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Recent Developments on Internal Combustion Engine Performance and Emissions Fuelled With Biodiesel-Diesel-Ethanol Blends

M. Mofijur*, M.G. Rasul, J. Hyde

School of Engineering & Technology, Central Queensland University, Queensland 4701, Australia

Abstract

Ever increasing drift of energy consumption due to growth of population, transportation and luxurious lifestyle has motivated researchers to carry out research on biofuel as a sustainable alternative fuel for diesel engine. Biofuel such as biodiesel and ethanol, produced from renewable feedstocks, are the most appropriate alternative of petroleum fuels. However, direct using of ethanol in diesel fuel face some technical problem especially in cold weather, due to low cetane number, lower flash point and poor solubility. Biodiesel can be blended with both ethanol and diesel fuel and biodiesel–alcohol–diesel blends can be used in diesel engines. The aim of this review paper is to discuss the effect of mixed blends of biodiesel alcohol and diesel on engine performance and emission parameters of a diesel engine. Most of the researchers reported that adding ethanol into biodiesel-diesel blend in diesel engines significantly reduce HC, PM, NOx and smoke emissions but slightly increase fuel consumption. The study concluded that biodiesel-diesel-ethanol blend can be used as a substitute of petro-diesel fuel to reduce dependency on fossil fuel as well as the exhaust emissions of the engine.

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Keywords: Global energy consumption; emission; diesel engine; ethanol; biodiesel

1. Introduction

The demand for energy, specifically the demand for petroleum fuels around the world is increasing every day [1]. From 2012 to 2015, 41% increase in global energy consumption is forecasted, 30% and 52% increase over last ten and last twenty years respectively. Non-OECD economies will account for 95% of this growth, half of which is expected to come from China and India. Compared to 2012, 69% higher energy will be used in 2035 in the non-OECD economics. Due to having benefits such as adaptability, high combustion efficiency, availability,

* Corresponding author. Tel.: +61749309634
E-mail address: m.rahman@cqu.edu.au

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reliability as well as the handling facilities, fossil fuels results in most energy consumption. Shares of the major fossil fuels are converging, with natural gas, oil and coal each contributing 27% of the total mix by 2035 and the remaining share supplied by nuclear and renewable energy. **Table 1** shows the primary energy consumption by fuel type between 2012 and 2035 [2]. Burning of fossil fuels produces emissions that have serious effect on both the environment as well as human health. Fuel, coal and gas each contributes 38% of the increase in emissions and 24% increase is coming from oil. It is predicted that by 2035 global CO_2 emissions from energy use will increase 29%. Compared to 1990, global emissions will be nearly double in 2035. Price hiking of the petroleum products, world-wide environmental concerns as well as the rapid depletion of fossil diesel fuel have encouraged researcher to search for alternative fuel sources which will provide cleaner combustion of diesel engines. Therefore, it has become a global agenda to develop clean alternative fuels which are domestically available, environmentally acceptable and technically feasible. According to the Energy Policy Act of 1992 (EPACT, US), natural gas, biofuel, electricity and methanol are the most suitable substitute to fossil fuels that can reduce global warming, fossil fuels consumption and exhaust emissions [3]. As an alternative fuel, biofuel such as ethanol, biodiesel are the best choices due to having properties such as environment friendly behaviour and similar functional properties with diesel fuel. In both developing and developed countries biofuel are at the top of their agendas and thus it is predicted that world biofuel production will be quadruple by 2020 [4].

Table 1: Global primary energy consumption by source [2]

Sources	2012		2035*	
	Mtoe	Share (%)	Mtoe	Share (%)
Oil	4130.5	33.10	4967.3	28.27
Natural gas	2987.1	23.94	4631.0	26.36
Coal	3730.1	29.89	4743.0	27
Nuclear	560.4	5.00	859.9	4.89
Hydropower	831.1	6.66	1245.8	7.09
Renewable	237.4	1.90	1118.9	6.36
Total	12476.6	100	17566.0	100

*Prediction

Biofuel such as biodiesel and ethanol are produced from renewable feedstocks. Especially, compared to fossil fuels, biodiesels, made from various crops and animal fat, are non-toxic, bio-degradable, eco-friendly and renewable. Biodiesel can be used in its pure form (B100) or may be blended with petroleum diesel in modern diesel engines. Using only alcoholic fermentation process, ethanol can be produced from agricultural products. Significant particulate matter (PM) emission reduction can be achieved by using ethanol in diesel fuel [5]. However, due to having properties such as low cetane number, lower flash point and poor solubility the direct use of ethanol in diesel engine faces some technical barriers. Biodiesel can be mixed with both alcohols and diesel; using biodiesel as an emulsifier with alcohols and diesel can be used as biodiesel–alcohol– diesel blends in diesel engines [6, 7]. Thus this review aims to investigate different fuel properties of diesel– biodiesel-ethanol/bioethanol blends and the performance of an internal combustion engine fuelled with these blends, investigated by many researchers.

Table 2: Physical and chemical properties of ethanol-biodiesel-diesel blend [7, 11, 14, 18]

D:BD:EtoH	**Density [kg/m^3]**	**Viscosity [mm^2/s]**	**Flash point [°C]**	**Calorific value [MJ/kg]**	**Cetane number**	**Pour point [°C]**	**CFPP [°C]**	**Cloud Point [°C]**
80:5:15 ROME 99.8%	823.5[b]	1.843	-	40.28	45.1	-	-	-
70:10:20 JBD 99.7%	832.87[a]	2.380[c]	14	39.93	50	−3	–	–
50:20:30 JBD 99.7%	834.55[a]	2.401[c]	12.5	38.96	50	−9	–	–
50:10:40 JBD 99.7%	820.42[a]	2.018[c]	12	36.33	41	−12	–	–
85:12:3 SBD 99.7%	840[b]	3.01[c]	–	41.50	–	–	–	–
80:16:4 SBD 99.7%	840[b]	3.03[c]	–	41.20	–	–	–	–
75:20:5 SBD	845[b]	3.04[b]	–	40.90	45		–	–
60:30:10 WCOBD 99.9%	826[d]	2.44[d]	18.5	39.10	47.3	−3	–	−1
50:40:10 WCOBD 99.9%	831[d]	2.60[d]	19	38.70	47.2	−3	–	3
50:30:20 WCOBD 99.9%	821[d]	2.14[d]	15	37.85	47.2	−6	–	4
90:5:5 RBD 99.3%	843.7[a]	2.435[c]	17.5	41.70	51.04	–	−18	–
85:10:5 RBD 99.3%	845[a]	2.421[c]	14	41.56	51.20	–	−17	–

80:15:5 RBD 99.3%	847.2[a]	2.527[c]	16	41.41	51.36	–	−13	–
75:20:5 RBD 99.3%	849.6[a]	2.645[c]	17	41.26	51.52	–	−17	–
70:25:5 RBD 99.3%	851.9[a]	2.756[c]	18	41.12	51.68	–	−16	–
75:15:10 RBD 99.3%	844.7[a]	2.374[c]	15.5	40.66	49.24	–	−4	–
70:20:10 RBD 99.3%	846.8[a]	2.480[c]	16	40.52	49.41	–	−7	–
80:15:5 PBD(PME) 99.5%	838.3[a]	2.63[c]	17	43.80	53.2	3	–	–
80:15:5 PBD(PEE) 99.5%	837.8[a]	2.72[c]	15.7	39.30	–	3	–	–
80:15:5 PBD(PBE) 99.5%	837[a]	2.73[c]	15	43.70	–	3	–	–
85:10:5 PBD(PME) 99.5%	836.1[a]	2.57[c]	15	43.70	52	3	–	–
85:10:5 PBD(PEE) 99.5%	835.9[a]	2.63[c]	15	43.90	–	3	–	–
85:10:5 PBD(PBE) 99.5%	835.4[a]	2.65[c]	16	44.00	–	3	–	–

2. Production and properties of diesel-ethanol-biodiesel blends

Using transesterification process biodiesel can be obtained from vegetable oils, animal fats, used cooking oil and waste grease from restaurants. Currently, the sources of biodiesel include soybean oil, sunflower oil, corn oil, used fried oil, olive oil, rapeseed oil, castor oil, lesquerella oil, milkweed (Asclepias) seed oil, *Jatropha curcas*, *Pongamia glabra* (karanja), *Madhuca indica* (Mahua) and *Salvadora oleoides* (Pilu), *Calophyllum inophyllum*, palm oil, linseed oil, algae etc [8]. Ethanol is a low cost oxygenates which contains 34% higher oxygen content by weight. Using fermentation process ethanol can be made biologically from a variety of biomass sources such as sugarcane, corn, sugar beet, molasses, cassava root etc. Rural economy can be boosted significantly by the use of ethanol in diesel engines. The large-scale production steps of ethanol are: microbial (yeast) fermentation of sugars, distillation, dehydration and denaturing. Some crops require saccharification or hydrolysis of carbohydrates such as cellulose and starch into sugars prior to fermentation process [5]. Ethanol and biodiesel both has several different chemical and physical properties. Several factors influences the quality of biofuel, such as: the quality of feedstock, fatty acid composition of the feedstock, type of production and refining process employed and post production parameters [9]. Modification of properties is achieved when biodiesel-diesel or diesel-ethanol or biodiesel-diesel-ethanol is blended. **Table 2** shows the properties of diesel- biodiesel-ethanol blends.

3. Performance and emission characteristics of biodiesel-diesel-ethanol blends in diesel engines

In many countries researchers have investigated the performance and emission characteristics of diesel engines fuelled with ethanol-biodiesel-diesel blends. It has been reported that performance of ethanol-biodiesel-diesel fuelled engine are in influenced by many factors such as engine type, operating condition, properties and fuel concentration. Fig.1 shows the CO (Carbon monoxide), NO (Nitric oxide) and HC (Hydrocarbon) of diesel engines using different percentages of biodiesel-diesel-ethanol blends. A study conducted by Labeckas et al. [10] studied the effect of ethanol-diesel and rapeseed biodiesel blends (15 vol% of ethanol and 5 vol% of biodiesel to 80 vol% diesel fuels) on performance and emission characteristics of a diesel engine at different loads and speed condition. The test results showed that engine running with composite blend BDE15 developed similar brake thermal efficiency as a straight diesel operating on slightly richer air–fuel mixture $\lambda = 1.5$ at rated 2200 rpm speed. The tertiary blend BDE15 showed a significant reduction of NO_X and the HC emissions by 6.3%, 11.9%, 9.5% and 24.6%, 14.6%, 15.1% compared to that of normal diesel fuel at 1400, 1800, 2200 rpm speeds. At 1400 rpm the emission of CO was 3.9% lower, but 14.7% and 1.0% higher at 1800 and 2200 rpm respectively. They also found that smoke opacity was 26.1% lower at 1400 rpm and 8.4% higher at 1800 rpm, and again 15.6% lower at 2200-rpm speeds. The lower NOx revealed exclusive role of fuel bound oxygen, HC emissions along with positive changes in the CO emissions and opacities of the exhaust. The authors concluded that the ethanol (15 vol %), diesel (80 vol %) and biodiesel (5 vol %) blend is the suitable blend and significantly can be used in diesel engines. The addition of anhydrous ethanol and RME to petro-diesel fuel suggests ecological advantages and increases the renewable biofuel concentration in the blend that is one of the targets recommended by the EU Directive 2009/28/EC. Yilmaz et al. [11] investigated the emission of biodiesel-diesel- ethanol (BDE3, BDE5, BDE15 and BDE25) blends in a diesel engine at different engine load condition. Experimental results indicate that emissions are strongly depended on engine operating conditions and biofuel concentration in the blend. Ethanol blended fuels increased CO emissions compared to that of diesel fuel for all operating conditions but the blended fuels reduced NO emissions for all concentrations. Overall, lower percentages of ethanol in the blend decreased HC emissions and vice versa. But ethanol blended fuel reduced HC emissions at over 50% load conditions. Fang et al. [12] studied the performance and emission of ethanol-diesel-biodiesel blend in a diesel engine at low combustion temperature condition. They found that ethanol–diesel–biodiesel blended fuel produce lower NO*x* emissions and higher HC and CO emissions due to higher latent heat of vaporization which causes lower combustion temperature. In case of smoke emission blended fuel (ethanol–diesel–biodiesel) lowered it compared to that of diesel and biodiesel–diesel fuel. The peaks of smoke emissions were reduced in a large extent with the increase of percentage of ethanol in blended fuels. Finally, they concluded that ethanol–diesel–biodiesel is suitable alternative to reduce NO*x* and smoke emissions in premixed lower temperature condition. Ferreira et al. [13] studied the performance and emission characteristics of a diesel engine connected to an electric generator operating with diesel-biodiesel-ethanol (D70B30-E5, D70B30-E9 and D70B30-E15) blend at 1800 rpm. They found that the use of ethanol in the biodiesel diesel blend is perfect to reduce NOx emissions of compression ignition engines. But the CO and THC emissions increased as the ethanol content increased in the blend. However, contradictory to the traditional inverse relationship between NOx and particulate matter emissions (PM), NOx emissions reduction was reported with a slight reduction in opacity. They concluded that the ethanol fumigation could be an effective method for controlling the emission of NOx from diesel engines when higher concentration of biodiesel is used in the blends. It also helps to preserves the natural resources and reduces the dependency on petro- diesel. Zhu et al. [14] studied the effect of ethanol-diesel-biodiesel blend on particulate and unregulated emission of a diesel engine at 1800 rpm and different engine load condition. The test results showed that adding ethanol into the biodiesel-diesel blend lowered particle number concentration and particulate mass emission as well. However, other than regulated emissions, blended fuels gives higher formaldehyde and acetaldehyde emissions, due to different H-abstraction reaction of ethanol, compared with biodiesel and diesel fuel. Armas et al. [15] investigated the effect of using ethanol-biodiesel-diesel in a city bus at real driving condition on particle size distribution and reported reduction of both the number and size of the accumulation-mode particles with the use of oxygenated fuel blends, with less proportion of aromatic hydrocarbons and sulphur in their composition. However the nuclei diameter remains constant as these fuels increase the nuclei concentration. Yilmaz et al. [16] studied the performance and emission of biodiesel-diesel-ethanol blends (B45E10D45, B40E20D40) in a diesel engine at different load conditions. They found that the use of ethanol in the biodiesel-diesel blend showed higher fuel consumption than that of diesel fuel. The blended fuel increased CO and HC emissions but reduced NO emissions. They concluded that adding ethanol in the blends would be the perfect choice to reduce NO emissions for the concentrations presented in this study. Pidol et al. [17] studied the performance and emission characteristics of a turbocharged diesel engine fuelled with diesel-biodiesel-ethanol (B40E10D40) blends at different speed and load conditions. They found that the main advantage of adding ethanol into the blend lowered smoke levels due to the presence of higher oxygen, higher volatility and reduction of soot precursor's concentration of ethanol- blended fuel. Hulwan and Joshi [6] used higher concentration of ethanol in diesel–ethanol– biodiesel blends to study the performance and emission characteristics of a direct injection diesel engine. The blends consisted of D70/E20/B10, D50/E30/B20 and D50/E40/B10 and the result compared with pure diesel fuel. They found that the blended fuel gives higher brake specific fuel consumption, slight improvement of thermal efficiency and reduction of smoke opacity at high loads. The variation of NO emission depends on operating conditions and at lower load condition CO emissions increased as compared to diesel fuel. Zhu et al. [18] tested Euro V diesel fuel and ethanol-biodiesel blends in a four-cylinder direct injection diesel engine and found that the addition of 5% ethanol in biodiesel improves engine performance slightly. It also reduces NOx, PM, CO and HC emissions compared to diesel fuel. In exception, higher concentration of ethanol in blend could increase CO and HC emissions, while significantly reducing NOx and PM emissions. Chhenkachorn and Fungtammasan [20] studied the performance and emission of a light duty track using ethanol-diesel-biodiesel-bioethanol blends (84% diesel, 0.25% hydrous ethanol, 4.75% anhydrous ethanol, and 11% biodiesel by volume).

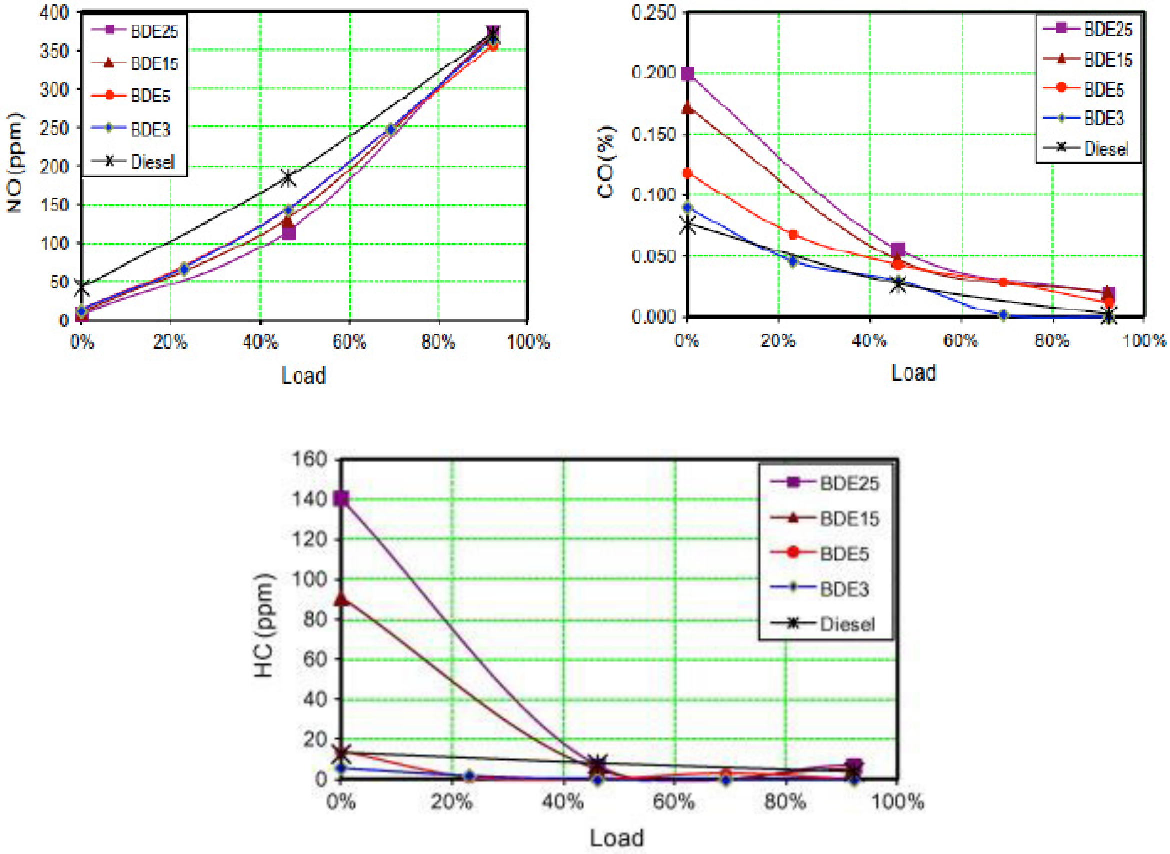

Fig. 1: Effect of diesel-biodiesel-ethanol blends on NO, CO and HC [11]

Both the blend and diesel fuel showed almost similar NO*x* emission result and fuel consumption. However, biodiesel–ethanol–diesel fuel indicated lower PM and CO emissions compared to that of baseline petro-diesel fuel. Barabas et al. [21] studied the performance and emission of diesel-biodiesel-ethanol (D85/B10/E5 D80/B10/E10 and D70/B25/E5) blends in a diesel engine and compared to diesel fuel. The test result indicated that, at all operating condition HC and PM emissions decreased for blended fuel. The emission of CO decreased and CO_2 emissions increased at low engine loads due to a prolonged oxidation process including the exhaust. Authors also found that blended fuel increased NO*x* due to the presence of higher oxygen that leads to complete combustion. Aydin and Ilkiliç [22] investigated the performance of a diesel engine using a blend containing 20% of ethanol in sunflower biodiesel (B80E20). They found that ethanol blended fuel produced lower specific fuel consumption than biodiesel-diesel blend (B20), and almost the same specific fuel consumption as diesel oil.

4. Discussions

Due to increase in petroleum price and adverse effect on environment of petroleum fuel, biofuel is taking its position every day over fossil fuel. Biofuel offer a sustainable source of energy and can play a significant role to reduce dependency on petro-diesel and green house gas emission. Although there have always been inconsistent trends for engine performances and its emissions fuelled with biofuel due to different factors such as the different tested engines, the different operating conditions or driving cycles, the different used biodiesel or reference diesel, the different measurement techniques or instruments, etc as shown in Fig.1.

5. Conclusions

This paper critically reviews on fuel properties, performance and emission of biodiesel-diesel- ethanol blends. Following findings can be summarized from the review:

1) Emissions are strongly depended on engine operating conditions and biofuel concentration in the blend.
2) Combined blends of biodiesel-diesel-alcohol reduce NO_X and HC significantly.
3) The peaks of smoke emissions were reduced in a large extent with the increase of percentage of ethanol in blended fuels.
4) Contrary to traditional belief, NO_X and PM emission both reduced due to the use of mixed blends.
5) Addition of ethanol into the biodiesel-diesel blend lowered particle number concentration and particulate mass emission as well.
6) The use of ethanol in the biodiesel-diesel blend showed higher fuel consumption than that of diesel fuel.

Future work

The authors of this paper will do investigation on engine performance and regulated exhaust emissions such as CO_2, HC and NOx, and unregulated emissions such as PAH, formaldehyde and dioxin emissions, etc from ethanol, Calophyllum oil based biofuels as there is not enough research on the emission of ethanol-Calophyllum biodiesel-diesel blend in diesel engines.

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