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ENVIRONMENTAL EMISSIONS AND EFFICIENCY OF A DIRECT INJECTION DIESEL ENGINE FUELED WITH VARIOUS FATTY ACID METHYL ESTERS

Environmental emissions and efficiency of a direct injection diesel engine fueled with fatty acid methyl esters (FAMEs) have been experimentally investigated and compared with petro-diesel. Rubber seed oil methyl ester, cotton seed oil methyl ester, neem oil methyl ester, and mahua oil methyl ester were used as fuels. The brake specific fuel consumption, brake thermal efficiency, and exhaust gas temperature, nitrogen oxides, carbon monoxide, hydrocarbons, and smoke emissions were investigated. Mahua oil methyl ester exhibits higher brake thermal efficiency compared to other FAMEs. The NO_x was found to be higher, while CO, HC, and smoke emissions of rubber seed oil methyl ester were lower than the other fuels at all loads.

1. INTRODUCTION

The esters of vegetable oils called biodiesels are alternative fuels and most suitable for use in unmodified, standard diesel engines. Biodiesel production in general involves transesterification of a triglyceride feedstock with methanol or other short-chained alcohols [1–3]. When methanol is used for transesterification, the mixture of fatty acid methyl esters (FAMEs) is obtained. The FAMEs have been gaining more importance as attractive alternative fuels in recent years since they are renewable and can be obtained when a vegetable oil is chemically reacted with an alcohol to produce mono-alkyl ester in which glycerol is obtained as a co-product [4–6]. Numerous studies [7–13] have been carried out on preparation of biodiesel from various feedstocks. A number of FAMEs from various feedstocks have been tested in diesel engines for several years as fuels. All these fuels perform differently in diesel engine in terms of performance, emissions, and combustion. It has been reported by various authors

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[14–16] that combustion of FAMEs results in increase in nitrogen oxides (NO_x) compared to diesel. On the other hand, FAME combustion results in decrease in hydrocarbon (HC), carbon monoxide, and particulate emissions compared to conventional petro-diesel [11, 17, 18]. Brake thermal efficiencies were found to be lower for biodiesel blends when compared to diesel [19–21]. In the present study, the environmental emissions and efficiency of a direct injection (DI) diesel engine fueled with various FAMEs were investigated and compared with the conventional petro-diesel. Four different FAMEs such as rubber seed oil methyl ester (RSME), cotton seed oil methyl ester (CSME), neem oil methyl ester (NME), and mahua oil methyl ester (MME) were prepared and utilized as fuels.

LIST OF ABBREVIATIONS

ASTM – American Society for Testing and Materials
aTDC – after top dead center
BSEC – brake specific energy consumption
BSFC – brake specific fuel consumption
BSN – Bosch smoke number
bTDC – before top dead center
CA – crank angle
CSME – cotton seed oil methyl ester
DI – direct injection
FAME – fatty acid methyl ester
HC – hydrocarbons
MME – mahua oil methyl ester
NME – neem oil methyl ester
NO_x – nitrogen oxides
RSME – rubber seed oil methyl ester

2. EXPERIMENTAL

Preparation of FAME. The parent vegetable oils, i.e. rubber seed, cotton seed, neem, and mahua oils were procured from a local supplier situated in Chennai. Fatty acid methyl esters of these four oils were produced through transesterification process. During transesterification, triglyceride and alcohol react to produce alkyl ester, while glycerol is obtained as a co-product. In the present study, methanol is used as alcohol. To catalyze reaction, alkali catalyst (potassium hydroxide or sodium hydroxide) or acid catalyst (hydrochloric or sulfuric acid) can be used. Transesterification using an alkali catalyst is most used commercially and is generally faster than acid catalyzed transesterification [22, 23]. During transesterification process, the viscosity of vegetable oil is reduced to a greater extent. In the present work, FAMEs were produced from 1000 g of parent vegetable oil, with 200 g of methanol, and 5 g of sodium hydroxide as a catalyst (generally the ratio of oil:alcohol:catalyst is 1:0.2:0.005). The ester conversion ratio of all the oils was found to be over 95%.

Engine experiments. Some of the important properties of FAMEs such as density, kinematic viscosity, cetane number, heating value, moisture content, carbon, hydrogen, and oxygen contents were determined following the methods specified in ASTM standards [24]. The FAME composition was determined by the gas chromatography. A single cylinder air-cooled stationary DI diesel engine with the rated power output of 4.4 kW at the rated speed of 1500 rpm was used for the experimental studies. The technical specifications of the engine are given in Table 1 and the test matrix is given in Table 2.

Table 1

Test engine specification

Parameter	Specification
Producer	Kirloskar
Model	TAF-1
No. of cylinders	1
Type of cooling	air cooled
Bore × stroke	87.5 × 110 mm
Compression ratio	17.5:1
Piston bowl	hemispherical
Rated power	4.4 kW at 1500 rpm
Nozzle opening pressure	20 MPa
Fuel injection timing	23° bTDC,

Table 2

Test matrix

Parameter	Specification
Load, % of rated power	25–100
Engine speed, rpm	1500
Nozzle opening pressure, bar	200
Esters used	RSME, CSME, NME, MME

The performance and emissions were studied at 25%, 50%, 75%, and 100% of the rated load corresponding to the load at maximum power at a constant speed of 1500 rpm. The volumetric fuel flow rate was measured as the time taken for 10 cm^3 of fuel consumption using a burette and a stop watch. Once the engine reached the stabilized working condition, the performance and emission parameters were measured. The exhaust gas temperature was measured using K-type (chrome-alumel) thermocouple with a digital indicating unit. The emissions such as NO_x, HC, and CO were measured with DELTA 1600-L make MRU OPTRANS 1600 exhaust gas analyzer. The smoke density was measured by Bosch make TI diesel tune, 114-smoke density tester. Five consequent readings were taken for each parameter and the average was taken to eliminate uncertainty.

3. RESULTS AND DISCUSSION

The FAME compositions and properties of various test fuels are given in Tables 3 and 4, respectively.

Table 3

FAME composition of different test fuels

FAME	C:N^a	FAME composition [wt. %]			
		RSME	CSME	NME	MME
Lauric	12:0	0.00	0.00	0.83	0.00
Myristic	14:0	0.24	0.80	0.47	0.00
Palmitic	16:0	12.46	22.90	18.20	24.20
Stearic	18:0	8.32	3.10	20.10	25.80
Oleic	18:1	27.78	18.50	43.70	37.20
Linoleic	18:2	37.65	54.20	16.40	12.80
Linolenic	18:3	13.55	0.50	0.30	0.00
% of saturated fatty acids		21.02	26.80	39.60	50.00
% of unsaturated fatty acids		78.98	73.20	60.40	50.00

[a] C indicates the number of carbon atoms and N the number of double bonds of carbon atoms in the fatty acid chain.

Table 4

Properties of various test fuels

Property	ASTM test standard	Diesel	RSME	CSME	NME	MME
Density at 15 °C, kg/m^3	D1298	830	889	886	883	881
Kinematic viscosity at 40 °C, mm^2/s	D445	2.63	4.92	4.97	5.09	5.28
Cetane number	D613	48.0	52.0	53.2	58.4	61.6
Heating value, MJ/kg	D240	42.0	39.1	39.4	39.7	40.1
Moisture content, vol. %	D95	–	0.05	0.04	0.06	0.04
Carbon, vol. %	D5291	87.30	77.60	77.16	76.53	75.69
Hydrogen, vol. %	D5291	12.50	11.90	12.32	12.63	13.04
Oxygen, vol. %	D5291	–	10.50	10.52	10.84	11.27
C/H ratio, vol. %	–	6.98	6.52	6.26	6.06	5.80

The variation of brake specific fuel consumption (BSFC) with load for the test fuels is shown in Fig. 1.

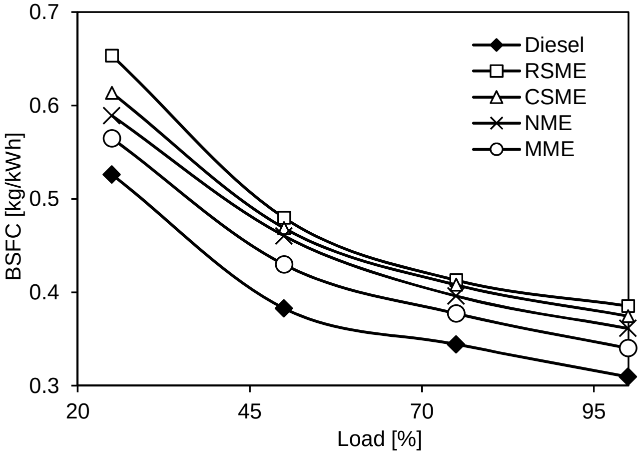

Fig. 1. Dependences of brake specific fuel consumption (BSFC) on load for various test fuels

The BSFC largely depends upon the fuel properties such as mass based heating values and density. From Figure 1, it can be observed that, the BSFC for RSME is higher than that of the other test fuels at all loads. Among the methyl esters, MME exhibits lower BSFC at all loads. This is due to the fact that MME has a lower density and higher heating value compared to other FAMEs. Similarly RSME has a higher density and lower heating value when compared to its counter parts. It is also believed that the BSFC increases with increase in percentage of unsaturated fatty acid methyl esters in the FAMEs (content of unsaturated FAMEs in RSME and MME is about 80 and 50 wt. %, respectively). However diesel has the lowest BSFC compared to the other test fuels at all loads. Diesel possess the higher heating value and lower density when compared to the other test fuels. At full load, the BSFCs for diesel, RSME, CSME, NME, and MME are found to be 0.309, 0.385, 0.374, 0.361, and 0.340 kg/kWh, respectively.

In order to compare the actual energy consumption of an engine, especially when operated with fuels with different heating values and densities, it is ideal to calculate brake specific energy consumption (BSEC). This is due to the fact that both density and heating value effects are taken into account with BSEC. The BSEC is obtained by multiplying the BSFC with the heating value. At full load, the BSECs for diesel, RSME, CSME, NME, and MME are found to be 13.00, 15.06, 14.75, 14.34, and 13.64 MJ/kWh, respectively. From the calculated values, BSEC was found to be higher for RSME and lower for MME within FAMEs; while diesel shows a lower BSEC at all the loads compared to the rest of the test fuels. This is due the combined effect of density and heating value of the respective test fuels. As stated earlier, RSME has a higher density and lower heating value whereas diesel has lower density and higher heating value compared to the other test fuels. The BSEC increases with increase in percentage contribution of unsaturated fatty acids in the FAMEs which is similar to BSFC.

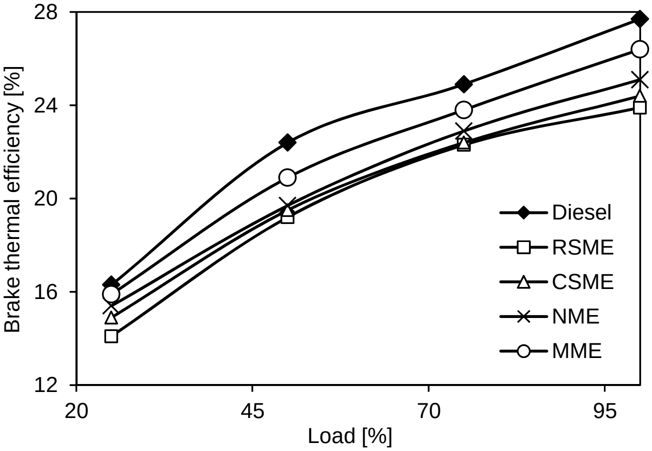

Fig. 2. Dependences of brake thermal efficiency with load for various test fuels

The variation of brake thermal efficiency with load for various test fuels is depicted in Fig. 2. The brake thermal efficiency shows an exactly the reverse trend compared to BSEC at all loads for all the test fuels. This is because of brake thermal efficiency is the reciprocal of BSEC. At full load, the brake thermal efficiencies for diesel, RSME, CSME, NME, and MME are found to be 27.7, 23.9, 24.4, 25.1, and 26.4%, respectively.

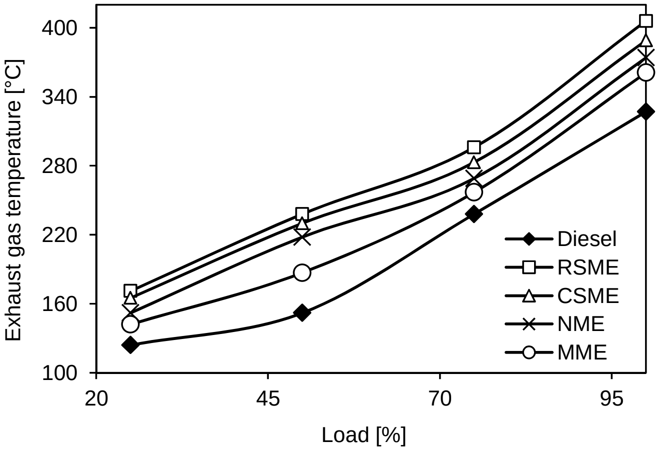

Fig. 3. Dependences of exhaust gas temperature on load for various test fuels

The variation of exhaust gas temperature with load is shown in Fig. 3. In general, exhaust gas temperature increases with increase in load. At all loads, it was found to be lower with diesel and higher with RSME, whereas, MME has a lower exhaust gas temperature compared to its other FAME counterparts. If energy balance is considered, then it is obvious that a higher exhaust temperature specifies poor energy utilization by the engine, which represents lower brake thermal efficiency in sequence. This can be confirmed by comparing the brake thermal efficiencies of the respective fuels. At full load, the exhaust gas temperatures for diesel, RSME, CSME, NME, and MME are found to be 327, 406, 389, 374, and 361 °C, respectively. The exhaust gas temperature also depends on temperature before start of combustion. At the end of compression stroke, while fuel has been injecting, it has been also partially vaporizing, hence, heat of vaporization affects pre-ignition temperature. It is believed that higher viscosity of biodiesels may exhibit poor atomization, which can result in slower rate of vaporization during the end of compression stroke and early stage of combustion. This can lead to poor combustion and hence less of the energy input in the fuel is converted to work, thereby increasing exhaust gas temperature.

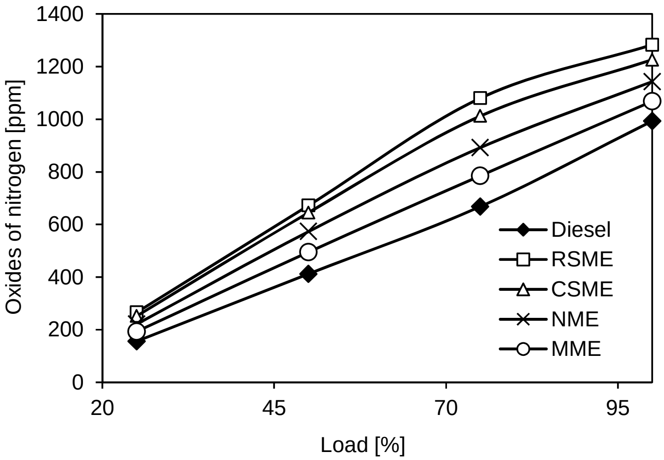

Fig. 4. Dependences of emissions of nitrogen oxides on load for various test fuels

The variation of nitrogen oxides (NO_x) emissions with load is shown in Fig. 4. The NO_x emission depends on combustion temperature, time, and oxygen availability. RSME exhibits a higher NO_x while MME has lower NO_x compared to the other FAMEs at all loads. Diesel shows lower NO_x emissions compared to the other test fuels at all loads. From the investigation, it can be found that NO_x concentration in the exhaust emissions increases with increase in density and percentage of unsaturated fatty acids. Increasing density may increase NO_x because the fuel injector injects an invariable volume, but larger mass of the more dense fuels. Another possibility is that the higher densities which can result in higher bulk moduli and advance the effective injection timing and thereby cause NO_x to increase. In addition, the presence of oxygen in the FAMEs can cause increase in NO_x emissions. At full load conditions, the NO_x for diesel, RSME, CSME, NME, and MME are found to be 993, 1283, 1226, 1143, and 1068 ppm, respectively. At full load, RSME shows 29% increase in NO_x compared to diesel. The MME shows 8% increase and 20% reduction in NO_x compared to diesel and RSME, respectively.

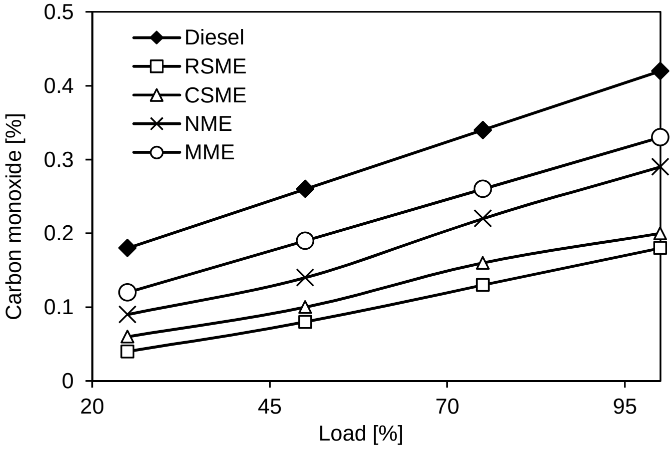

Fig. 5. Dependences of emissions of carbon monoxide on load for various test fuels

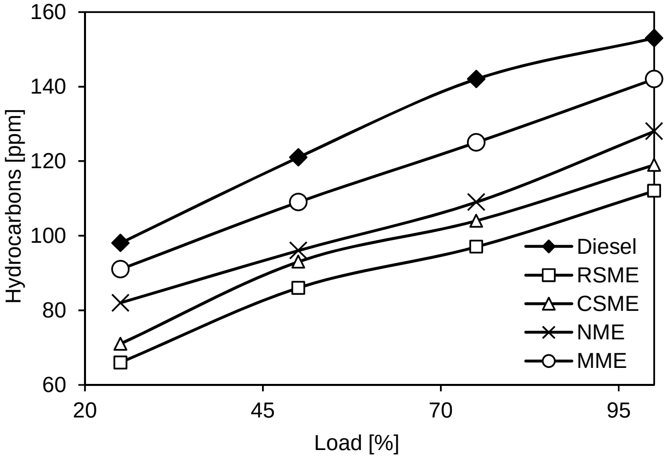

Fig. 6. Dependences of emissions of hydrocarbons on load for various test fuels

The variation of CO and HC emissions are shown in Fig. 5 and 6, respectively. Both CO and HC emissions are higher for diesel at all loads compared to the other test fuels. The decrease in CO and HC emissions could be an outcome of improved oxidation of CO and HC due to additional oxygen content in the FAMEs. It can be noted that the FAME chain has oxygen molecules by about 10–11% which helps for improved combustion. On the other hand, among the FAMEs, MME has higher CO and HC emissions whereas and RSME has lower CO and HC emissions at all loads. This can be explained as follows.

The unsaturation represents the deficiency of hydrogen content, i.e. greater unsaturation represents greater deficiency of hydrogen atoms in a particular FAME. Hydrogen has a greater affinity towards oxygen than carbon. Hence carbon atoms in FAMEs with higher amount of unsaturated fatty acids could find more oxygen to react compared to FAMEs with lesser amount of unsaturated fatty acids for a given air supply. This could possibly improve the oxidation and hence reduce the CO and HC emissions in the case of RSME. At full load conditions, the CO emissions for diesel, RSME, CSME, NME, and MME are found to be 0.42, 0.18, 0.20, 0.29, and 0.33%, respectively. The HC emissions at full load conditions for diesel, RSME, CSME, NME, and MME are found to be 153, 112, 119, 128, and 142 ppm, respectively.

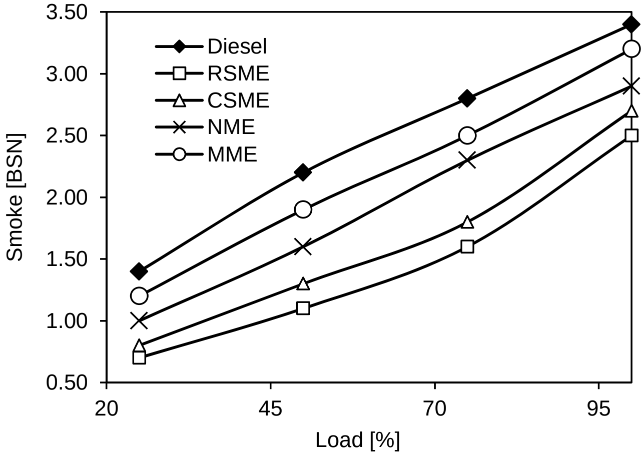

Fig. 7. Dependences of smoke emissions on load for various test fuels

The variation of smoke density in Bosch smoke number (BSN) with load for different fuels is illustrated in Fig. 7. From the figure it can be seen that the smoke increases with increase in load for all the test fuels. Smoke is emitted as a product of the partial combustion process, mainly at elevated loads. The smoke emissions at full load conditions for diesel, RSME, CSME, NME, and MME are found to be 3.4, 2.5, 2.7, 2.9, and 3.2 BSN, respectively. Diesel exhibits higher smoke emissions compared to the FAMEs at all loads. This reduction in smoke with FAMEs can be due to the presence of additional oxygen in their fuel molecules. This additional oxygen can reduce the smoke emissions at the rich mixture of fuel spray and the cooler part of spray impingement of combustion chamber wall. Fuels with higher air to fuel ratio need relatively higher air for complete combustion than the fuel that has a lower stoichiometric air to fuel ratio in a specific time period. The previous research study [25] reveals that the stoichiometric air to fuel ratio for FAMEs derived from palm, coconut, and rapeseed oils were found to be lower than that of diesel. Within the FAMEs, RSME has a lower smoke intensity and MME has a higher smoke intensity compared to their counterparts. As discussed in the previous section, the reduction in smoke for RSME is believed due to its higher percentage of unsaturated fatty acids. The reductions in smoke intensity are 36% and 6.25% with RSME and MME compared to diesel at full load conditions, respectively. Similarly, RSME shows 28% decrease in smoke compared to MME at full load.

4. CONCLUSION

Tests were conducted to investigate the environmental emissions and efficiency of a DI diesel engine fueled with diesel and various FAMEs such as RSME, CSME, NME, and MME. The NO_x emissions were higher with FAMEs compared to diesel. The HC, CO, and smoke emissions of RSME were lower than those of other test fuels at all loads. It was found that at all loads MME exhibits higher brake thermal efficiency compared to other FAMEs; while diesel has a higher brake thermal efficiency at any given load compared to other test fuels. From the present study, it is concluded that the FAMEs exhibit very similar performance and better emission results compared to diesel. In order to realize higher performance and emissions, these FAMEs can be blended and utilized in the engine.

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