INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 2, Issue 5, 2011 pp.899-908

Journal homepage: www.IJEE.IEEFoundation.org

Performance and emission characteristics of diesel engine run on biofuels based on experimental and semi analytical methods

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Abstract

Performance and emissions from a constant speed single cylinder diesel engine was observed with different kinds of fuels blends like diesel-ethanol, and diesel-palm stearin methyl ester. The engine setup was modified to operate in different modes like naturally aspirated condition, supercharged condition and with exhaust gas recirculation (EGR). The air fuel ratio was predicted from exhaust emission data using correlations and the particulate matter (PM) was estimated from smoke data. Fuel air equivalence ratio values of the engine at different operating conditions have been compared. Engine is operated with higher fuel air equivalence ratios with EGR. Particulate matter emissions were considerably reduced with ethanol-diesel, biodiesel-diesel blends in comparison to pure diesel. With EGR rate the particulate matter emissions are increased. An EGR rate of 10% will be best for the present engine which can give better trade-off among HC, NOx and PM.

Keywords: Diesel engine emissions; Biofuels; Equivalence ratio; Particulate matter.

1. Introduction

Reducing of the quantity of pollutant emissions from the diesel engine exhaust is a challenged task in the view of current emission legislation. Combustion modifications, usage of eco friendly fuels are the key technologies to reduce the amounts of pollutant emissions. Biofuels like ethanol, biodiesel have become an attractive alternative to petro diesel as it conquers the dependency on foreign petroleum and offers lower pollutant emissions in the present context of emission legislation [1-4]. Most attractive attribute of biofuel is of its low or no sulphur content. The biofuels are used in diesel engines as direct fuels as well as blends. Many options have been studied like blends of biodiesel to ethanol as a fuel substitute to reduce certain types of emissions. Researchers observed that esters when added to ethanol-diesel blends can significantly reduce emissions like unburnt hydrocarbons and NOx etc.

Studies show that the PM from the diesel engine decreases when operated with low sulphur fuels and biofuels [5]. Diesel particulate matter emissions are measured usually with the help of dilution tunnel [6]. The estimation of PM can also be done by correlations which are based on amounts of other emissions like HC and smoke which is adopted in this article. This would considerably lessen the complexity of measurement system and also one can reduce the number of trails of accurate measurement process.

Present study deals with experimental investigation of biofuels usage in a single cylinder diesel engine operated with different modes like natural aspiration, supercharging and exhaust gas recirculation (EGR).

The emissions measured are unburnt hydrocarbons (UHC), carbon monoxide (CO), nitric oxide (NO), unused oxygen (O_2) and carbon dioxide (CO_2). The effect of the engine operating parameters on PM emissions and fuel air equivalence ratio is studied. The engine was run with biodiesel-diesel blends and ethanol-diesel blends. Biodiesel was derived from raw palm stearin under the process of methanol transesterfication in the presence of catalyst NaOH.

When biodiesel was added in little amounts to ethanol-diesel blends enhance solubility of ethanol in diesel and observed that blends were stable for long time. The blends of biodiesel and diesel are named as B10, B20 and B100. The blends of ethanol-diesel are named as E10B, E20B and E30B. The details of the fuels used along with fuel properties are shown in Table 1. The engine is operated with variable load condition and at constant speed of 1500 rpm. The engine performance is evaluated in terms of brake specific fuel consumption (BSFC), and brake thermal efficiency (BTE). The emission species are measured with the help of Kane-May exhaust gas analyser and smoke opacity was measured with the help of AVL 439 smoke meter. Ranges and sensitivities of test devices are shown in Table 2.

Table 1. Properties of selected fuels

Property	Diesel	Ethanol	PSME
Density (kg/m^3)	840	789	874
Kinematic Viscosity (cSt)	2.44	1.52	4.76
Heating Value(kJ/kg)	42,500	29700	39,900
Cloud Point,^{0}C	3	-25	16
Pour Point,^{0}C	-6	-113	19
Flash Point,^{0}C	70	17	145
Stoichiometric A/F	14.7	10	14

Table 2. Ranges and sensitivities of test devices

Analyzer	Make	Range	Sensitivity
O_2	Kane-May	0-20%	0.01%
CO	Kane-May Quintox	0-10%	0.01%
CO_2	Kane-May Quintox	0-10%	0.01%
NO	Kane-May Quintox	0-5000 ppm	1 ppm
HC	Kane-May Quintox	0-3000 ppm	1 ppm
Smoke meter	AVL 439	0-100%	0.01%

2. Engine performance and emissions

The selected engine has been used for small power applications in developing countries like India. The details of the engine are given in Table 3. The calorific values of E10B, E20B and E30B found to be 40,750kJ/kg, 39,033kJ/kg and 37542kJ/kg respectively. B10 and B20 have the calorific values of 42200kJ/kg and 41900kJ/kg respectively.

Table 3. Specifications of test engine

Engine manufacturer	Kirloskar Oil Engines Limited, India
Engine Type	Single cylinder, 4-stroke, D.I
Cooling	Water Cooled
Dynamometer	DC Shunt
Rated Power	3.7 kW at 1500 rpm
Bore/Stroke	80/110 (mm)
Compression ratio	16.5
Start of Fuel Injection	26^0 BTDC
Nozzle Opening Pressure	180 bar
Cubic Capacity	0.553 m3

The engine when operated with biofuels showed improved fuel economy with B10, B20, and E10B. Biofuels contain oxygen which when added in little amounts to diesel improved the quality of combustion. As the blend quantity of biofuels increased the fuel consumption increased this is because of reduction in heating value of the blend. Specific gravity of the pure biodiesel is more in comparison to diesel which is the reason for more fuel consumption. Supercharging operation was carried out with the help of reciprocating compressor. The inlet air pressure of 0.5 bar (g) was maintained with an estimated value of volumetric efficiency of 107%. Supercharging operation showed progress in fuel economy with improved engine torque performance.
Unburnt hydrocarbon (UBHC) emissions increased with load on the engine. Higher UBHC emissions were observed with ethanol diesel blends in comparison to pure diesel operation. A rise in ethanol content in diesel gives lower equivalence ratios leading to lower combustion and exhaust temperatures that restrain the oxidation of hydrocarbons in the cylinder and in exhaust pipe. UBHC emissions are low for biodiesel diesel blends, further reduced with pure biodiesel operation. Carbon monoxide emissions in some way follow the same trend as that of UBHC. The CO emissions are fairly reduced with higher biodiesel blends in diesel, whereas an opposite trend like higher CO emissions was observed with increased ethanol content due to concealed oxidation at lower equivalence ratios and lower temperatures. However the amounts of CO emissions are not higher for diesel engine in comparison to other fuel air cycles. Nitrous oxide formation is temperature based phenomena along with residence time of fuel with air. For diesel engine NOx mainly consists of nitric oxide (NO). Figure 1 gives the values of NO emissions for the selected fuel options at full load of engine operation. With ethanol blending to diesel the amounts of NO emissions are reduced, the opposite trend can be observed for biodiesel diesel blends. With supercharging the maximum temperature and pressure are increased leading to higher NOx emissions. A rise of 16.55% of NOx was observed for diesel with supercharging in comparison to no supercharging case.

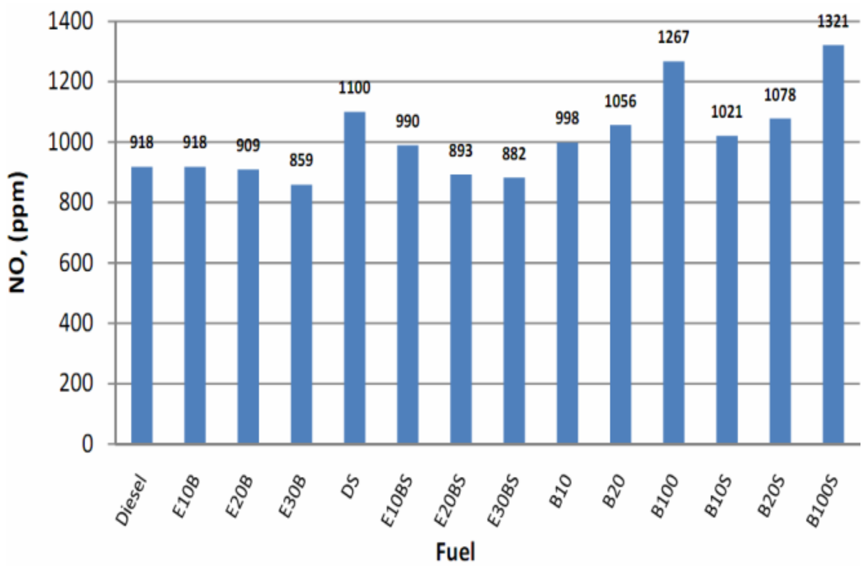

Figure 1. Comparison of NO emissions at full load for different fuels

The UBHC emissions at full load of the engine are shown in Figure 2. Hydrocarbon emissions increased with ethanol concentration and reverse can be applied for the case of biodiesel. The percentage change of NO and UHC emissions at full load on the engine for all fuels in comparison to diesel are shown in Figure 3 and Figure 4. Pure biodiesel showed higher rate of rise (27.55%) in NO emissions in comparison to diesel. 30% of ethanol in diesel (E30B) helped in reducing NO (6.87%) at the cost of greater rise in HC emissions (58%). Smoke opacity values rise with increase of load, and with biodiesel smoke opacity values are reduced, this may indicate lower emissions of PM. Ethanol blending to diesel has showed a significant outcome of reduction in smoke emissions. However, the smoke values are affected by ignition delay. Higher the Cetane number, shorter the ignition delay and less smoke is produced. With supercharging the smoke values are reduced due to reduced ignition delay values.

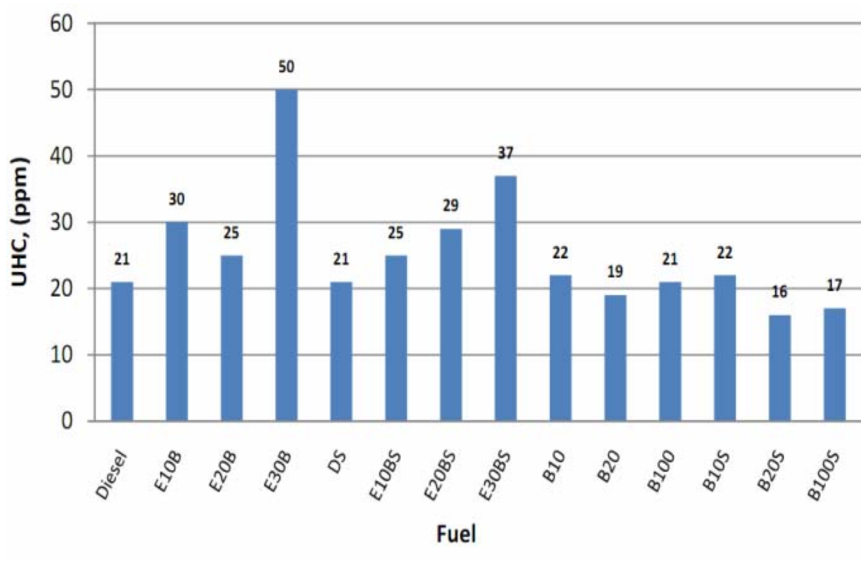

Figure 2. Comparison of UHC emissions at full load for different fuels

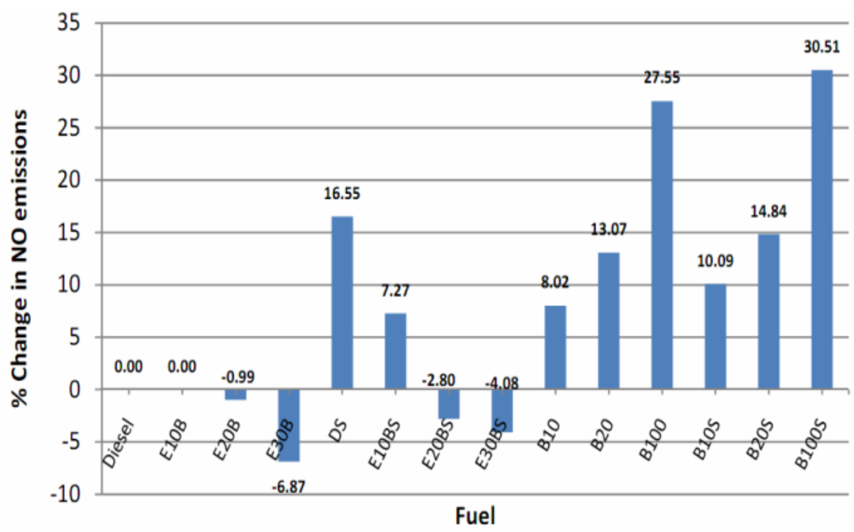

Figure 3. Comparison of percentage change in NO emissions for different fuels with reference to diesel

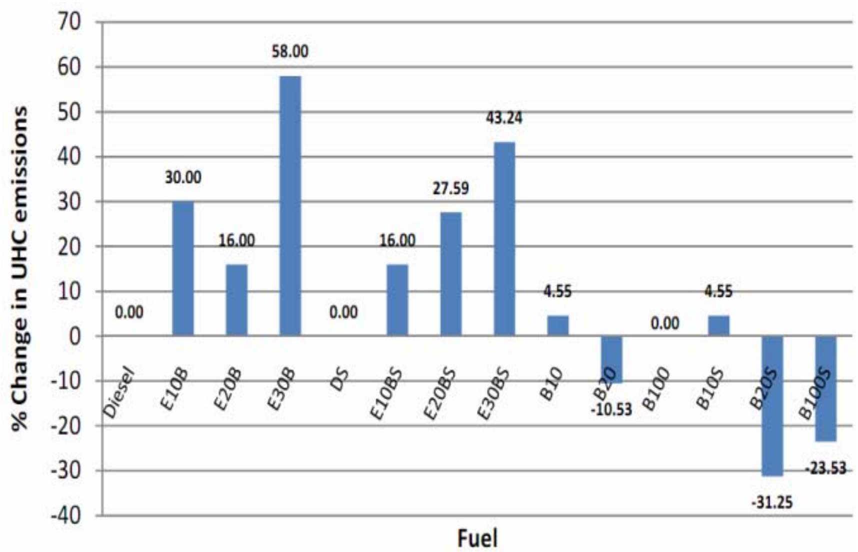

Figure 4. Comparison of percentage change in UHC emissions for different fuels with reference to diesel

Exhaust gas recirculation is an effective and simple means to control NOx emissions by lowering combustion temperature and reducing oxygen concentrations in the intake air. EGR involves replacement of oxygen and nitrogen of fresh air entering in the combustion chamber with the carbon dioxide and water vapour from the engine exhaust [7]. However, EGR results in increasing the PM, UHC and CO emissions, with the observed outcome of reduction in NO emissions. EGR rate was calculated employing equation (1). Flow rates of recirculated gas and inlet air charge was measured with the help of rotameters. A venturi arrangement is made for proper mixing of the exhaust gas with fresh air.

$$\% \text{ EGR} = \frac{\text{Volume flow rate of EGR}}{\text{Volume flow rate of charge into the cylinder}} \times 100 \quad (1)$$

The engine when operated with higher EGR rates resulted in increase in fuel consumption. This is more in case of ethanol-diesel, biodiesel-diesel blends due to their lower heating values. The engine with EGR can be effective in reducing NOx emissions particularly in the case of biodiesel. In the Figure 5, the percentage of reduction of NOx emissions with EGR for different fuels at full load operation is presented. For diesel at 20% EGR rate the reduction of NO is 64.52% with a rise in UHC by 72.37%, at 10% and 15% EGR rates the reduction in NO and rise in UHC are nearly same, so engine can be operated with 10% EGR instead of 15% which gives lower fuel penalty. For the fuel E10B also 10% EGR rate can give better compromise between NO and UHC emissions. However, the amount of NO emissions at full load for E10B is same as that of diesel only advantage of E10B would be of reduction in fuel consumption. With B100 the rise in UHC emissions is not profound as the reduction of NO, now the engine can be operated with higher EGR rates (20%). This increases the fuel consumption since the biodiesel have higher specific gravity compared with diesel. For better reduction of NO emissions an EGR rate of 15% can be suggested.

3. Analysis of engine emissions

It would be the best method to predict the engine performance with the help of fuel air equivalence ratio. Estimation of equivalence ratio by knowing the concentrations of emission is a fine technique as the emission data are direct indication of the nature of combustion process. The characteristic diagram (fuel air equivalence ratio Vs emissions) is capable of capturing interdependencies between engine emissions and engine performance. The fuel air equivalence ratio (Ø) is given by

$$\text{Fuel air equivalence ratio} = \frac{\text{(Fuel/Air) actual}}{\text{(Fuel/Air) stoichiometric}} \quad (2)$$

The stoichiometric air fuel ratio values for diesel, biodiesel and ethanol are assumed to be 14.7, 14 and 10 respectively. For a given fuel, by knowing the chemical formula and emission species like CO, CO_2, O_2, HC, NO and NO_2 the air fuel ratio can be estimated [8, 9]. For fuel blends like biodiesel-diesel and ethanol-diesel prediction of C/H ratio will be difficult and the air fuel ratio can be determined from exhaust emission data as proposed by R.S.Spindt [10]. This procedure uses emissions CO, CO_2, UHC and un used oxygen to predict air fuel ratio.

In the present study air fuel ratio has been estimated using the emission data of the engine by using the correlation given by R.S.Spindt. Having understood the complexity of PM measurement system, simplified correlations given by different researchers, with smoke and hydrocarbons may be used to estimate particulate matter. A.C.Alkidas [11] has developed a correlation between the soot concentration (mg/m^3) and FSN from the exhaust measurements.

$$\rho_c = 581.4\{\ln [10/(10 * FSN)]\}1.413 \quad (3)$$

Greeves et al.[12] have given a correlation for calculating particulate mass (mg/m^3) by knowing the soot, hydrocarbon concentration in the exhaust.

$$\rho_p = 1.024\, \rho_c + 0.505\, \rho_{HC} \quad (4)$$

J. Arregale et al.[13] have given a correlation based on smoke opacity, FSN and HC measurements for predicting particulate matter and proposed a relation between FSN and smoke opacity values.

$$\rho_p = 4.78\, FSN + 9.14\, FSN^{1.83} + 0.28\, \rho_{HC} \quad (5)$$

In the present study smoke opacity has been measured with AVL 439 smoke meter and FSN values are estimated from smoke opacity values using Figure 6. A polynomial fit for the data between FSN and smoke opacity obtained with R^2 value 0.963.

$$Y= -0.001X^2+0.155X+0.369 \quad (6)$$

where Y= Filter Smoke Number, X= Smoke Opacity (%)

For a diesel engine soot mainly consists of the particulate matter, so PM has been estimated based on the correlations developed by A.C.Alkidas [11].The values of particulate matter has been compared for different operating conditions and with different fuels.

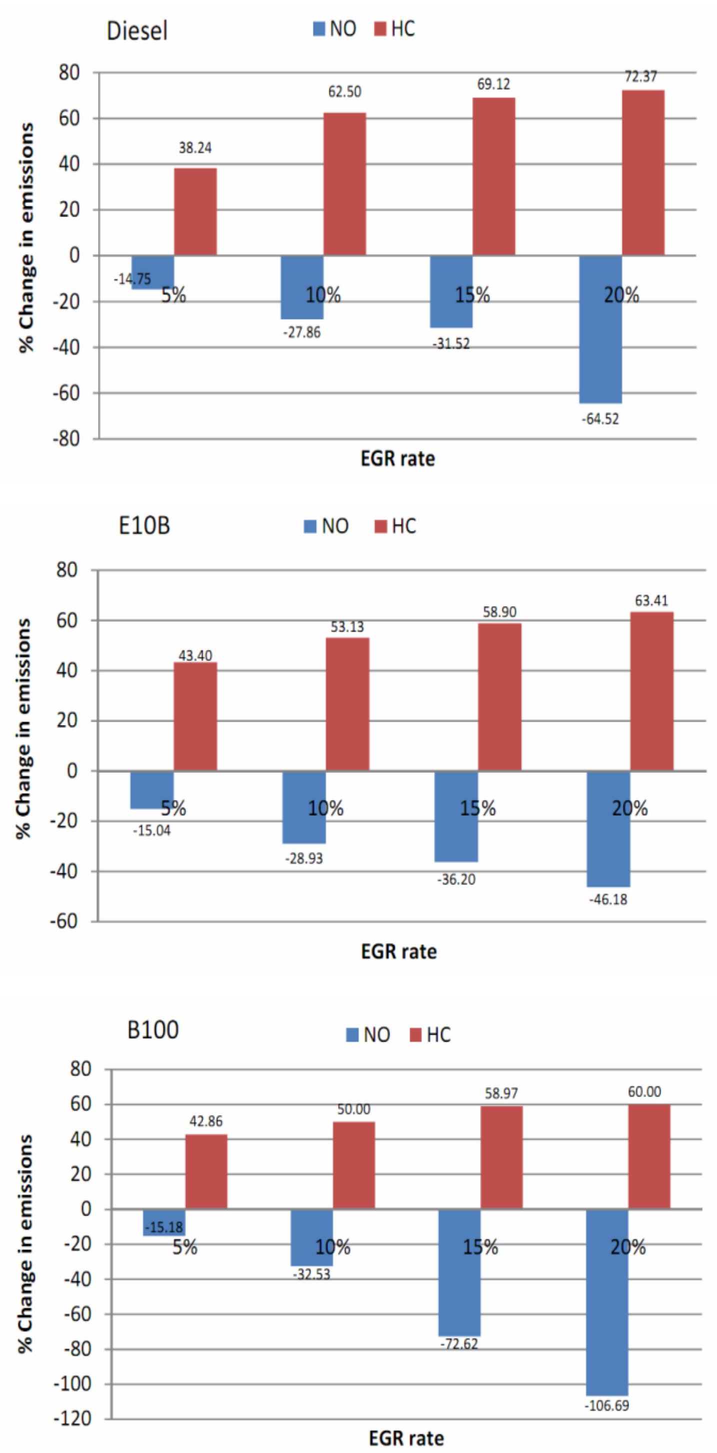

Figure 5. Comparison of percentage change in NO, UHC emissions with EGR rate for different fuels

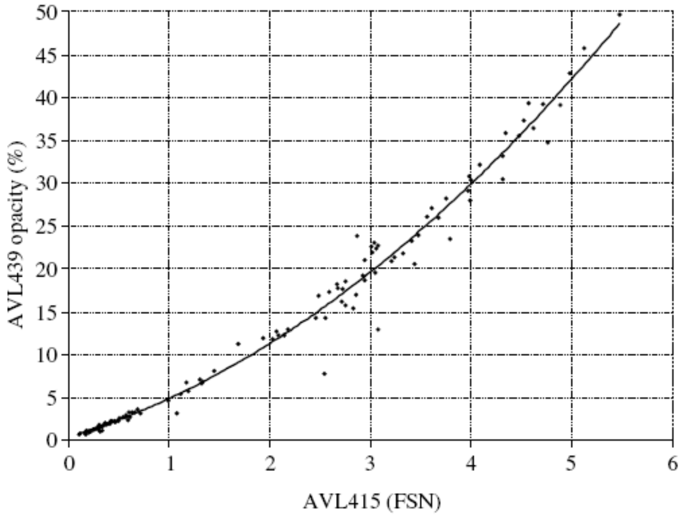

Figure 6. Graph of FSN versus smoke opacity [13]

4. Results and discussion

Figure 7 showing the graphs of equivalence ratio versus engine load percentage with different fuel options, with naturally aspiration condition and with supercharging. It is clear that with a rise in load the values of equivalence ratio increases. And ethanol-diesel blends are with lower values of Ø in comparison to diesel during part load operation. With supercharging the Ø values for diesel increased showing more fuel consumption at part loads, whereas for biofuels the Ø values decreased in comparison to naturally aspiration condition. Pure biodiesel and biodiesel-diesel blends except B10 showed little higher values of Ø in comparison to pure diesel, biodiesel with supercharging has showed lower values of Ø in comparison to diesel except B100 at full load. The effect of EGR on overall equivalence ratio is shown in Figure 8. Engine was operated with higher values of Ø with increased percentage of EGR.

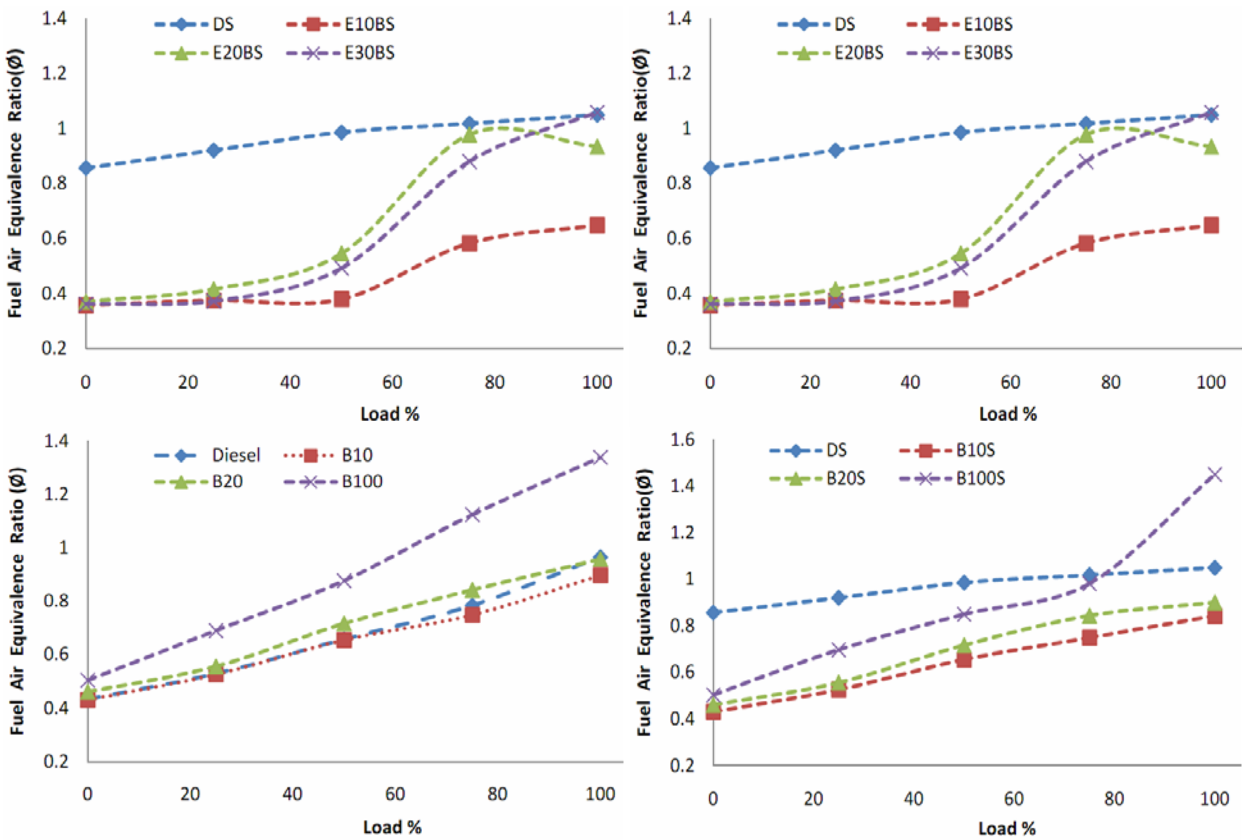

Figure 7. Fuel air equivalence ratio versus load percentage for the selected fuels

ISSN 2076-2895 (Print), ISSN 2076-2909 (Online)

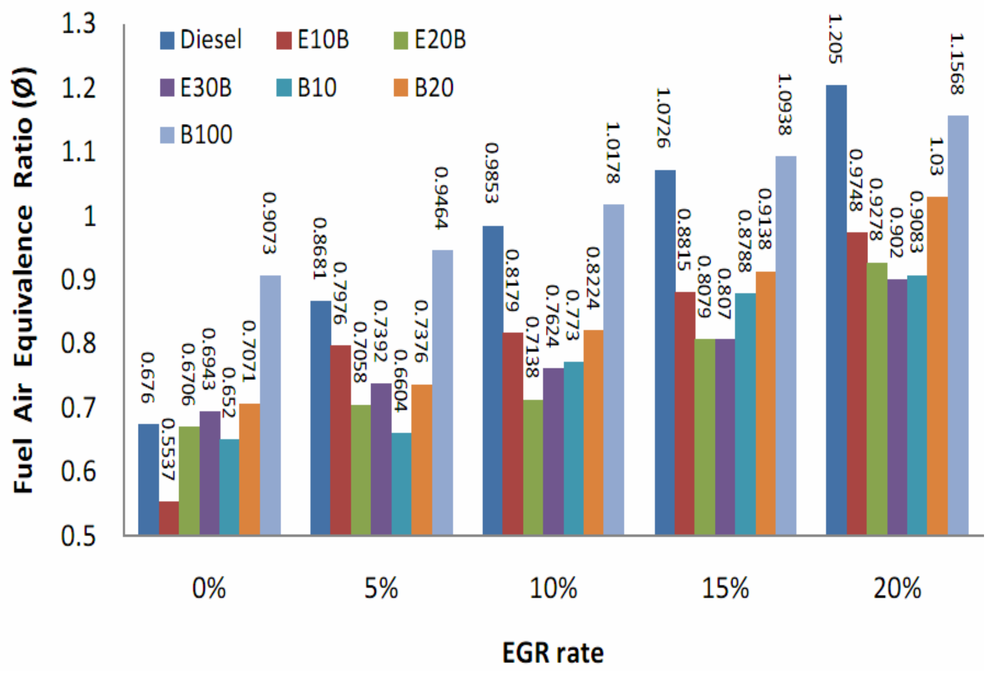

Figure 8. Variation of Ø with EGR rate for different fuels

Overall equivalence ratio can give the fuel consumption trend of an engine. The results show that B20, B100 got higher values of Ø hence higher fuel consumption whereas B10 have low values of Ø shows lower fuel consumption. E10B have very low value of overall equivalence ratio giving less fuel consumption among all the selected fuel options. Supercharging of the engine with B10 and E10B resulted in further reduction of overall equivalence ratio showing good fuel economy.

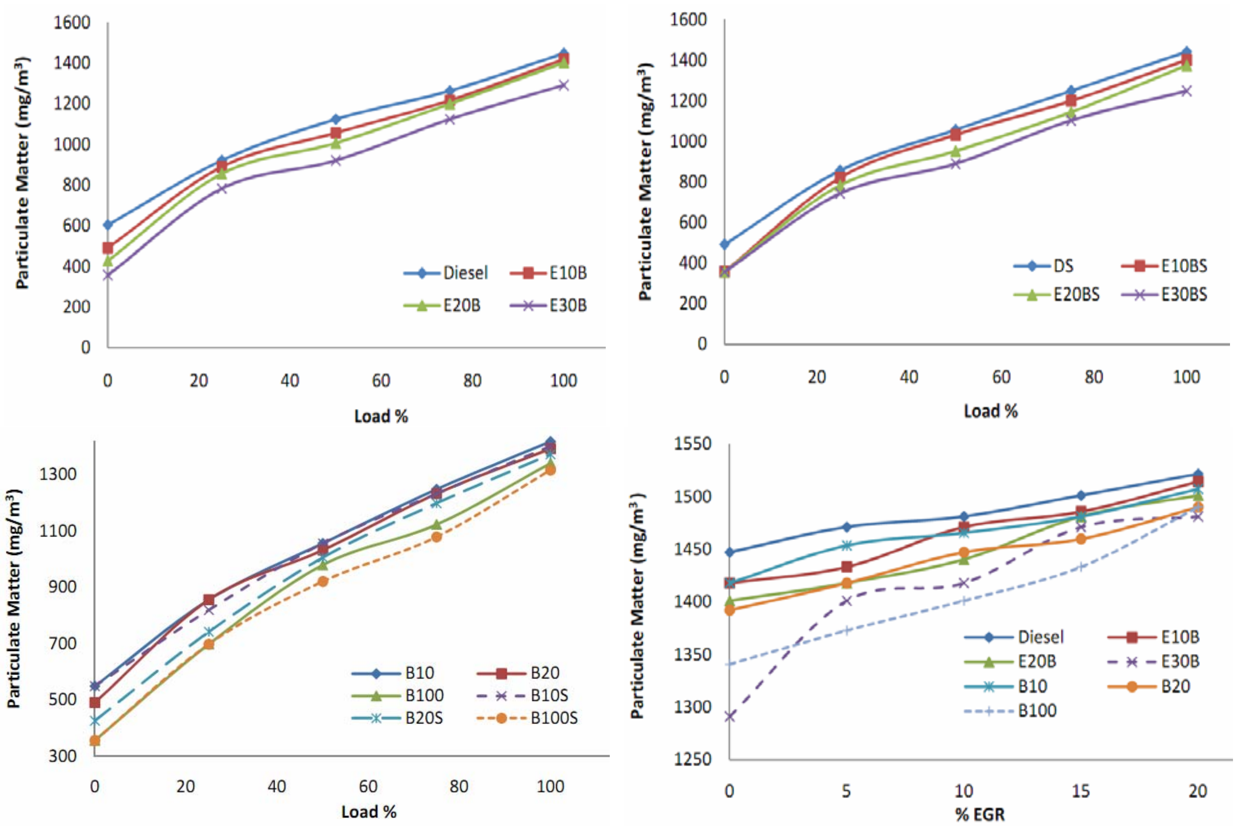

Figure 9. Variation of particulate matter emissions with load percentage, EGR for the selected fuels

The variation of the Particulate matter emissions with load is shown in Figure 9. It can be observed that with the increase of load the PM emissions increased for all the fuels. The PM emissions are reduced with ethanol blending to diesel in little amounts (up to 30%) in comparison to pure diesel. With supercharging the amounts of PM emissions are reduced in comparison to normal operating conditions. Similarly the amounts of PM emissions are considerably reduced with the biodiesel-diesel blends. EGR has adverse effect on engine with a rise in PM emissions at higher EGR rates. Nevertheless, B100, E30B showed reduced amounts of PM with lower EGR rates (up to 15%) when compared with other blends.

5. Conclusion

An experimental investigation has been carried out to find out the performance of single cylinder diesel engine operated on biofuels. Biodiesel was prepared from palm stearin by methanol transesterfication process with the catalyst NaOH. Brake thermal efficiency of the engine is improved with little amounts of blends like B10, E10B. However, higher quantities of blending leads to increase in fuel consumption. Supercharging operation resulted in reduction in fuel consumption. The NOx emissions seem to reduce with ethanol blending to diesel. E10B showed reduced amount of NO formation when compared with diesel. With EGR this is further improved. A little rise in NO emissions was observed with B10 in comparison to diesel with considerable fuel economy. B20 gives a little reduction in HC emissions (10.53%) with a little rise in NO emissions (13.07%). Smoke emissions are considerably reduced with biofuels owing to its higher Cetane number and nature of combustion. Effect of EGR on different fuel options observed and best EGR rate of 10% can be suggested for diesel, ethanol-diesel blends and 10-15% for biodiesel diesel blends depending upon the emissions and fuel economy trade-off.

The fuel air equivalence ratio values have been obtained from exhaust emission data analysis. Overall equivalence ratio values for different fuels are compared and E10B and B10 showed fewer values among all fuels. With EGR rate there is rise in values of Ø (nearly 2.0). The particulate matter has been estimated based on correlations.PM emissions are considerably reduced with blends of ethanol-diesel, biodiesel-diesel in comparison to pure diesel operation. With EGR rate the particulate matter emissions are increased, this effect was observed to be lower for biofuels. The methods used to predict equivalence ratio and PM can be useful in eliminating time and cost requirements of experimentation..

Acknowledgements

The authors are highly grateful to the staff at I.C.Engines laboratory Department of Mechanical Engineering and Chemical Engineering Department for providing the test facilities.

Nomenclature

A/F	Air Fuel Ratio
Ø	Fuel Air Equivalence Ratio
BTDC	Before Top Dead Centre
BSFC	Brake Specific Fuel Consumption [kg/kW.hr]
BTE	Brake Thermal Efficiency [%]
B10	Blend of 10% biodiesel, 90% diesel
B20	Blend of 20% biodiesel, 80% diesel
B100	Pure biodiesel
EGR	Exhaust Gas Recirculation
E10B	Blend of 10% ethanol,5% ester,85% diesel by volume
E20B	Blend of 20% ethanol,10% ester,70% diesel by volume
E30B	Blend of 30% ethanol,10% ester,60% diesel by volume
NOx	Nitrous Oxides
PM	Particulate Matter
UBHC	Unburnt Hydrocarbons

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