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Investigation of CI engine emissions in biodiesel–ethanol–diesel blends as a function of ethanol concentration

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HIGHLIGHTS

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

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ABSTRACT

In this work, ethanol was mixed with biodiesel–diesel blends and the effect of ethanol concentration on diesel emissions was investigated. Both low and high concentrations of ethanol were studied. Ethanol concentrations were varied at 3%, 5%, 15% and 25% in biodiesel–diesel–ethanol (BDE), while biodiesel and diesel concentrations were maintained equal (BDE3, BDE5, BDE15 and BDE25). Emission characteristics for biodiesel–diesel–ethanol blends were compared to baseline curves of diesel as a function of engine load.

1. Introduction

Alcohols have been widely used in compression ignition engines as alternative fuels. Although alcohols are cheaper than standard diesel fuel, there are challenges with respect to utilization of alcohols in diesel engines and blending these fuels with diesel. While it is possible to directly evaluate alcohols in diesel engines, it is necessary to overcome the disadvantages of alcohols including low lubricity, difficulty of vaporization and high auto-ignition temperature. Using additives and increasing intake air temperature are two of the methods to overcome lubricity and vaporization problems [1,2]. A way of solving lubricity and vaporization problems is to mix alcohols with diesel fuels. However, it is very well-known that diesel fuel and alcohols are immiscible and require co-solvents or emulsifiers, which are expensive and the mixing process could become complicated because of splashing, blending, heating, separation or other processes [3]. However, biodiesel is known to be miscible with alcohols and diesel fuel. Because of that, use of biodiesel–methanol [4–6], biodiesel–ethanol [7–10] and comparisons of biodiesel–methanol and biodiesel–ethanol fuels [11–13] have been investigated as an alternative way of using alcohols, as well as biodiesel fuels, in order to improve engine emissions and performance. Overall, investigations showed that biodiesel–alcohols reduce NO emissions while increasing CO and HC emissions, perhaps due to the cooling effects of alcohols. Studies with regard to the effects of intake air preheat and alcohol blend ratio, showed that preheating the intake air or lowering the alcohol concentration tends to decrease CO and HC emissions and increase NO emissions [6,13].

Because biodiesel is miscible with alcohols and diesel, it can also be used as an emulsifier to blend alcohols and diesel and to be used as biodiesel–alcohol–diesel blends in diesel engines. Studies regarding the mixing stability and fuel properties of biodiesel–ethanol–diesel fuels showed that the addition of biodiesel prevented phase separation and its high cetane number improved the low cetane number of diesel–ethanol blended fuels [14]. The same work also indicated that the increased ethanol blending ratio resulted in a small decrease in spray tip penetration, while inducing a decrease in the droplet size distribution of diesel–ethanol blended fuels.

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Although there has been much research in terms of alcohols, biodiesel, diesel, biodiesel–diesel or biodiesel–alcohol, investigation of utilization of biodiesel–alcohol–diesel blends is relatively limited in the literature.

Shi et al. [15] used ethanol–methyl soyate–diesel fuel with a blend ratio of 5:20:75 by volume. Oxygenated diesel fuel blends showed a significant reduction in PM emissions and a 2–14% increase of NO*x* emissions. Total hydrocarbons (THC) from ethanol–biodiesel–diesel were lower than for diesel fuel under most test cases. But, change of CO emission was not conclusive and depended on engine operating conditions. Pang et al. [16] used ethanol–biodiesel–diesel blends containing 5% ethanol, 20% biodiesel and 75% diesel by volume and investigated the characteristics of carbonyls and regulated emissions from biodiesel–ethanol–diesel blends. As compared to diesel, the blended fuel showed lower formaldehyde emission because of less aliphatic hydrocarbons in the blended fuel. But, the acetaldehyde emissions from the blended fuel were significantly higher than that from diesel, due to ethanol addition. In terms of regulated emissions, biodiesel–ethanol–diesel fuel showed significantly lower PM and THC and slightly higher NO*x*. Guarieiro et al. [17] used various blends of diesel and ethanol with soybean oil, castor oil, soybean biodiesel and castor oil biodiesel, while ethanol addition was 15% or 7% by volume. It was noted that the combustion efficiencies of diesel fuel can be enhanced by the addition of the oxygenated fuels such as ethanol, biodiesel and vegetable oils, resulting in more complete combustion. However, no significant difference was observed in CO emission. Jha et al. [18] studied emission characteristics of biodiesel–ethanol–diesel fuel blends in both used and new engines. The blend ratios (biodiesel:ethanol:diesel) were 25:5:70, 20:10:70, and 15:15:70 by volume. Biodiesel–ethanol–diesel blends showed a significant reduction in NO*x* emissions in new engines with increased ethanol concentration, whereas the old engine showed increase in NO*x* emission under similar conditions. CO emissions increased with increasing ethanol proportion in the blends in both old and new engines. Chhenkachorn and Fungtammasan [19] used 84.00% diesel, 0.25% hydrous ethanol, 4.75% anhydrous ethanol, and 11.00% biodiesel by volume, tested it in a light-duty truck and results were compared to baseline diesel fuel. Both the blend and diesel fuel showed no significant difference on NO*x* emission. However, biodiesel–ethanol–diesel fuel showed lower PM and CO emissions as compared to baseline diesel. Also, there was no significant difference in the fuel consumption of the two fuels. Hulwan and Joshi [20] used diesel–ethanol–biodiesel blends of high ethanol content and studied performance and emission characteristics of a DI diesel engine. The blends consisted of D70/E20/B10, D50/E30/B20, D50/E40/B10 and diesel (D100). Based on the comparison of blended fuels with baseline diesel, results indicated higher brake specific fuel consumption, slight improvement of thermal efficiency and reduction of smoke opacity at high loads. NO variation depended on operating conditions and CO emissions increased at low loads as compared to diesel fuel. In a similar study by Barabas et al. [21], D85/B10/E5 D80/B10/E10 and D70/B25/E5 blends were compared to diesel fuel. Comparisons showed that CO emissions decrease at low engine loads an increase of CO_2 emissions as a result of a prolonged oxidation process including the exhaust. NO*x* emission increased at medium and high loads due to more complete combustion and increased combustion temperature, which is caused by the presence of more oxygen in the fuel. HC emissions decreased at all engine operating conditions. Overall, the literature clearly indicates that biodiesel–ethanol–diesel blends significantly reduce PM emissions. However, contradictory results are reported in terms of CO and NO*x* emissions. While some studies indicated increase in NO*x* emissions, other studies reported a reduction of NO*x* emissions, depending on whether the engine was old or new. Also, while some studies showed an increase in CO emissions, others reported a decrease or no clear trend.

In this paper, emission characteristics of a diesel engine running on biodiesel–diesel–ethanol (BDE) blended fuels are reported as functions of blend ratios and engine loads. Ethanol concentrations in biodiesel–diesel blends were varied at 3%, 5%, 15% and 25% by volume while biodiesel and diesel concentrations were maintained equal by volume. Effects of both low and high concentrations of ethanol on engine emissions were investigated. As the aim of this work was to investigate effects of ethanol concentrations on engine emissions, the findings showed that low concentrations of biodiesel–ethanol–diesel blends could have opposite effects compared to high concentrations. Although there is similar work done in the literature, no reported work includes investigation of a wide range of ethanol concentrations. As far as the findings, there are mixed reports in the literature that reported low and high ethanol concentration studies separately. This paper combines both studies and make conclusions based on its own operating conditions.

2. Experimental procedure and specifications

Experiments were carried out using a two-cylinder, 4-cycle, direct injected, liquid-cooled Kubota GL7000 diesel engine generator. Specifications of the engine are shown in Table 1.

CO, NO and unburned HC emissions were measured using a Sun Diagnostics DGA1000 5-gas analyzer. CO measurement represents an important component of emissions testing. For example, in New Mexico, total allowable annual CO discharge from any point source is limited to 100 tons/year. Although NO*x* encompass all the oxides of nitrogen, chemical equilibrium calculations show that by far, the only significant oxide is NO, e.g., at 2400 K and 3 MPa, equilibrium calculations indicate that both NO_2 and N_2O will each be less than 0.1% of NO. Hence, since NO is the emission measured in the particular gas analyzer utilized, the indicated analysis will be the same as a calibrated NO*x* emissions gas analyzer will indicate, considering the instrument measurement uncertainty. The gas analyzer was calibrated using BAR97 low and BAR97 high calibration gases. The calibration process was repeated regularly for the engine tests. Exhaust gas temperature was measured with a type-K thermocouple.

Ethanol, biodiesel and diesel fuels were blended to make biodiesel–diesel–ethanol (BDE) mixtures with 3%, 5%, 15% and 25% ethanol concentrations while maintaining equal amounts for biodiesel and diesel (BDE3, BDE5, BDE15, BDE25). Ethanol blended fuels were compared to baseline diesel for further assessment of advantages and disadvantages of the blends. Biodiesel was made of used cooking oil following the standard transesterification process. It followed ASTM D6751 and met the standard specification.

Table 1
Specifications for diesel engine generator.

Generator	Kubota Diesel Generator
Type	GL-7000
Maximum output (kW)	6.5
Rated output (kW)	6
Engine cooling	Horizontal liquid-cooled
Combustion system	E-TVCS
Intake system	Natural aspirated
Cooling system	Radiator cooling
No. of cycles	4-Cycle
Model	Z482
Rated output (kW/rpm)	8.95/3000
Bore × stroke (mm)	67 × 68
Displacement (cm^3)	479
No. of cylinders	2
Combustion system	Indirect injection
Compression ratio	23.5:1

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