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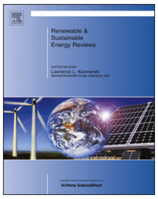

Use of higher alcohol biofuels in diesel engines: A review

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ABSTRACT

Biofuels have grabbed the attention of engine researchers ever since the oil-crisis and escalating costs of petro-chemicals cropped up in the '70s. Ethanol and methanol were the most widely researched alcohols in IC engines. However, the last decade has witnessed significant amount of research in higher alcohols due to the development of modern fermentation processes using engineered micro-organisms that improved yield. Higher alcohols are attractive second/third generation biofuels that can be produced from sugary, starchy and ligno-cellulosic biomass feedstocks using sustainable pathways. The present work reviews the current literature concerning the effects of using higher alcohols ranging from 3-carbon propanol to 20-carbon phytol on combustion, performance and emission characteristics of a wide range of diesel engines under various test conditions. The literature is abound with evidence that higher alcohols reduce carcinogenic particulate emissions that are prevalent in diesel engines. NOx emissions either increased or decreased based on the domination of either cetane number or heat of evaporation. Brake specific fuel consumption (BSFC) of the engine usually suffered due to low energy content of alcohols. A notable feature is that the combination of higher alcohols (like butanol or pentanol), high exhaust gas recirculation (EGR) rates and late injection timing enabled low temperature combustion (LTC) in diesel engines that can simultaneously reduce smoke and NOx emissions with improved engine efficiency. It can be concluded that higher alcohols reduce smoke emissions with their fuel-borne oxygen; enhance air/fuel mixing by offering long ignition delay and eventually replace fossil diesel (partially or wholly) to enable a clean and efficient combustion in compression-ignition engines. The chief thrust areas include developing mutant strains with higher yield, higher tolerance to toxic inhibition and low-cost substrates for fermentation. Further work is required in stipulating optimum blend-fuel characteristics and ensuring the long-term durability of the engines using these fuels.

Contents

Abbreviations: CA, Crank Angle; CI, Compression Ignition; CN, Cetane Number; CO, Carbon Monoxide (% volume); CO_2, Carbon Dioxide (% volume); DI, Direct-Injection; HC, Hydrocarbon (ppm volume); HCHO, Formaldehyde; HCOOH, Formic acid; NOx, Nitrogen Oxides (ppm Volume); PPM, Parts Per Million; rpm, revolutions per minute; *v/v*, per volume

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1. Introduction

Diesel engines are indispensable equipment in public transportation, heavy-duty machinery, power generation, agricultural and industrial equipment owing to their higher fuel-conversion efficiency, higher power output, higher torque capacity, higher durability and higher reliability than gasoline engines. Moreover they emit lesser carbon monoxide (CO), hydrocarbons (HC) and carbon dioxide (CO_2) emissions than gasoline engines. The use of fossil diesel in diesel engines produces high NOx (nitrogen oxides) and soot emissions that are detrimental to both environmental and human health. Diesel exhaust is classified as carcinogenic to humans by the International agency for research on cancer (IARC) based on sufficient evidence that its exposure is associated with an increased risk of lung cancer [1]. While soot emissions can cause cardiovascular diseases [2], NOx present in diesel exhaust is a chief cause for smog [3], ground level ozone [4], acid rain [5] and sick building syndrome [6].

Growing concerns of fossil fuel depletion, oil-price fluctuations, escalating energy demands and stringent emission regulations are driving the scientific community to find alternative renewable biofuels for use in diesel engines. Among the biofuels like bio-gas, bio-alcohol and bio-diesel, alcohol seems to be most attractive. Biogas requires high pressure for its use in automobile and its leakage can be hazardous. Biodiesel from edible vegetable oil can cause shortage in food supply. Non-edible oil sources require large scale cultivation which can take up the land resources meant for food crops. Alcohols can be obtained by anaerobic fermentation of ligno-cellulosic biomass which includes agricultural waste biomass (rice straw, corn stalks and sugarcane bagasse), forestry biomass (wood-pulp, saw-mill and paper-mill discards) without much reliance on food crops [7]. Further energy crops like switch grass (*Panicum virgatum*) and elephant grass can produce high yield of ligno-cellulosic biomass than can serve as raw materials for alcohol production. Hence, availability of alcohols would not be an issue.

Nevertheless, the use of lower alcohols like methanol and ethanol in compression-ignition engines presents certain complications due to their low cetane number, high latent heat of vaporization and high resistance to auto-ignition [8]. Further the less calorific value, poor miscibility with diesel and poor lubricating properties restricts their use in diesel engines [9]. Several techniques like alcohol fumigation, dual-injection, alcohol–diesel blends and alcohol–diesel emulsions have been used to deal with these limitations of the alcohols as a diesel engine fuel [10]. From the safety perspective, lower alcohols have low flash point (FP) and are classified as Class I liquids (FP below 37.8 °C) along with gasoline by the National Fire Protection Association (NFPA) in the US. Meanwhile, diesel fuel is classified under Class II liquids (FP above 37.8 °C). But addition of lower alcohols to diesel lowers the flash point and would make the blend to fall under Class I liquids, consequently requiring the same infrastructure as gasoline for storage and handling. On the other hand, there are some positive aspects of alcohols that can be advantageous in diesel engines. The reduction of smoke is strongly related to the oxygen-content of the blends [11]. Alcohols being oxygenated fuels with a hydroxyl (OH) group, increase the availability of oxygen during combustion and reduce smoke emissions in diesel engines especially at high engine loads [12]. With respect to the chemical structure, it is asserted that smoke reduction efficiency is high in alcohol and low in ether [13].

Recently higher alcohols have gathered interest among the researchers owing 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, methanol. Increase in length of the carbon chains also improves the ignition quality of alcohol molecules [14]. The term ‘higher alcohol’ usually refers to the series of straight chain alcohols containing four or more carbon atoms, viz. butanol (C_4), pentanol (C_5), hexanol (C_6), octanol (C_8), dodecanol (C_{12}), phytol (C_{20}) etc. However propanol (C_3) is also included in this study, as this three-carbon alcohol is used as a solvent to bind lower alcohols with diesel and also as a blending component with diesel fuel in diesel engine. Table 1 presents a comparison of physical and chemical properties of some lower and higher alcohols with diesel. It can be inferred from the table that higher alcohols (when compared to lower alcohols like methanol and ethanol) have greater potentials to replace fossil diesel wholly or partially. Higher alcohols can mix with diesel without any phase separation which is attributed to their high carbon content, low polarity and less hygroscopic nature [15,16]. Therefore no co-solvents or emulsifying agents would be required to maintain blend stability when higher alcohols are used. The increase in length of carbon chain and the absence of branches in an alcohol provides high calorific value, density and cetane number while conserving self-igniting characteristics and less tendency to knock [15]. Higher alcohols have less corrosive