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Experimental evaluation of a diesel engine running on the blends of diesel and pentanol as a next generation higher alcohol

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ABSTRACT

Alcohols are effective alternatives for use in diesel engines. Higher alcohols, as opposed to lower-chain alcohols (methanol and ethanol) have a promising future for diesel engines. 1-Pentanol, a higher-chain alcohol, has better fuel characteristics and can be made of biomass. Thus, it is important to examine it, as well as, its blends with diesel fuel in internal combustion engines for the characteristics of emissions and power generation. The aim of the present study was to evaluate the engine performance and exhaust emission characteristics of a diesel engine fueled with diesel-1-pentanol blends. For experimental use, fuel blends were prepared by adding 1-pentanol (5%, 10%, 20%, 25% and 35% by volume) into diesel to achieve blends of D95Pen5, D90Pen10, D80Pen20, D75Pen25 and D65Pen35. In order to determine engine characteristics, engine tests were performed at four engine loads (0, 1.5, 2.25 and 3 kW) with a constant engine speed (2000 rpm). The addition of 1-pentanol to diesel decreased lower heating value and cetane number (CN) of the blends. As compared to diesel fuel, the blends increased brake specific fuel consumption (BSFC) but also had a positive impact on exhaust gas temperature (EGT). The higher latent heat of evaporation of 1-pentanol caused a cooling effect in-cylinder, reduction in combustion efficiency and increase in carbon monoxide (CO) and hydrocarbon (HC) emissions. Also, the addition of 1-pentanol to diesel had a significant impact on the increase of oxides of nitrogen (NO_x) emissions. However, the D95Pen5 blend does hold potential as a promising candidate for decreasing exhaust gas temperature, CO and NO_x emissions, but at the expense of increasing HC emissions.

1. Introduction

Demands to use the world's fossil fuel reserves have been getting higher recently due to global industrialization and the increase of road vehicles running on petroleum-based fuels. Nowadays, fossil fuels are used mostly in the transportation sector; in which diesel is the most commonly used fuel [1]. Due to the decrease in petroleum resources and increase in tighter emission regulations, countries have been inclined to find and use alternative energy resources that are renewable, cost-effective and clean. Among these energy alternatives, it is anticipated that bioalcohols could serve as suitable resources for diesel engines because of the beneficial economic and environmental impacts [2,3].

Alcohols, a family of organic molecules, can be used in internal combustion engines and have become an ideal alternative in gasoline engines because of their high octane numbers. In recent years, alcohols have been investigated for their potential use in diesel engines as well. Because alcohols can be produced from biomass, they have big potential for use in diesel engines. Literature shows that research with regards to alcohol use in diesel engines shows mostly evaluation of methanol (CH_3OH), ethanol (C_2H_5OH), propanol (C_3H_7OH) and butanol (C_4H_9OH) [4–8]. While ethanol is produced from the fermentation of renewable biomass, methanol can be made of coal and petroleum based materials. Methanol is hygroscopic in nature and may absorb water vapor directly from the atmosphere [1,7]. Ethanol and propanol are flammable polar solvents and are miscible with water. Moreover, if ethanol is mixed with diesel fuel for use in diesel engines, phase separation occurs under 10 °C [9–12]. Propanol, a higher alcohol as compared to ethanol and methanol, has been investigated in diesel engines with a limited number of studies. There is an increasing number of works involving the use of butanol in diesel engines [2,5,6,11–16]. However, butanol, in the class of higher alcohols, affects diesel engine performance negatively due to its lower cetane number and lower heating value compared to diesel [10–16].

Use of alcohols in diesel engines is important due to reduction of emissions and use of less fossil fuels [17–20]. However, because of such fuel properties of alcohols including low cetane numbers, calorific value and higher latent heat of evaporation, it may not be possible to use

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Table 1
Fuel properties of pentanol in comparison with lower alcohols [7,18,25,30,34,40,51].

Properties	Methanol	Ethanol	Propanol	Butanol	Pentanol
CAS Number	67-56-1	64-17-5	71-23-8	71-36-3	71-41-0
Chemical formula	CH_3-OH	C_2H_5-OH	C_3H_7-OH	C_4H_9-OH	C_5H_{11}-OH
Density (g/ml) at 15 °C	0.791	0.789	0.803	0.810	0.815
Kinematic viscosity (mm^2/s) at 40 °C	0.58	1.08	1.74	2.22	2.89
Lower heating value (MJ/kg)	20.1	26.9	30.6	33.1	34.65
Latent heat of evaporation (kJ/kg)	1162.64	918.42	727.88	585.40	308
Research octane number	136	129	112	96	78
Cetane number	3.8	5–8	12	17	20
Boiling point (°C)	65	78	97.1	117	137.9
Flash point (°C)	12	13	22	35	49
Autoignition temperature (°C)	463	420	350	345	300
Stoichiometric air/fuel ratio	6.47	9.01	10.35	11.19	11.8
Molecular weight (kg/kmol)	32.04	46.07	60.09	74.12	88.15
Oxygen content (wt%)	49.93	34.73	26.62	21.59	18.15
Hydrogen content (wt%)	12.48	13.02	13.31	13.49	13.61
Carbon content (wt%)	37.49	52.15	59.96	64.82	68.24
Solubility in water at 20 °C (wt%)	Miscible	Miscible	Miscible	7.7	2.2

them directly in diesel engines [21–24]. In addition, alcohol molecules contain alkyl and hydroxyl which allow alcohols to mix with diesel regardless of the number of carbon molecules [24–28]. As the number of carbons increases, cetane number increases and latent heat of evaporation decreases. Thus, 1-pentanol ($C_5H_{11}OH$) which has only 5 carbons in its structure is seen as a future generation alternative fuel for diesel engines. But, there is very limited research regarding this fuel in literature [29,30]. It is a promising alternative fuel, however, as it can be produced through natural microbial fermentation of engineered micro-organisms and biosynthesis from glucose [7,18,25]. 1-Pentanol, due to the number of carbons in its chemical structure, can easily be blended with diesel and has similar fuel properties to diesel. Moreover, as compared to lower alcohols, 1-pentanol has a better cetane number and latent heat of evaporation which are two of the most important parameters affecting combustion performance [7,25]. Table 1 shows the fuel properties of methanol, ethanol, propanol, butanol and pentanol in order.

Several investigations with regards to the use of pentanol-biodiesel blends indicated that pentanol in fact can be used to overcome/reverse the negative side effects of biodiesel [30–32]. In other studies, pentanol was proved to be a promising future generation fuel and additive, as its addition improved the fuel properties (e.g. high viscosity, cold flow properties) of diesel-biodiesel blends and reduced NO_x [33–39]. A literature review outlined below clearly indicates pentanol's potential as a future generation alternative fuel. The following outcomes can be summarized for the binary blends of pentanol and diesel.

Campos-Fernandez et al. [40] examined four different 1-butanol/diesel and 1-pentanol/diesel blends in a direct injection diesel engine. They found a slight decrease in BSFC for 1-butanol/diesel blends compared to that of 1-pentanol/diesel blends and diesel fuel. Also, they proposed 30% butanol/diesel fuel blend and 25% 1-pentanol/diesel fuel blend as an alternative diesel fuel without significant loss of performance. Wei et al. [41] tested DP10, DP20 and DP30 (10, 20 and 30 vol% pentanol fraction in diesel fuel) blends and found higher BSFC, HC, CO and NO_x emissions, and lower particulate mass concentration as compared to diesel. Campos-Fernandez et al. [42] examined pentanol-diesel blends in a diesel engine with 10, 12, 20, 25 vol% pentanol fraction in diesel, and results indicated pentanol-diesel blends showed similar characteristics to diesel fuel and up to 25% of pentanol can be used in diesel engines without any engine modification. Li et al. [43] investigated the direct use of pentanol at different injection conditions and was able to reduce NO_x emissions without exhaust gas circulation (EGR). Ma et al. [44] tested 20% and 40% pentanol blended with diesel in a constant volume chamber for ignition and combustion characteristics. There was a slight increase in the natural flame luminosity and a slight decrease in soot because of the oxygen content of pentanol. Zhang et al. [45] studied engine emissions and performance characteristics of a diesel engine running on diesel-butanol and diesel-pentanol blends (10 and 20 vol% alcohol fraction in diesel fuel). Alcohol addition decreased particulate matter and elemental carbon emissions, and pentanol resulted in a better BSFC than butanol. A summary of various studies under different test conditions done by Kumar et al. is as follows [46–50]: higher alcohols reduced NO_x and PM emissions significantly when a diesel engine was tested in premixed low temperature combustion (LTC) mode with 40% iso-butanol or *n*-pentanol in diesel fuel under EGR conditions and two injection timings [46]. In another study, 10%, 20%, 30% and 45% of pentanol with diesel fuel in a diesel engine under 3 different EGR modes was tested and resulted in engine performance loss, higher HC and CO emissions and lower NO_x emissions [47]. In further work, a single cylinder diesel engine was tested under different EGR modes with various blends of diesel with iso-butanol or *n*-pentanol (alcohol vol% 15, 38, 45) [48]. Addition of alcohol to diesel decreased NO_x emissions but increased HC and CO emissions. Two other investigations suggest the use of pentanol in diesel engines if it is blended with diesel or other fuels [49,50]. Yilmaz et al. [51] tested 10% and 20% 1-pentanol blended with diesel fuel in a diesel engine. According to the test results, BSFC and EGT increased and brake thermal efficiency (BTE) decreased. Diesel blends with 1-pentanol increased CO and unburned HC emissions, while reducing the production of NO_X.

As compared to the lower alcohols, pentanol can be easily blended with diesel due to the number of carbons in its chemical structure, higher cetane number, calorific value, viscosity, flame speed, lower latent heat of evaporation and pressure, ignition temperature, lower risk for corrosion, lower polarity (*δpnP: 2.2)* and the ability to create miscible solutions with it [7,18,24–30]. Although there is limited research in literature with regards to the use of pentanol in diesel engines, it is a kind of alcohol that has more potential than lower alcohols due to pentanol's advantages as outline above [27,30,33,34].

The objective of the current study is to investigate the emission characteristics of a diesel engine running on diesel and 1-pentanol/diesel blends, where 1-pentanol is currently viewed as a next generation alternative fuel. With that purpose, 5 vol%, 10 vol%, 20 vol%, 25 vol% and 35 vol% of 1-pentanol was blended with diesel to create D95Pen5, D90Pen10, D80Pen20, D75Pen25 and D65Pen35, respectively. Engine performance and emission characteristics of diesel-1-pentanol blends were compared to baseline fuels of diesel.

2. Test facilities and procedure

The experiments were performed on a Subaru RGD 3300H type, direct injected, single-cylinder diesel engine generator (Fig. 1). The main technical characteristics of the test engine are shown in Table 2. The exhaust emissions were measured with an EMS 5002 exhaust gas analyzer. The analyzer provided a HC measurement range of 0–2000 ppm with a resolution of 1 ppm, CO range of 0–10 vol% with a resolution of 0.01 vol%, CO_2 range of 0–20 vol% with a resolution of 0.1 vol%, O_2 range of 0–25 vol% with a resolution of 0.01 vol% and NO range of 0–5000 ppm with a resolution of 1 ppm. In order to perform the EMS 5002 exhaust gas analyzer calibration procedure, BAR 97 Low gas was used. The calibration process was repeated regularly for the engine tests.

In order to prevent cold-start effects, the engine ran on neat diesel