Performance and Emission Characteristics of Modified Jatropha oil Methyl Ester in a DI Diesel Engine

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Abstract –Alternate fuel as a diesel substitute needs to be developed to fulfill the energy demands in the future for developing countries like India. Therefore, researchers show interests in developing the alternative fuel, based on the local available renewable sources. In this paper jatropha oil methyl ester (JOME) and coconut oil methyl ester (COME) taken for the study. The objective of the present research is to optimize the use of JOME in diesel engine. The present study analyzes the effect of biodiesel (COME and JOME) and modified biodiesel (blends of COME in JOME) on diesel engine. Experiments were conducted in a single cylinder direct injection diesel engine. The results indicate that COME shows good performance and reduced pollutants emission compared to JOME. The poor cold flow properties of COME resists its use at low ambient temperature. JOME has poor oxidation stability since it comprises of 70 % unsaturated fatty acid. Hence to use JOME effectively, COME was blended with JOME and the blend ratio was optimised based on engine performance, pollutants emissions, cold flow properties and oxidation stability. The 40 % COME blend fuel gives higher thermal efficiency with reduced oxides of nitrogen (NO_X) emissions compared to other blends. It also shows better oxidation stability and possesses good cold flow properties. From the present investigation, it is concluded that 40 % COME blend with JOME is the optimum fuel for diesel engine application.

Index Terms— Biodiesel, Jatropha, Diesel engine, Environmental emissions, Performance

1 Introduction

The diesel engines are highly preferred in the transportation sector because of its higher thermal efficiency. However, diesel engines exhaust emissions have serious impact on the environment. For example oxides of nitrogen (NO_X) and particulates are the major pollutants that are emitted from diesel engines. NO_X, which is green house gas, also reacts with the hydrocarbons (HC) in the presence of sunlight to form photochemical smog. Particulates may also lead to carcinogenic problems. The fossil fuels are depleting drastically which increases the demand in the international market that affects the economy of the developing countries like India. Thus an alternate energy source has to be identified to overcome the problems with the petroleum based diesel fuel. One of such energy sources is fuel derived from vegetable oils called as biodiesel. Many biodiesels are being experimented to suit the diesel engine without any major engine modifications [1- 5]. One of such fuels is Jatropha Oil Methyl Ester (JOME). Pure coconut oil usage in diesel engine shows lesser smoke, Carbon Monoxide (CO) and HC emissions compared to diesel fuel. This is because it has oxygen molecules which results in enhanced oxidation. NO_X emission decreases with increase in brake specific fuel consumption. This is attributed to lower heating value of the fuel. Emissions like smoke and NO_X are reported as lower, whereas there is an increase in HC and CO emission levels. This is attributed to decreased combustion efficiency due to poor atomization characteristics of pure coconut oil [6-8]. If pure coconut oil and diesel fuel blends are used in the Indirect Injection [IDI] diesel engines, increase in brake power and net heat release rate with net reduction in emissions such as HC, CO, NOx and smoke are reported for the 30% of coconut oil in the fuel. The increase in brake power is expected due to larger fuel droplets and oxygen content in coconut oil, which contribute to better atomization. When the coconut oil percentage is increased above 30 %, decrease in performance is reported. This is attributed to lower calorific value; however reduction of emissions is still reported [6]. COME was investigated by couple of authors in a variable speed direct injection (DI) diesel engine and the result shows that COME shows maximum torque at little higher speed compared to diesel and the emissions are lowest for COME compared to diesel and pure coconut oil [7]. COME gives positive effect on performance and emissions characteristics compared to other biodiesels [9]. JOME gives lesser performance compared to diesel baseline with lesser pollutants emissions [10]. The biodiesel can be categorized as oxygenated fuel, since the fuel has oxygen molecules on its own. This oxygen enhances the oxidation during the combustion resulting in lesser CO, HC, and smoke emissions with penalties in NO_X emission [11-14]. Even though the coconut oil gives significant reduction in emissions, the cost of the oil restricts its usage as fuel for replacing diesel in terms of economical basis. Thus jatropha oil has been investigated which is economical compared to diesel fuel but at the same time it has higher deviation from diesel properties. Thus it can be used in diesel engine by blending or by transesterifying to match the properties as close as to diesel fuel to obtain the performance closer to diesel with significant reduction in emissions [13]. In the present study, experimental results of a DI diesel engine fueled with various fuel blends of COME and JOME are presented. Only few blends of COME (30 %, 40 %, 50 %, and 60 %) show significance in the results. While only a marginal or no significance were observed for other blends of COME.

2 Test Fuels

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Jatropha oil and coconut oil were transesterified to reduce the viscosity of the oil to use in conventional diesel engine without any engine modification. Before transesterification the oil has to be checked for free fatty acid (FFA) content, if it is more than 5 % [15-17] then the oil must be subjected to two stage transesterification. For coconut oil, the FFA content is less than 5 % and thus single stage transesterification is sufficient. Transesterification is a reaction of oil with methanol in the presence of the sodium hydroxide (NaOH) as catalyst. Initially the oil was preheated to a temperature of about 50°C. Then catalyst (NaOH) and methanol was mixed well and allowed to react with the oil. The glycerine was allowed to settle at the bottom and collected frequently. After the reaction, the ester was formed and it is called methyl ester since methanol is the reactant. Then the ester was washed with water to remove the traces of the catalyst and methanol in the ester. For one litre of oil, the glycerine collected was about 100 ml and methanol required was 200 ml with the NaOH quantity of 2 grams (0.2 % for 100 ml of fuel). Jatropha oil possesses higher FFA (>15%) and single stage transesterification process was difficult. Hence jatropha oil was initially reacted with methanol in the presence of sulphuric acid (H_2SO_4) as a catalyst. After that the procedure remains the same. Thus the JOME and COME were obtained. The fatty acid profile and properties for the test fuels were analysed and given in Table 1 and Table 2 respectively. From the fatty acid profile the chemical formula for the fuels were derived. The chemical formula are $C_{17}H_{33}O_2$ and $C_{13}H_{26}O_2$ for JOME and COME respectively.

Table 1 Fatty Acid Profile for Test Fuels

Fatty acids	C:N	JOME	J/Ct 70/30	J/Ct 60/40	J/Ct 50/50	J/Ct 40/60	COME
Caproic acid	C6:0	—	1	1	2	2	3
Capric acid	C10:0	—	1	2	2	2	4
Lauric acid	C12:0	—	14	18	23	28	46
Myristic acid	C14:0	—	7	9	11	13	22
Palmitic acid	C16:0	16	14	14	13	12	10
Stearic acid	C18:0	10	8	8	7	6	4
Oleic acid	C18:1	42	32	28	25	22	8
Linoleic acid	C18:2	31	23	20	17	14	3

In C: N, C indicates the number of carbon atoms and N the number of double bonds of carbon atoms in the fatty acid chain.

3. Experimental Set-up and Test Procedure

A single cylinder, 4-stroke, air-cooled, DI diesel engine was used for the experimental work. The details of the engine are given in Table 3. The schematic view of the experimental setup is shown in Figure 1.

Table 2 Properties of Test Fuels

Properties	JOME	J/Ct 70/30	J/Ct 60/40	J/Ct 50/50	J/Ct 40/60	COME
Heating value	39.23	39.35	39.39	39.43	39.47	39.63
Kinematic Viscosity (cSt @ 40ºC)	5.65	5.39	5.31	5.22	5.14	4.8
Density (kg/m³)	880	877	876	875	874	870
Cetane number	51	50	50	50	50	57
Flash Point, °C	160	142	137	130	125	106
Fire Point, °C	172	157	151	146	137	116
Pour Point, °C	-12	-6	-4	-2	0	8
Carbon, (wt %)	75.8	74.9	74.6	74.3	74	72.9
Hydrogen (wt %)	12.3	12.3	12.2	12.2	12.2	12.1
Oxygen, (wt %)	11.9	12.8	13.1	13.4	13.7	14.9
Stoichiometric AFR	12.4	12.2	12.2	12.1	12.1	11.9
Oxidation Stability (hr) @ 110 °C	3	4.5	5	5.5	6	8

Table 3 Test Engine Specifications

Parameters	Specifications
Make	Kirloskar TAF 1
Number of cylinders	One
Cycle	Four stroke
Injection	Direct Injection
Aspiration	Naturally aspirated
Cooling	Air cooled
Bore	85.5 mm
Stroke	110 mm
Compression ratio	17.5 : 1
Power output	4.4 kW @ 1500 rpm
Injection pressure	200 bar
Static Injection timing	23º b TDC

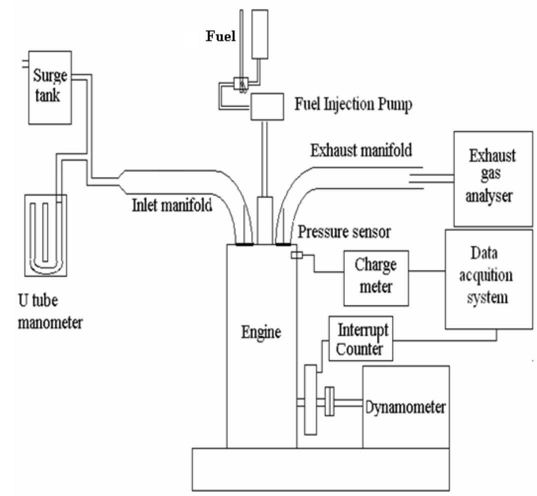

Fig. 1. Schematic layout of experimental set-up

The systems included in this schematic are the engine, air instrumentation systems, and emission measurement analyzer system. Airflow rate was measured by means of an orifice meter. A water cooled piezoelectric transducer flush mounted with engine cylinder head was used for obtaining the cylinder pressure data and was amplified by means of a charge amplifier [make Kistler 5015A type, sensitivity 79 pC/bar]. The output from the charge amplifier is fed to the data acquisition system where the cylinder pressure curve with respect to crank angle was obtained. An interrupt counter was provided to enable the top dead centre (TDC) position and the output was fed to one terminal of the data acquisition system. An exhaust gas analyzer (Qrotech QRO-301) was used to measure NOX, HC, CO, and Carbon dioxide (CO_2) the exhaust emissions. Exhaust gas temperature was measured by means of a K-type thermocouple. Smoke levels were measured using a Bosch smoke meter. The detailed test matrix is given in Table 4.

Table 4 Test Matrix

SI.NO	Load			
	25 %	50 %	75 %	100 %
1	JOME	JOME	JOME	JOME
2	COME	COME	COME	COME
3	J/Ct 50/50	J/Ct 50/50	J/Ct 50/50	J/Ct 50/50
4	J/Ct 60/40	J/Ct 60/40	J/Ct 60/40	J/Ct 60/40
5	J/Ct 70/30	J/Ct 70/30	J/Ct 70/30	J/Ct 70/30
6	J/Ct 40/60	J/Ct 40/60	J/Ct 40/60	J/Ct 40/60

4. Results and Discussion

The experimental results different test fuels are discussed in detail as follows.

Heat Release Rate

The variation of heat release rate with crank angle for all the fuels tested in the engine at full load is shown in Figure 2.

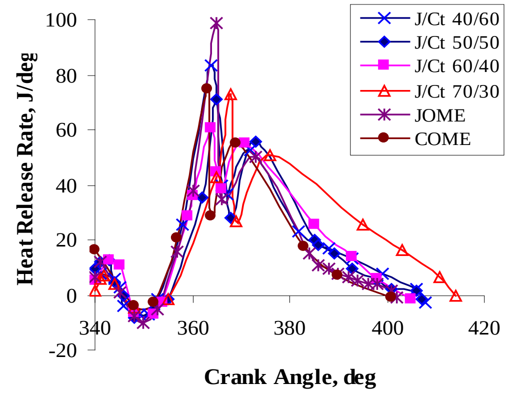

Fig. 2. Variation of heat release rate with crank angle

The maximum heat release occurs at uncontrolled combustion phase and it is higher for JOME compared to other fuels. It is 98.5 J/deg at 5° aTDC and for COME it is 74.7 J/deg at 3° aTDC. For J/Ct 50/50, J/Ct 60/40, J/Ct 70/30 and J/Ct 40/60, the maximum heat release rate are 71.2 J/deg at 5° ATDC, 60.63 J/deg at 4° aTDC, 72.7 J/deg at 8° aTDC, and 83.6 J/deg at 4° aTDC respectively. The maximum heat release rate during the uncontrolled combustion phase occurs at aTDC for all the fuels. JOME has the maximum heat release rate which can be attributed to higher ignition delay leading to knocking combustion [18] whereas for COME it occurs closer to TDC since the ignition delay for COME is lower compared to the other fuels. COME has 90 % saturated fatty acid and it is a low carbon fuel (the chemical formula is derived from fatty acid profile and it is $C_{13}H_{26}O_2$). It has high cetane number and lower viscosity. These factors may result in lower ignition delay as compared to the other fuels. The heat released after the TDC accounts for engine performance and in the controlled combustion phase the maximum heat release rate for COME is 54.9 J/deg at 9° aTDC, and for JOME it is 50.2 J/deg. For J/Ct 50/50, J/Ct 60/40, J/Ct 70/30 and J/Ct 40/60, the maximum heat release rates are 55.5 J/deg at 13° aTDC, 55.1 J/deg at 11° aTDC, 50.5 J/deg at 16° aTDC, and 52.3 J/deg at 12° aTDC respectively. The variation of maximum heat release rate between different test fuels was found to be marginal. But it can be noted that the maximum heat release rate occurs at 9° aTDC for COME which is closer to TDC as compared to the other fuels.

Cumulative Heat Release

The variation of cumulative heat release with crank angle is shown in Figure 3. J/Ct 70/30 has higher cumulative heat release as compared to the other fuels. The COME has lesser cumulative heat release compared to the other fuels and this can be attributed to lesser ignition delay of fuel that results in gradual combustion. Though J/Ct 70/30 has a higher cumulative heat release, it is not reflecting in the engine performance since the significant portion of the heat release occurs at later stages of combustion, which is 30° aTDC. During the expansion stroke, COME releases maximum cumulative heat which occurs closer to TDC. Whereas the cumulative heat released within the same region by J/Ct 70/30 found minimum. Thus COME has the positive effect on engine performance when compared to the other fuels.

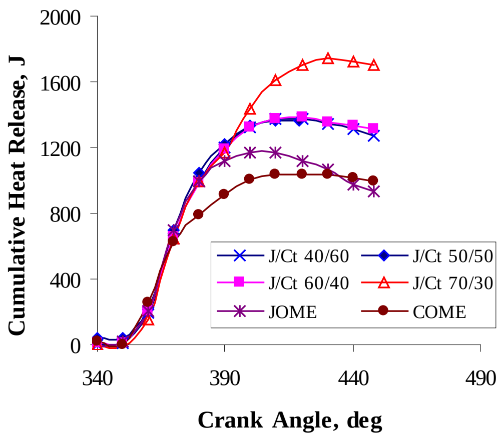

Fig. 3. Variation of cumulative heat release rate with crank angle

Pressure versus Crank angle

The variation of cylinder pressure with crank angle at full load is shown in Figure. 4. From the figure it is clear that the peak pressure of COME occurs closer to TDC which is 67.3 bar at 8° CA aTDC. This is because the COME has lower ignition delay compared to all other fuels. For JOME, J/Ct 50/50, J/Ct 60/40, J/Ct 70/30 and J/Ct 40/60, the peak pressures are 66.2 bar at 14° aTDC, 68.5 bar at 12° aTDC, 67.3 bar at 13° aTDC, 67.8 bar at 13°aTDC and 66.1 bar at 11°aTDC respectively. Higher the COME blend in the fuel, the occurrence of the peak pressure is closer to TDC.

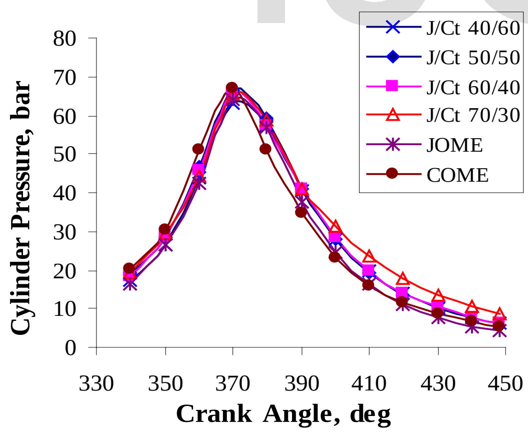

Fig. 4. Variation of cylinder pressure with crank angle

Brake Thermal Efficiency

The variation of brake thermal efficiency with load is shown in Figure. 5. Brake thermal efficiency found to be higher for COME and is 29.3% at full load. JOME is the next fuel that gives higher efficiency, which is 27.7 % at full load. There is no significant variation for the other fuels at full load. Up to 50 % load, there is no much difference in the brake thermal efficiency for all the fuels. But there after COME gives higher efficiency. From Figure 2 it is clear that the effective heat release for COME occurs closer to TDC when compared to the other fuels. Also from the pressure crank angle diagram, the peak pressure for COME occurs closer to TDC. This means that the gas thrust acting on the piston increases, which results in higher efficiency eventually.

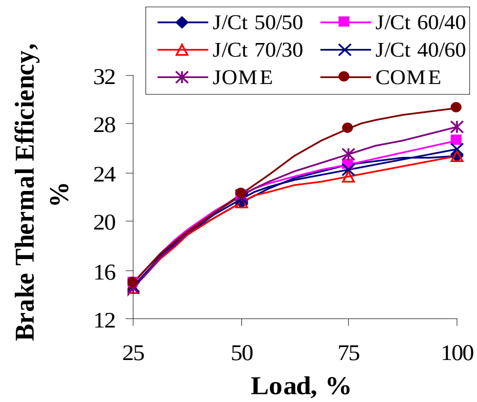

Fig. 5.Variation of brake thermal efficiency with load

Brake Specific Fuel Consumption (BSFC)

The variation of brake specific fuel consumption (BSFC) with load is shown in Figure 6. The BSFC is lower for COME as compared to the other fuels and it is 0.315 kg/kWh at full load. BSFC was found to be lower for J/Ct 70/30 which is 0.364 kg/kWh. From Figure 2, it can be seen that the effective heat release during the controlled combustion phase is minimum (for fuels other than J/Ct 60/40). Hence more fuel quantity is required to produce the desired power output. Whereas the heat release is more, during the later stages of combustion (fuels other than J/Ct 60/40), which is of no use since piston starts moving down towards BDC.

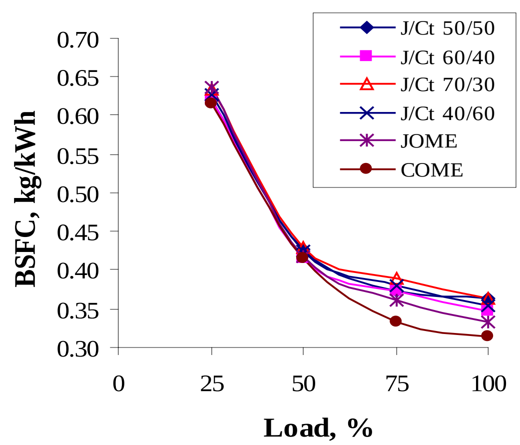

Fig. 6. Variation of BSFC with load

Brake Specific Energy Consumption (BSEC)

The variation of brake specific energy consumption with load is shown in Figure 7. The energy equivalence is the best parameter to compare the performance of alternate fuels. Since the heating value for the fuels are different, the energy required to produce the desired power output for the fuels has to be compared. It was observed that the BSEC found to be lower for COME, which is 12.3 MJ/kWh at full load, whereas it was found to be higher for J/Ct 70/30 which is 14.22 MJ/kWh. For J/Ct 60/40 the BSEC was found be 13.5 MJ/kWh. For the all other blends no significant variation was observed. As far as the blended fuels are concerned, J/Ct 60/40 has lower specific energy consumption.

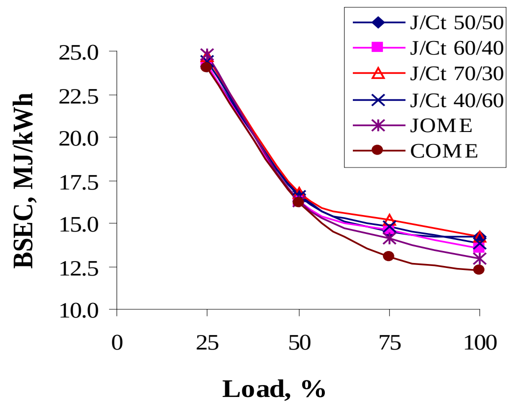

Fig. 7. Variation of BSEC with Load

Exhaust Gas Temperature

Figure 8 illustrates the variation of exhaust gas temperature with load. At full load, the exhaust gas temperature was found to be lower for J/Ct 70/30 and it is 372°C. The exhaust gas temperature may be higher due to high combustion temperature. This may be due to higher ignition delay or due to late combustion. From the heat release pattern, the fuel J/Ct 70/30 shows significant heat release in the later stages of combustion which may cause an increase in the exhaust gas temperature. COME has a lower exhaust gas temperature and is 329°C. COME is a low carbon fuel and also the ignition delay is lower compared to all other fuels and thus combustion is gradual and faster compared to the other fuels. This results in lower exhaust gas temperature for COME.

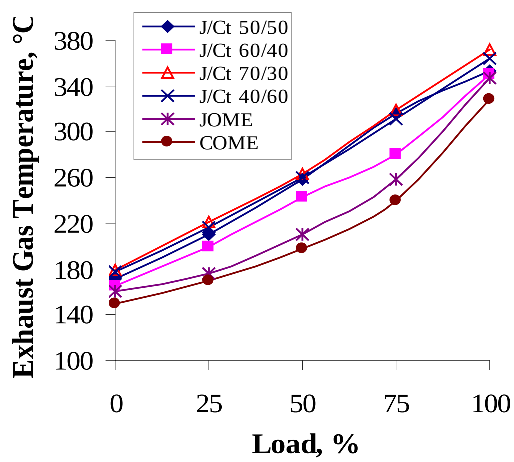

Fig. 8. Variation of exhaust gas temperature with load

Carbon Monoxide (CO)

The variation of carbon monoxide with load is shown in Figure 9. For compression ignition the CO emissions will be very low since it is always operated with excess air. The CO emission is due to the incomplete combustion. CO was found to be higher for JOME that is 2.6 g/kWh at full load and it is lower for COME at the same load which is 0.5 g/kWh. COME contains higher amount of saturated fatty esters and also it has oxygen molecules on its own. This enhances the oxidation process during combustion resulting in lower CO emissions. For all the other fuels the CO emission is in between JOME and COME. This shows that increasing the percentage of COME in the blend will increase the oxidation.

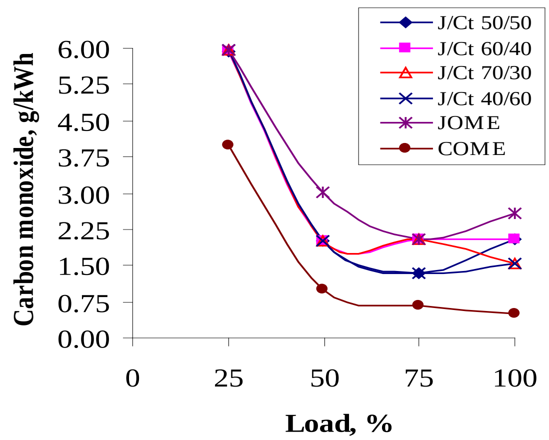

Fig. 9. Variation of carbon monoxide with load

Carbon Dioxide (CO_2)

The variation of CO_2 with load is depicted in Figure 10. CO_2 emission is the resultant of the complete combustion of the fuel molecule. The CO_2 emission was found to be higher for J/Ct 50/50 which is 411 g/kWh at full load as compared to the other fuels. JOME has 70 % unsaturated fatty acid esters and also it is a heavier hydrocarbon fuel. Thus if complete combustion occurs, JOME can emit more CO_2 emissions as compared to COME. Similarly, incomplete combustion will result in higher CO and a lower CO_2 as compared to complete combustion. When JOME is mixed with COME at 50/50 proportion, the COME present in the fuel enhances the later stages of combustion and this will result in higher CO_2 for J/Ct 50/50. The lower CO_2 was found to be with J/Ct 70/30 operation which is 3.86 g/kWh.

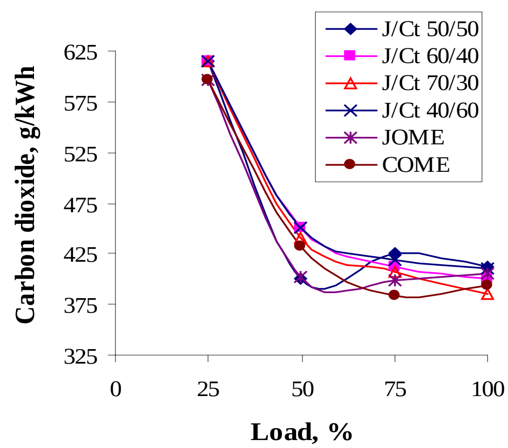

Fig. 10.Variation of carbon dioxide with load

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Hydrocarbon (HC)

The variation of HC emission with load is illustrated in Figure 11. The hydrocarbon emission was found to be higher for JOME and it is 0.83 g/kWh at full load. COME has lower HC emission which is 0.5 g/kWh. As COME increases in the blends, the hydrocarbon emission decreases. JOME has higher viscosity and it is a heavy hydrocarbon fuel that could cause incomplete combustion, leading to increased hydrocarbon emission. While increase in percentage of COME in the blends results in reduction of viscosity. This reduction in viscosity helps to have a better atomization and penetration which in turn results better combustion. Thus the HC emission found lower in the case of COME.

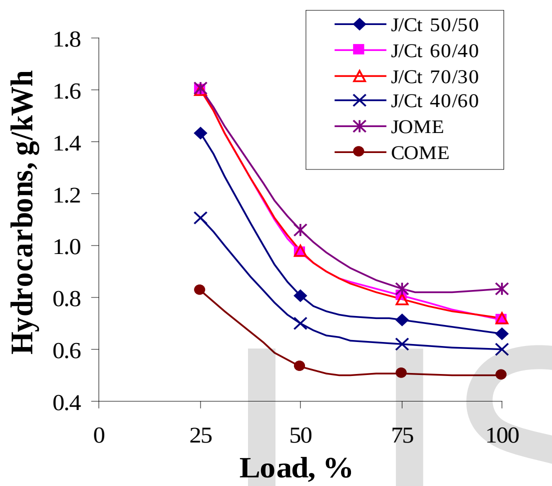

Fig. 11. Variation of hydrocarbons with load

Oxides of Nitrogen (NO_X)

The variation of NO_X with load is depicted in Figure 12. The NO_X emission was lower for COME which is 0.4 g/kWh at full load as compared to the other fuels and. It can be recalled that the ignition delay for COME was observed to be lower hence the combustion is gradual for COME when compared to the other fuels. Also the air fuel ratio for COME is lower than that of other fuels. This can lead to over all lean operation and resulting in lower NO_X emissions. J/Ct 50/50 has higher NO_X and it is observed as 12.6 g/kWh at full load. This can be attributed to effective heat release in the controlled combustion phase. The NO_X emission for JOME was found to be 12.3 g/kWh. The uncontrolled combustion phase for JOME is higher as compared to the rest of the fuels. Thus the rate formation of NO_X emissions will be more in this region. Whereas the controlled combustion phase is lesser as compared to J/Ct 50/50 thus NO_X emission is lesser for JOME as compared to J/Ct 50/50.

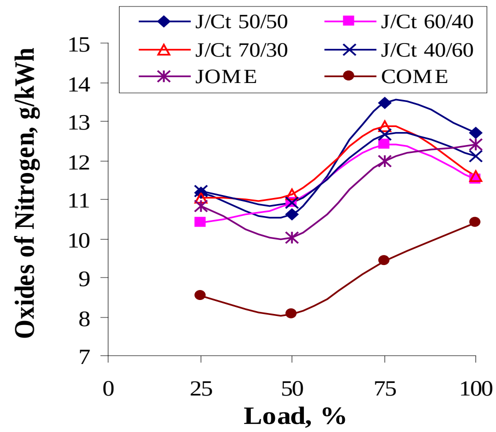

Fig. 12. Variation of oxides of nitrogen with load

Smoke

The variation of smoke emissions with load is shown in Figure 13. The smoke emission is higher for J/Ct 40/60 and which is 0.8 BSU at full load. Smoke emission is carbon particles that are exhausted without taking part in the combustion. The smoke emission is lower for COME which is 0.1 BSU at the same load condition. This may be due to the resultant effect of lower viscosity, better atomization and better combustion.

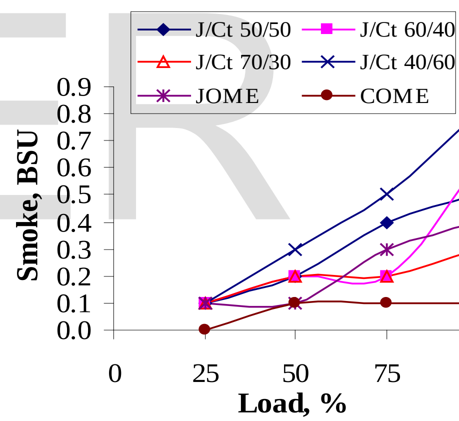

Fig. 13. Variation of smoke with load

Conclusion

Experiments were carried out to investigate the effect of JOME and its blend with COME on combustion, performance and emission characteristics of a single cylinder DI diesel engine. From the experiments it was found that COME was found to be a better fuel as compared to the other fuels in terms of engine performance and pollutants emissions.

- The brake thermal efficiency of COME increases by 1.7 % compared to JOME. It also increases by 2.7 %, 3.3 %, 4.1 %, and 4 % as compared to 40 %, 60 %, 30 % and 50 % of COME in the blend respectively.
- The brake specific energy consumption of COME decreases by 5.2 % as compared to JOME. It decreases by 9 %, 11.2 %, 13.3 % and 13.6 % compared to 40 %, 60 %, 30 %, and 50 % of COME in the blend respectively.
- The NO_X emission of COME decreases by 15.9 % as compared to JOME. Also it decreases by 9.6 %, 10.1 %,

14.1 % and 17.9 % compared to 40 %, 30 %, 60 % and 50 % of COME in the blend respectively.

- The smoke emission of COME decreases by 75 % as compared to JOME. Also it decreases by 66.7 %, 80 %, 83.3 % and 87.5 % compared to 30 %, 50 %, 40 % and 60 % of COME in the blend respectively.

It is difficult to use COME at lower temperature due to poor cold flow properties. Similarly usage of JOME is restricted due to its poor oxidation stability. Therefore it can be concluded that J/Ct 60/40 fuel is the optimum blend that gives good performance with reduced pollutants emission compared to the other blends.

Abbreviation and Nomenclature

aTDC	After Top Dead Centre
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BSU	Bosch Smoke Unit
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COME	Coconut Oil Methyl Ester
DI	Direct Injection
FFA	Free Fatty Acid
g/kWh	grams per kilowatt hour
H_2SO_4	Sulphuric acid
HC	Hydrocarbon
IDI	Indirect Injection
JOME	Jatropha Oil Methyl Ester
J/Ct 40/60	Blend of 40 % of JOME and 60 % of COME on volume basis
J/Ct 50/50	Blend of 50 % of JOME and 50 % of COME on volume basis
J/Ct 60/40	Blend of 60 % of JOME and 40 % of COME on volume basis
J/Ct 70/30	Blend of 70 % of JOME and 30 % of COME on volume basis
kg	kilogram
kW	kilowatt

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