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Effect of biodiesel–butanol fuel blends on emissions and performance characteristics of a diesel engine

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HIGHLIGHTS

- Biodiesel–butanol blends as a function of butanol concentration are tested and compared to standard diesel fuel.
- Exhaust gas emissions are reported.
- Advantages and disadvantages of butanol as an additive are discussed.

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ABSTRACT

The purpose of this work is to investigate the effect of butanol–biodiesel blends on the emissions and performance characteristics of a four-stroke, naturally aspirated, water-cooled, indirect injection diesel engine (IDI). Testing was performed comparing butanol blended with biodiesel, standard diesel (D100) and neat biodiesel (B100) at four engine loads. The biodiesel–butanol blends were 5%, 10%, and 20% butanol in volume basis (B95Bu5, B90Bu10, B80Bu20). Compared to biodiesel, butanol blended fuels showed lower exhaust gas temperatures and nitrogen oxides (NOx) emissions while exhibiting higher carbon monoxide (CO) and unburned hydrocarbons (HC) emissions. Butanol blended fuels produced lower CO and higher NOx emissions than diesel fuel for low concentrations of butanol (5% and 10%), but there was no significant change in terms of HC emissions. The biodiesel blend containing the highest concentration of butanol (20%) caused higher CO and HC emissions and lower NOx emission than diesel. Brake specific fuel consumption increased with biodiesel and biodiesel blended fuels as compared to diesel.

1. Introduction

Alternative fuels have been widely used in internal combustion engines due to extensive research in finding alternative sources to fossil-based fuels. Vegetable oils, biodiesel, simple alcohols such as ethanol and methanol, and blended fuels are utilized in combustion engines.

Vegetable oils can be used in an engine without any modification if it is blended with 80% diesel [1]. Direct use of vegetable oils, without any blending, may cause incomplete combustion and carbon deposit build-up on engine parts resulting from poor atomization due to their high viscosity; although viscosities can be lowered by preheating the vegetable oils to the extent comparable to the viscosity of diesel [2]. Biodiesel fuels of various origins are studied in the literature extensively regarding their productions, performance characteristics, and characterizations [3–5]. Literature shows that the use of biodiesel decreases HC, CO, and particulate matter (PM) emissions while increasing NOx emissions. Simple alcohols such as ethanol and methanol are the most used alcohols as additives or blended fuels in compression ignition engines. Low lubricity, high heat of vaporization, high auto-ignition temperature, low cetane number, and solubility are some of the disadvantages of ethanol and methanol. Low lubricity can be improved by adding castor oil to simple alcohols [6]. Intake air preheat is one of the simple ways to overcome the high heat of vaporization problem for alcohols in order to achieve ignition and improve combustion characteristics [7]. It was shown in [7] that for an idle engine the minimum air intake preheat temperature for methanol and ethanol to achieve 99% fuel conversion during combustion is 450 °C and 250 °C, respectively. Under full load either fuel will be fully combusted with only 150 °C of preheat. Solubility is another issue for simple alcohols. In fact, ethanol and methanol are not miscible with diesel. Thus, an emulsifier must be used to fully mix simple alcohols with diesel. Biodiesel serves as an excellent binder, or emulsifier, to diesel–alcohol mixtures. Miscible fuel blends such as biodiesel–ethanol/methanol or biodiesel–ethanol/methanol–diesel can be achieved by limiting the alcohol

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concentration [8–16]. It was shown that simple alcohols blended with biodiesel decrease NOx and PM emissions while there are mixed results in terms of CO and HC emissions depending on the magnitude of methanol or ethanol concentration. Biodiesel–ethanol–diesel blends lead to higher CO and HC while producing fewer NOx emissions than diesel for increasing alcohol concentrations. The difference is most pronounced at lower loads (below 50% engine output).

Butanol is a good alternative fuel or fuel additive for use in compression ignition engines and provides several advantages over ethanol and methanol such as higher cetane number, lower heat of vaporization, higher heating value, and better miscibility with diesel. A higher cetane number means better fuel ignition and shorter ignition delay. In order to achieve favorable conditions for ignition, butanol requires less heat and a lower intake air temperature than ethanol or methanol because it has a lower heat of vaporization. Because butanol is easier to vaporize, it has better combustion characteristics. Butanol has a higher heating value than methanol or ethanol which means a smaller volume of butanol is required for the same power from an engine running on an alcohol-based fuel. Importantly, butanol can be mixed with diesel without miscibility problems unlike methanol or ethanol. Overall, butanol has physical properties close to those of diesel. Thus, it makes butanol an important alternative fuel or additive over methanol and ethanol.

There have been a number of studies in the literature regarding the performance, combustion and emissions characteristics of butanol–diesel blends in compression ignition engines [17–26]. Karabektas and Hosoz [17] experimented with isobutanol–diesel fuel blends with 5%, 10%, 15%, and 20% isobutanol in a naturally aspirated, four-stroke, direct injection (DI) diesel engine at full load at various engine speeds. Isobutanol was mixed well and homogeneous mixtures were achieved with no phase separation. Compared to diesel fuel, all blends increased brake specific fuel consumption (BSFC, g/kW h), but the increase was highest with the 20% concentration isobutanol blend. The blends decreased exhaust gas temperature, brake thermal efficiency (BTE), CO, and NOx emissions while increasing HC emissions compared to neat diesel. It was observed that the exhaust emissions changed as a strong function of isobutanol concentration. It was noted that although 20% isobutanol can be used, 10% isobutanol provided the best outcome in terms of emissions and performance characteristics. Rakopoulos et al. [18] investigated the effect of butanol–diesel blends on the performance and emissions of a DI diesel engine with 8%, 16%, and 24% of n-butanol concentrations at 2000 rpm and three engine loads. Results showed that exhaust gas temperature, smoke density, NOx, and CO emissions were reduced as butanol concentration increased, while unburned HC emissions, BSFC, and BTE increased as compared to diesel. These results were supported by Dogan [19] using n-butanol/diesel fuel blends with 5%, 10%, 15%, and 20% n-butanol concentrations in a single cylinder, four stroke, unmodified, DI diesel engine at a constant speed at four engine loads.

Similar trends were obtained by Rakopoulos et al. [20] using a turbocharged, medium/heavy-duty, DI diesel engine. Yao et al. [21] also studied n-butanol as an additive in a heavy-duty diesel engine with 5%, 10%, 15% of n-butanol content using multiple injections. Exhaust gas recirculation (EGR) rate was adjusted to keep NOx emissions constant. The results showed that n-butanol addition decreased soot and CO emissions, but did not have a serious impact on BSFC. Chen et al. [22] investigated the combustion and emission characteristics of n-butanol–diesel blends with 40% of n-butanol (Bu40) in a single cylinder, heavy-duty diesel engine at a constant engine speed and evaluated the impact of percent EGR experimentally. As compared to diesel fuel, Bu40 showed higher cylinder pressure, longer ignition delay, faster burn rate, higher NOx emissions, lower soot emissions, and higher CO emissions. EGR decreased NOx emissions without any change in the soot emissions. There was no change in HC emissions, CO emissions, or indicated thermal efficiency (ITE) with EGR until the EGR threshold was reached. Once the EGR rate exceeded the certain limit, HC and CO emissions increased and ITE decreased. The study showed that a combination of high n-butanol–diesel blends with EGR has the potential to decrease NOx and soot with high ITE. In another study by Chen et al. [23], diesel fuel was mixed with 0, 30, and 40 vol% butanol and evaluated in a high-speed, DI diesel engine for passenger-car application for various loads at 2000 and 4000 rpm. As compared to diesel fuel, butanol–diesel blends increase combustion pressure and burn rate while having little impact on maximum power and torque. Blended fuels slight increased BSFC with a large increase in thermal efficiency. HC emissions increased as the butanol concentration increased, and at low loads, CO emissions increased while NOx emissions decreased with the increase of butanol in the blend ratio. However, at high loads, CO emission decreased and NOx emissions increased. Soot emissions were reduced at all conditions and less smoke was produced with higher butanol concentrations. Overall, butanol–diesel blends showed advantages in terms of thermal efficiency and soot emissions up to a high blending ratio of 40% butanol. In a recent study by Merola et al. [24], a diesel (80%)-n-butanol (20%) blend was tested using conventional and optical techniques. Smokeless conditions were obtained with a minor increase in NOx emissions and specific fuel consumption. Optical investigations showed that butanol blends led to faster formation and a higher concentration of OH, which affected smokeless combustion in early injection conditions.

It is important to understand the effect of ambient conditions on alcohol blended fuels and exhaust emissions. Armas et al. [25] investigated a special transient process of engine operation included in the New European Driving Cycle of light duty vehicles (NEDC). A turbocharged, DI diesel engine, equipped with a common rail injection system and EGR strategy, was tested in cold (temperatures between 15 °C and 20 °C) and warm (over 20 °C) start conditions. Ethanol–diesel and butanol–diesel blends tested at cold start produced combustion instabilities with higher NOx, HC, and CO emissions as compared to diesel. This is perhaps due to the lower cetane numbers and the higher heat of vaporization requirements of alcohols. Smoke opacity and particle concentration were consistent with HC emissions. But, when the engine was tested under warm conditions, the effect of the oxygen content in the alcohol blends became the dominant factor because the warm conditions reduced the influence of the heat of vaporization. Thus, smoke opacity, particle concentration, and gaseous emissions decreased as the temperature increased.

Besides the exhaust emissions such as CO, HC, and NOx, particulate emissions and polycyclic aromatic hydrocarbons (PAH) are influenced by butanol blended fuels. According to Zhang and Balasubramanian [26], butanol addition to diesel reduces PM and elemental carbon emissions while increasing the proportion of organic carbon in particles. Also, a higher percentage of butanol in fuel blends leads to higher PAHs. Since PAHs may cause wetstacking, which might potentially lead to diesel engine failure [27], high butanol concentrations in butanol–diesel blends need to be limited.

Overall, butanol–diesel blends have been extensively investigated in the literature and the effects of these blends on the emissions and performance of diesel engines are identified. However, there is not much work done regarding butanol–biodiesel blends in the literature. Thus, the intention of the current work is to begin exploring the effects of butanol–biodiesel blending on the performance and emissions characteristics of a small diesel engine. Results are compared to baseline diesel fuel and neat biodiesel.