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ORIGINAL ARTICLE

Experimental investigation of effects of addition of ethanol to bio-diesel on performance, combustion and emission characteristics in CI engine

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KEYWORDS

Biodiesel;
Transesterification;
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Anhydrous ethanol

Abstract The study presents the experimental evaluations of performance, combustion and emission characteristics of blends containing non-edible cotton seed oil methyl ester and anhydrous ethanol in a diesel engine at various loads. Blends are made from bio-diesel from cotton seed oil by transesterification and anhydrous ethanol (200 proof) in various proportions ranging from 10% to 50%. The results of the investigation are compared with diesel as base fuel. It is observed from the results that the brake thermal efficiency of the blends is similar to that of diesel. There is a decrease of emissions of oxides of nitrogen and smoke, there is a decrease of emissions of carbon monoxide and hydrocarbon at higher loads and increase at lower loads. Also there is increase of maximum heat release rate and maximum pressure for the blends at higher loads. However, there is a decrease of maximum heat release rate and maximum pressure at lower load. This study gives a direction of renewable fuel blends to replace diesel for fueling diesel engine thereby reducing the dependency of fossil fuels.

1. Introduction

The limited availability of resources of fossil fuels and increased demand in various fields such as power generation, transport, and agriculture triggered the research in finding out alternate sources of fuel to replace or reduce the dependency. Among the alternate fuels alcohols and biodiesel from various vegetable oils are the major resources [1]. Utilizing ethanol in diesel engine was first investigated by direct blending in late 1970s in South Africa. The author also studied the properties of diesel-ethanol blends and reported that the solubility of ethanol was one of the major limitations. This can be prevented by adding an emulsifier or co-solvent [2]. Various researchers studied the effect of additives to ethanol diesel blends. Letcher et al. [3–5] identified tetra hydro furan and ethyl acetate as additive for ethanol-diesel blends and has reported the ratio of additive requirement to be 1:2 (50% quantity of ethanol). Goering et al. [6] investigated the change of viscosity of ethanol diesel blends with increase of ethanol and reported that 18.5% dry ethanol is maximum quantity that equals to the minimum viscosity of 2.0 mm^2/s

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Nomenclature

BD	bio-diesel	NOx	oxides of nitrogen (ppm)
E	ethanol	HRR	heat release rate (kJ/m^3 deg)
CN	cetane number	TDC	top dead center
CSO	cotton seed oil	BDC	bottom dead center
CSOME	cotton seed oil methyl ester	RPM	revolution per minute
BTE	brake thermal efficiency (%)	°CA	degree of crank angle
BSFC	brake specific fuel consumption (kg/kW h)	B90E10	blend of biodiesel 90% and ethanol 10%
BMEP	brake mean effective pressure (bar)	B70E30	blend of biodiesel 70% and ethanol 30%
HC	hydrocarbon (ppm)	B50E50	blend of biodiesel 50% and ethanol 50%
CO	carbon monoxide (%)		

(as per ASTM standards), and some more additives were also suggested by Riberio et al. [7].

Datta et al. [8] studied the low temperature characteristics of ethanol-diesel blends containing up to 15% of ethanol by simulation modeling and reported that there was an increase in combustion efficiency and ignition delay. Also it was reported that there was a significant reduction of emissions of NOx and particulate matter for the blend containing 15% ethanol. Nura et al. [9] studied the performance characteristics of diesel-bio-ethanol blend containing 10% ethanol in an indirect diesel engine and emulsifier of SPAN 80 using uniplot software and reported that there was a reduction of emissions NOx and CO as compared to diesel. Praptijanto et al. [10] studied the performance characteristics of ethanol-diesel blends containing up to 15% ethanol by virtual simulation tool and reported that there was an increase of emissions of NOx for the blend containing 15% ethanol at all speeds tested between 1000 rpm and 1500 rpm.

It was also reported that more than 20% ethanol in ethanol-diesel blends increases the cost of the additive. One more alternative for reducing the dependency of fossil fuel is addition of biodiesel to diesel. Also biodiesel has higher lubricity and cetane number [11]. Higher viscosity of biodiesel affects the power produced from the engine. Many researchers have tried diesel-biodiesel blend in various proportion as fuel for diesel engine. Agarwal et al. [12] studied the properties, performance, combustion and emission characteristics of biodiesel from various vegetable oils and reported that 20% of biodiesel can be blended to diesel for reducing the diesel consumption. Imtenan et al. [13] studied the emission characteristics of palm biodiesel-diesel blends containing 80% diesel, 15% biodiesel and 5% diethyl ether and concluded that there was a reduction in hydrocarbon (HC) and carbon monoxide (CO) compared to diesel. De et al. [14] studied the emission and performance of Jatropha biodiesel-diesel blends in various proportions and reported that the viscosity of the blend containing 30% biodiesel was closer to conventional diesel. Also, it was reported that BTE of the blend was lower and the emissions of NOx and CO were higher compared to diesel. Karabektas et al. [15] studied the performance and emission characteristics of biodiesel from cotton seed oil–diesel by preheating the biodiesel up to 90 °C and 120 °C and concluded that biodiesel heated up to 90 °C can replace diesel. It was also concluded that there was an increase in BTE and NOx emissions and decrease in CO emissions.

How et al. [16] studied the performance, combustion and emission characteristics of biodiesel from coconut oil-diesel blends with 5% ethanol and reported that for the blends containing 75% diesel, 20% biodiesel and 5% ethanol the brake thermal efficiency (BTE) was higher than diesel. It was also reported that the emissions of oxides of nitrogen (NOx) and CO were lesser than diesel. Also, the maximum pressure and heat release rate (HRR) for the blends were lower than those for diesel. Labekas et al. [17] studied the performance, combustion and emission characteristics of blends of diesel-biodiesel–ethanol and it was concluded that for the blend containing 80% diesel, 5% biodiesel (from rapeseed oil) and 15% anhydrous ethanol, the brake specific fuel consumption (BSFC) was higher than diesel. Also, there was an increase in emissions of HC and decrease of CO and NOx as compared to diesel. Nurun Nabi et al. [18] studied the variation of properties of biodiesel obtained from cotton seed oil by the addition of ethanol and reported that there was a significant reduction of properties such as viscosity, pour point and cloud point. Also it was reported that there was an increase of BTE, BFSC, NOx emissions and a decrease of smoke and particulate emissions. Viswanatharao Bhale et al. [19] studied the low temperature properties of mahua methyl ester by the addition of ethanol and reported that the cold flow performance of the blends can be increased. It was also reported that there was a reduction of CO and smoke. However, the NOx emission for the blend containing 20% ethanol was lower than diesel. Ali et al. [20] studied the cyclic variation of addition of ethanol and butanol to diesel biodiesel blends and reported that there was low cyclic variation for the blend containing 30% biodiesel with butanol as additive compared to ethanol. Corsini et al. [21–25] compared the performance and emission characteristics of waste cooking oil biodiesel-diesel blend and rape seed oil biodiesel-diesel blend and reported that higher power output was observed from the blend containing the biodiesel of waste cooking oil.

From the previous studies, it is observed that most of the researchers have tried with blends which are containing diesel as one of the fuels. The present study is to analyze the performance, combustion and emission characteristics of biodiesel from non-edible cotton seed oil and anhydrous ethanol in various proportions in a diesel engine at 1500 rpm in five different loads.

2. Materials and methods

Cotton seed is primarily used to make cotton seed oil, and biodiesel from cotton seed oil is obtained by reaction of these with

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Table 1 Properties of fuel.

Sn	Properties	Diesel	Ethanol	CSOME	B90E10	B70E30	B50E50
1	Density @ 15 °C (kg/m^3)	840	821	871	862	853	842
2	Kinematic viscosity @ 40 °C (mm^2/s)	2.6	1.1	4.3	3.8	2.7	2.3
3	Flash point (°C)	56	13	199	181	142	106
4	Fire point (°C)	68	–	208	192	151	112
8	Cetane number	50	8	52	44	35	23
9	Oxygen (%weight)	0	35	12	16	20	24
10	Lower caloric value (MJ/kg)	43	27	35.66	34.8	33	31.33
11	Latent heat of evaporation (kJ/kg)	250	840	230	289	388	510

methanol, by means of reaction of transesterification which produces glycerin as secondary product.

Ethanol is also known as ethyl alcohol obtained by biological sources: Anhydrous ethanol 99.9%.

The test was conducted in a conventional stationary diesel engine.

The blend is prepared by the proportion of ethanol added in the neat biodiesel; three proportions of the blend were taken for the test analysis that was 10%, 30% and 50% of ethanol contents added in neat biodiesel by volume basis. The properties of the blends are determined as per the ASTM standards. Properties of the blends, neat biodiesel and diesel are shown in Table 1.

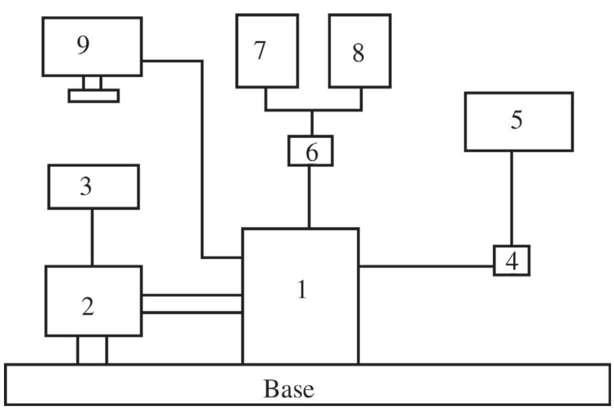

Figure 1 Engine setup block diagram.

3. Experimental setup

The layout of the Engine setup chosen to carry out experimentation is shown in Fig. 1. The engine specification is shown in Table 2. The standard diesel engine is coupled with a swing field electrical powered eddy current dynamometer to apply the load. The combustion chamber pressure variation was measured using an AVL Pressure Transducer GH14D/AH01, which has the Sensitivity of 18.99 pC/bar, Linearity of $< \pm 0.3\%$, Measure range of 250 bar, Temperature range of 400 °C, and Natural frequency of 115 KHZ, which is mounted on the cylinder head. The crank angle and the position of top dead center were measured using an AVL365C ANGLE ENCODER INDI ADVANCED, an accuracy of less than $\pm 0.2\%$ of measured value, which is standard, mounted at the free crankshaft of the engine. The charge amplifier outputs and the encoder were connected to an AVL INDIMICRA 602-T10602A, which converts analog input to digital output, and software version V2.5 for data acquisition system was used to analyze the output data. The variation of generated pressure crank angle and heat release rate at every crank angle can analyze and record through a personal computer when the engine runs. An average value of 100 cycles is measured by recorded

Table 2 Engine specification.

Property	Description
Name	Kirloskar oil engine
Engine type	Four stroke, single cylinder, Vertical, direct injection, Air cooled, Compression ignition Engine
IS rating at 1500 rpm	4.41 kW
Bore	87.5 mm
Stroke	110 mm
Cubic capacity	0.662 l
Nominal compression ratio	17.5:1
Injector type	Single, 3-hole jet injector
Fuel timing by spill (BTDC)	23 deg
Nozzle opening pressure	200–205 kg/cm^2
BMEP	5.44 kg/cm^2
Governor type	Mechanical centrifugal type

SWINGFILED Electrical powered EDDY CURRENT Dynamometer (make – power stars)

kVA-5	PH-1	Hz-50	Volt-240	Amps-21	RPM-1500

parameters at particular load. Eqs. (1) and (2) are used to calculate net heat release rate shown as follows:

$$\frac{dQ_{hr}}{d\theta} - \frac{dQ_{ht}}{d\theta} = \frac{\gamma}{\gamma - 1} p \frac{dv}{d\theta} + \frac{1}{\gamma - 1} v \frac{dp}{d\theta} \quad (1)$$

$$\frac{dQ_n}{d\theta} = \frac{\gamma}{\gamma - 1} p \frac{dv}{d\theta} + \frac{1}{\gamma - 1} v \frac{dp}{d\theta} \quad (2)$$

$dQ_n/d\theta$ is the heat release, $dQ_{hr}/d\theta$ is the heat released by combustion, $dQ_{ht}/d\theta$ is heat transfer with the chamber wall, and γ is the ratio of specific heats [22].

AVL DIGAS 444 (five gas analyzer) was used to measure the constituents of CO, CO_2, HC, NOx and O_2 in the exhaust gas: Power supply 110 V–220 V ≈ 25 W, Warm up time ≈7 min, Connector gas in ≈180 l/h, max overpressure 450 hPa, Response timeT95 ⩽ 15 s, Relative humidity ⩽95%, non-condensing, Interfaces RS 232 C, Pick up, and Oil temperature Probe. The instrument range is as follows: CO 0–10%, HC 0–10000 ppm, and NOx 0–5000 ppm. The accuracy for the gas analyzer is as follows: CO ± 0.02%, HC ± 0.03%, NOx ± 5 ppm for the percentage uncertainties is CO ± 0.2 HC ± 0.2 and NOx ± 0.2.AVL 436 Smoke meter is used to measure the exhaust gas opacity, absorptivity and smoke temperature; Accuracy of ±1FSN, Measurement range 0–10 FSN, Detection limit 0.002 FSN, and Resolution 0.001 FSN. The measurement is taken by the average value of thrice the recorded value for accuracy.

Testing was carried out at various loads at constant engine speed of 1500 rpm, and for each load warm time of 15 min was given before taking the readings. Base readings were taken for diesel fuel. The uncertainty values are as follows: for load ±0.7, Temperature ±0.5, BTE ±0.8, Specific fuel consumption ±1.5, Combustion pressure ±1.0 and Efficiency ±1.5.

4. Results and discussion

4.1. Performance parameters

BTEs of the fuel blends are presented in Fig. 2. It is observed from the figure that there is an increase of BTE for all the fuel blends at 50% load compared to diesel and at full load the blend of 50% ethanol is equivalent to diesel. Also, the increase is proportional to the increase of ethanol in the blend. This is due to the reduction of viscosities of the blends with the addition of ethanol to biodiesel. This leads to better atomization and better fuel-air mixing leading to increase in BTE. The BTE of the blend containing 50% ethanol and 50% CSOME is the highest. It is also observed that the BTEs of the fuel blends are increasing along with the load. This is due to the reason of increase of average combustion chamber temperature at higher loads.

BSFC of fuel blends is presented in Fig. 3. It is observed that the BSFC of the blends is higher than diesel at all loads. However, the increases of BSFC of the blends are lesser at higher loads compared to lower loads. The increase of BSFC is due to the lower calorific value of the blends compared with diesel with the addition of ethanol. The reason for the decreasing trend of BSFC for blends at higher loads is due to the better reactivity of oxygen at higher average temperature of the combustion chamber leading to more complete combustion. BSFC of the blend containing 50% ethanol was the least compared with the other blends at higher loads.

4.2. Combustion parameters

Pressure crank angle diagram for the blends is presented in Figs. 4 and 5. It is observed that there is a maximum pressure for the blends containing 50% ethanol and 50% biodiesel and it is lesser than diesel till 50% of load. The reason is due to the slower evaporation of the blends at lower load resulted from the higher heat of vaporization as the blend contains higher ethanol. After 50% load the maximum pressure is higher than diesel. This is due to rapid combustion of the accumulated fuel as the temperature of the combustion increases at higher loads. For other blends the maximum pressure is higher than diesel at all loads. The reason is due to higher cetane number and lower heat of vaporization compared with the blend containing 50% ethanol. The maximum pressures for the blend containing 50% ethanol are 45.36 bar, 46.46 bar, 55.99 bar, 69 bar and 77.63 bar against diesel 50.86 bar, 56.184 bar, 64.24 bar, 69.41 bar and 75 bar at no load to full load respectively. The maximum pressure for other two blends is 75.11 bar and 75.16 bar for 30% and 10% ethanol content

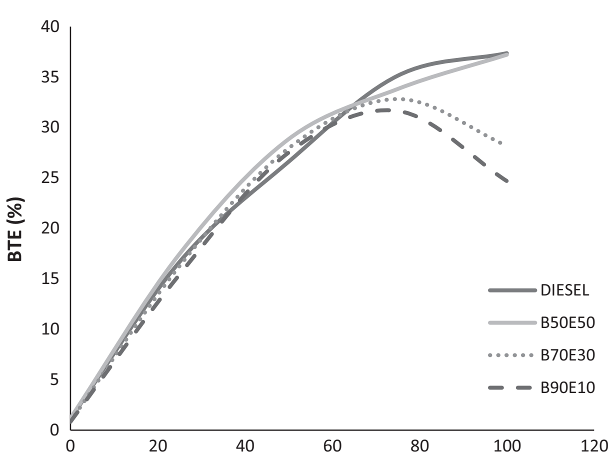

Figure 2 Brake thermal efficiency.

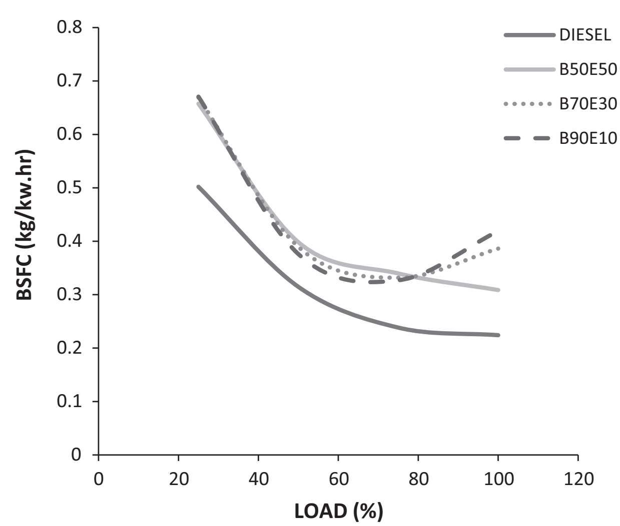

Figure 3 Brake specific fuel consumption.

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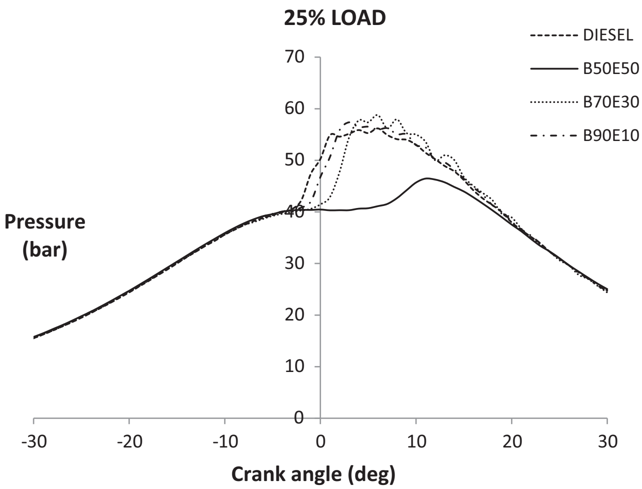

Figure 4 Pressure crank angle diagram at 25% load.

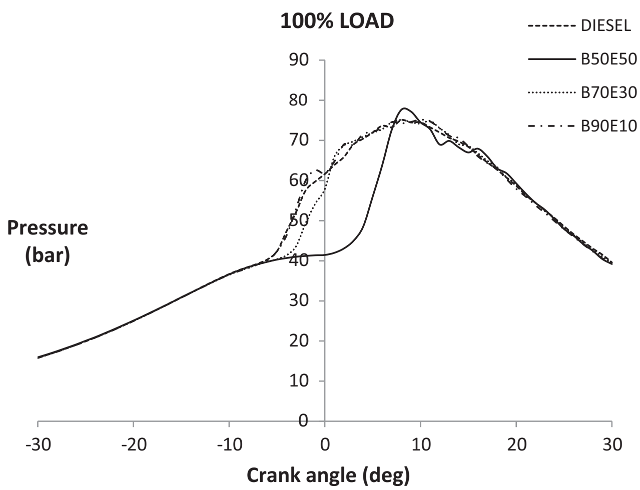

Figure 5 Pressure crank angle diagram at full load.

blends respectively. The angles of occurrence of maximum pressure for the 50%, 30% and 10% ethanol content blends are 8°CA, 8°CA, and 10°CA and 8°CA respectively for the diesel at full load.

HRR of the fuel blends is presented in Figs. 6 and 7. It is observed that for the blend containing 50% ethanol and 50% biodiesel HRR is higher than diesel after 50% of the load. This is due to the better reactivity of oxygen at higher loads as the combustion chamber temperature is higher. At lower loads than 50% the HRR for the blends is lesser than diesel as the heat of vaporization of the blend is higher (as the ethanol content is more) led to slower evaporation. For other blends HRR is higher at all loads. The angles of occurrence of maximum heat release rate for the blends are-3°CA, 0°CA and 6°CA against −3°CA for diesel at full load. This shows that the maximum heat release occurs away from the top dead (TDC). The HRR for the blends containing 50% ethanol is 45.82 kJ/m^3, 55.44 kJ/m^3, 92.1 kJ/m^3, 143.26 kJ/m^3 and 171.1 kJ/m^3 from no load to full load against 59.26 kJ/m^3, 62.6 kJ/m^3, 80.58 kJ/m^3, 75.45 kJ/m^3 and 73.26 kJ/m^3 for diesel respectively. The HRR of the blend containing 30% and 10% ethanol content blends is 96.1 kJ/m^3 and 102 kJ/m^3 at full load.

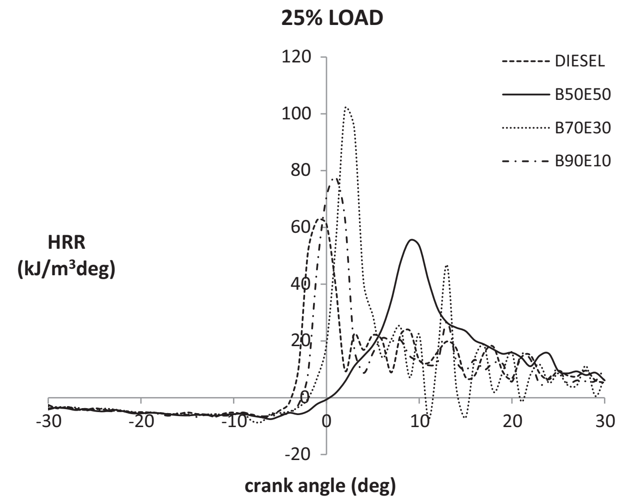

Figure 6 Heat release rate at 25% load.

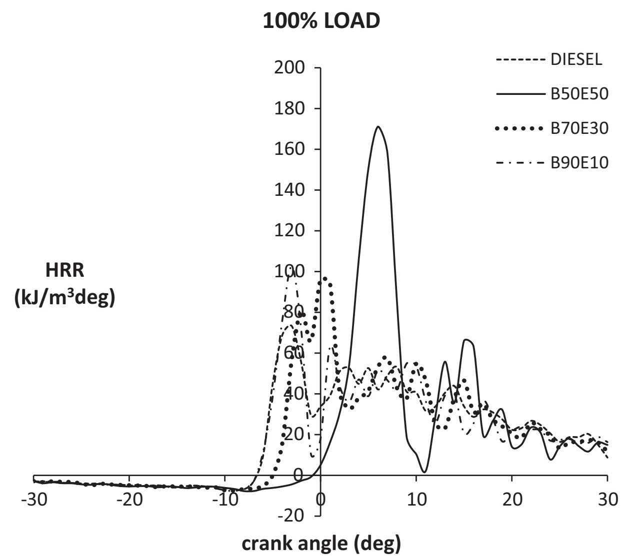

Figure 7 Heat release rate at full load.

The reason for the increase of HRR is due to the longer ignition delay enhancing more fuel accumulation resulted from the lower cetane number of the blends compared to diesel.

4.3. Emission parameters

Emissions of CO of the fuel blends are presented in Fig. 8. It is observed that there is a decrease of CO emissions at all the loads for all the blends except the blend B50E50 in lower loads compared to diesel. However, at loads lesser than 50%, CO emissions for the blends are increasing along with the increase of ethanol content. The reason for the increase of CO emissions is due to the higher of heat of vaporization of the blends resulting from the addition of ethanol. This increase of heat of vaporization led to poorer fuel-air mixing and flame quenching as the temperature is lower at lower loads. This is also observed from the decrease of exhaust gas temperature of the blends at lower loads. As the load increases better fuel-air mixing happened, which increases the average temperature

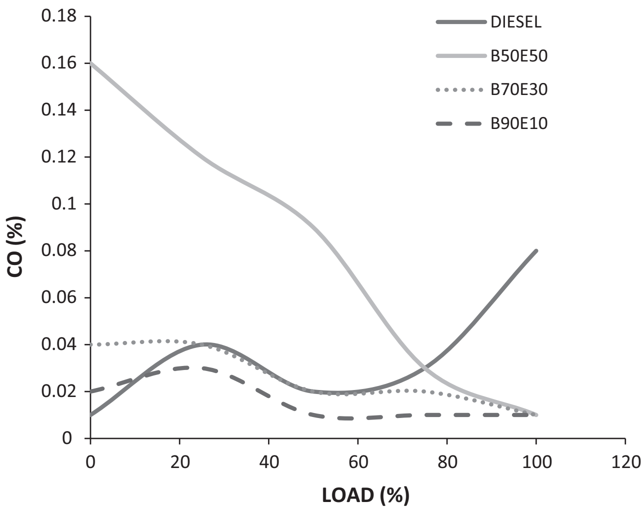

Figure 8 Carbon monoxide.

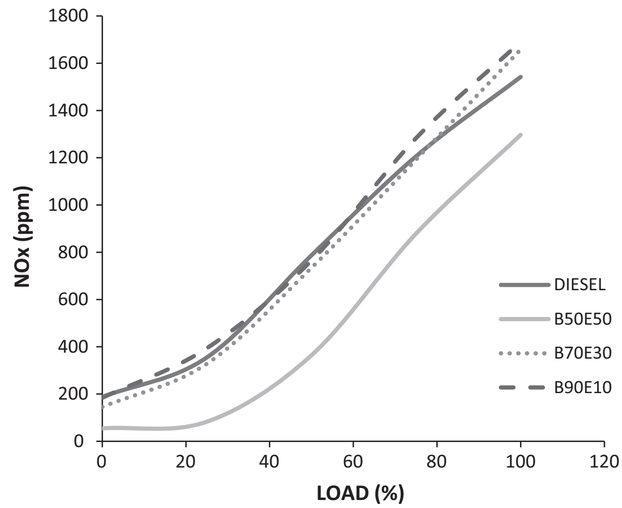

Figure 10 Oxides of nitrogen.

of the combustion chamber resulting in more complete combustion, thereby reducing the CO emissions.

HC of the fuel blends is presented in Fig. 9. It is observed that the emissions of HC are lower than diesel for all the blends at all the loads except the blend B50E50 at 25% and 50% loads. The reduction of HC emissions is due to the higher temperature at higher loads. Also, the oxygen reactivity is increased at higher temperature of the combustion chamber. However, there is an increase of HC emissions at lower loads for the blend containing 50% of ethanol. This is due to the slower evaporation of the blends as the heat of vaporization is higher than diesel. The increase of loads nullifies the dominance of heat of vaporization as the temperature increases along with the load.

NOx of the fuel blends is presented in Fig. 10. It is observed that NOx emission is reduced in blend containing 50% ethanol for all the loads comparing to the diesel. This is due to addition of ethanol in biodiesel blend. There are three types of NOx formation normally, thermal NOx, fuel NOx and prompt NOx. Out of three Thermal NOx is essential for engine efficiency improvement. The evaporation characteristic of the blend (B50E50) is also one of the reasons for reduction of NOx. Lower NOx is due to the lower calorific value and higher heat of evaporation is the reason for lower in-cylinder temperature. NOx decreases with increase of the ethanol oxygen content. The increase of NOx emissions in blend B70E30 and B90E10 is the higher oxygen content of biodiesel which results the better combustion, and leads to combustion temperature increases and provides additional oxygen for NOx formation in higher loads. The increase of ethanol content reduces the viscosity of the blend and thereby increases the atomization of the blend especially at higher loads (above 50%) leading to higher temperature and higher NOx emissions.

Smoke of the fuel blends is presented in Fig. 11. It is observed that the smoke emissions for all the blends are lower than those for diesel at the loads higher than 50%. The decreasing trend of the smoke emission for the fuel blends is proportional to the ethanol content added in the fuel blends. The reduction of smoke is due to lower viscosity of the blend led to better atomization and thereby increasing the better reactivity as the blend contains oxygen. The smoke is nothing but solid soot particles suspended in exhaust gas. It is also

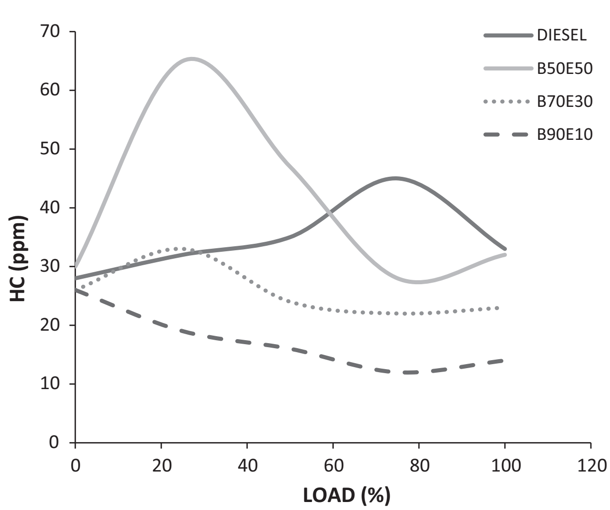

Figure 9 Hydrocarbon.

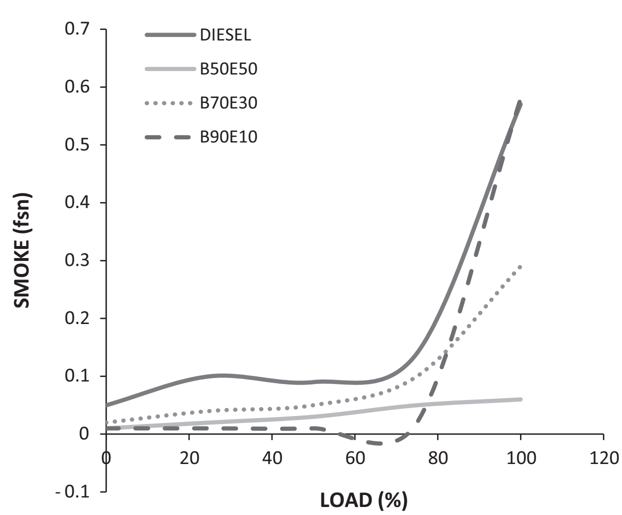

Figure 11 Smoke.

observed that addition of ethanol to biodiesel significant reduces smoke emission as the temperature is higher even at fuel rich zone.

5. Conclusion

An experimental investigation of performance, combustion and emission characteristics of blends of biodiesel from cotton seed oil and ethanol has been performed in a diesel engine for three proportions at five different loads at 1500 rpm.

(1) Brake Thermal Efficiencies of the blends are higher than those of diesel. The maximum increase of BTE of 8% is for the blend B50E50.
(2) BSFC of the blends is higher than diesel only at lower loads.
(3) Maximum pressure and Maximum heat release rate for all the fuel blends are higher at higher loads. The increase of maximum pressure for the blend B50E50 is 17% higher than diesel at full load. The heat release rate of the blend B50E50 is 2.5 times that of diesel at full load.
(4) CO emissions of the fuel blends are decreased up to 66% for all the blends at full load compared to diesel and higher at lower loads for the blend B50E50.
(5) HC emissions for all the fuel blends are lower as compared to diesel at the loads higher than 50%. The blend B90E10 is showing maximum reduction of HC emission up to 57% at full load.
(6) NOx emissions for all the fuel blends are showing lower than diesel for all the loads. The blend B50E50 is showing 29% reduction in NOx emission at full load.
(7) Smoke emissions for all the fuel blends are lesser than diesel at the loads higher than 50% for B50E50, and the smoke emissions are reduced up to 67% at full load.
(8) From the results it can be concluded that the blend B50E50 can replace diesel in diesel engine without any modifications thereby reducing the dependency of fossil fuels. Further research for varying the parameters can be done for the improvement of performance of the blends.

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