustion process in diesel engines is that the ignition delay period is at the desired level. High cetane number (*CN*) of a fuel has a direct and significant effect on the ignition delay [2,9]. Alcohols generally have low cetane and high octane numbers. This makes alcohols ideal for gasoline engines [9,10]. Use of alcohols in gasoline engines has gained acceptance of the industry with significant potential in commercial vehicles. However, alcohols used in diesel engines have shown performance problems due to low *CN*, low heat value and high *LHE* [11]. Thus, alcohols must be mixed with diesel fuel in order to have potential in diesel engines. However, in such blends, there is phase separation because alcohols' −OH group is polar and hydrophilic at low temperatures [11–15]. This causes damage to the storage and fuel system components in the long term. There have been many studies on the use of alcohols in diesel engines, such as methanol and ethanol which have low carbon numbers [9,16–18]. However, due to the problems mentioned previously, effective results could not be obtained for long-term use of such alcohols in diesel engines.

As the number of carbons in alcohols' chemical structures increases, their basic fuel properties improve as well. With that, the cetane number increases which leads to lower ignition delay [19–21]. Another significant effect is that the increased carbon number makes the non-polar structure in the alcohol molecule more effective by virtue of the extended straight chair structure, leading to the hydrophobic nature and water-repelling characteristics at low temperatures. Also, as compared to lower carbon alcohols, they have higher heating value, lower volatility, less ignition problems, inter-solubility, higher viscosity and lubricity, lower corrosion risk and lower heat of vaporization [1,2]. For these reasons, high carbon alcohols are suggested as an important alternative for diesel engines. In recent years, n-butanol (C_4H_9OH) has been observed as a potential higher alcohol [3]. Studies also indicate that n-pentanol ($C_5H_{11}OH$), another higher alcohol, has a lot of advantages and promise for use in such diesel engines [2]. Production of both alcohols from agricultural wastes does not affect food security. Therefore, major issues such as energy security and environmental degradation can be addressed by the use of second and third generation biofuels, in which category n-butanol and 1-pentanol are the two most important higher alcohols [2,21–24].

Multiple studies are available in literature with regards to the use of n-butanol as a binary mixture with diesel fuel in diesel engines. Mack et al. used a homogeneous charge compression ignition (HCCI) engine and showed that butanol's performance is better than ethanol and gasoline [25]. Satsangi et al. used four different diesel/n-butanol blends and tested for combustion/emission and noise/vibration parameters. Engine tests were performed on a single-cylinder 4-stroke naturally aspirated direct injection diesel genset engine operated at a fixed rpm and at six different load conditions. The ratio of butanol changed between 4.9% and 19.5%. Higher loads produced more noise/vibration, heat release rate and rate of pressure rose. And, as CO, NO_x and smoke emissions reduced, HC emissions increased [26]. In a different study by Xiao et al., n-butanol/diesel reactivity stratification combustion (RSC) and n-butanol/diesel concentration stratification combustion (CSC) were numerically compared in a light-duty diesel engine at the indicated mean effective pressure (IMEP) of around 0.7 MPa and 1500 rev/min. In both strategies, BSFC and NO_x values reduces in the case of lower n-butanol in the blends [27]. Lapuerta et al. tested a Euro 6 vehicle under driving cycle with 10%, 13%, 16% and 20% n-butanol diesel blends at 24 °C and −7 °C. Butanol blends up to 16% showed benefits in particle number and mass emissions. However, NO_x emissions were increased at the test cold temperature (−7 °C) and CO and HC increased at both temperatures [28].

In other studies, with different mixing ratios, PM or smoke emissions significantly decreased due to the high oxygen content of butanol (due to the positive role played by the oxygen content on the oxidation process). For CO, HC and NO_x emissions, there was no clear outcome due to increase/decrease in emissions based on different test setups and test engines [29,30]. However, in the case of studies involving n-butanol, it was shown that n-butanol had a positive effect on improvement of emissions, in spite of increasing BSFC, which is because of the lower heat content of n-butanol as compared to the diesel fuel [24,31,32].

Among alcohols, 1-pentanol is one of the most promising alcohols in the class of high carbon alcohols. 1-pentanol, which has a five-carbon straight chain structure, has been tested in diesel engines [33–40]. Li et al. directly used pentanol in a diesel engine at different injection conditions. The experiments were conducted at constant engine speed of 1600 rpm and constant load of IMEP 0.6 MPa. NO_x and soot emissions decreased significantly by 90% and 50%, respectively, while CO and HC emissions increased for pentanol with comparable efficiencies under a single injection strategy without EGR (exhaust gas recirculation) [41]. A very limited number of studies are available with regards to investigation of 1-pentanol and diesel mixtures. Yilmaz et al. tested diesel-1 pentanol blends in a Subaru 330 H engine with the pentanol blend ratios of 5%, 10%, 20%, 25% and 35%. In order to determine engine characteristics, engine tests were performed at four engine loads (0, 1.5, 2.25 and 3 kW) and a constant engine speed (2000 rpm). As compared to the diesel fuel, diesel-pentanol blends increased BSFC (average by 9.79%) but also had a positive impact on EGT with average increasing of 3.74%. From emissions perspective, the blends averaged increases in CO and HC emissions of 69.43% and 144.30%, respectively. However, NO_x emissions showed mixed results [42]. Ma et al. tested 20% and 40% pentanol blended with diesel in a constant volume chamber for ignition and combustion characteristics in two different studies. Results showed a slight increase in the natural flame luminosity and a slight decrease in soot because of the oxygen content of pentanol. This study indicates that pentanol blends could decrease final soot emissions in diesel engines [43]. In other study, with increasing blending ratios of pentanol, the high *LHE* and specific heat of pentanol takes a more important role to influence liquid length compared to the drop of fuel density resulting from the addition of pentanol. Addition of pentanol increased spray cone angles in all test conditions and the result shows pure diesel fuel has a poor air–fuel mixing compared to pentanol blends [44]. Wei et al. operated an ISUZU 4HF1 diesel engine at various engine loads and used 10, 20 and 30 vol.% pentanol fractions in diesel fuel blends. Results showed higher BSFC, HC and CO emissions increased for a 30% n-pentanol blended fuel at low engine load but decreased at high engine load with a slight increase (maximum 8%) in NO_x emissions and lower particulate mass concentration as compared to diesel. The addition of 1-pentanol caused longer ignition delay and increased the peak heat release rate in the premixed combustion phase