Indian Journal of Science and Technology Vol.2 No 4 (Apr. 2009) ISSN: 0974- 6846

Study of the performance, emission and combustion characteristics of a diesel engine using Sea lemon oil-based fuels

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Abstract: Experiments were conducted to study the performance, emission and combustion characteristics of a DI diesel engine using sea lemon oil-based fuels. In the present work, sea lemon oil and sea lemon oil methyl ester are tested as diesel fuels in diesel engine in neat form. The reduction in NOx emission and an increase in smoke, hydrocarbon and CO emissions were observed for Neat sea lemon oil compared to those of standard diesel. From the combustion analysis it was found that ignition delay was slightly more for both the fuels tested compared to that of standard diesel. The combustion characteristics of sea lemon oil and its methyl ester closely followed those of standard diesel.

Keywords: Biofuel, Sea lemon oil, diesel engine, energy

Introduction

Vegetable oils have better ignition qualities for diesel engines than light alcohols, since their cetane number being over 40 (Agarwal, 2007).There are many vegetable oils, which can be used as fuels in diesel engines like peanut oil, linseed oil, rapeseed oil and sunflower oil (Srivastava & Prasad, 2000). The chemical composition of vegetable oil helps in reducing the emission of unwanted components when they are burned (Murayama, 1984). Vegetable oil fuels generated an acceptable engine performance and exhaust gas emission levels for short-term operation only, because they caused carbon deposit buildups and sticking of piston rings after extended operation. The practical solutions to overcome these problems include increasing fuel temperature to 200 °C, blending vegetable oil with diesel, blending it with ethanol or converting vegetable oil into methyl ester (Barsic & Humke, 1981; Murayama, 1984; Ali & Hanna, 1994; Babu & Devarajane, 2003). Blending of vegetable oils with diesel fuel would solve the problems of diesel engine operation with Neat vegetable oils. Vegetable oil dissolves quite well in diesel fuel. It was reported that a diesel engine would run successfully on a blend of vegetable oil and diesel fuel without damage to engine parts for short-term operation. Vegetable oil fuels resulted in lower thermal efficiency; lower NOx and higher CO and HC emissions (Ali & Hanna, 1994; Altin *et al*., 2001; Babu & Devarajane, 2003). Considerable efforts have been made to develop vegetable oil derivatives that approximate the properties and performance of hydrocarbon-based diesel fuels. The problems with substituting triglycerides for diesel fuels are mostly associated with their high viscosities and low volatilities. These can be changed by transesterification (Bhattacharyya & Reddy, 1994; Altin *et al*., 2001). The methyl ester produced by transesterification of vegetable oil has a high cetane number, low viscosity and improved heating value compared to those of Neat vegetable oil which results in shorter ignition delay and longer combustion duration and hence low particulate emissions. Its use results in the minimization of carbon deposits on injector nozzles (Sahoo *et al*., 2007). Bio-diesel has been used in blends with hydrocarbon based diesel fuels. Several studies have shown that diesel-biodiesel blends reduce smoke emission, particulates, unburned hydrocarbons, carbon dioxide and carbon monoxide emissions with a slight increase in oxides of nitrogen emissions (Senthil Kumar *et al*., 2003; Cheng *et al*., 2006; Rakopoulos *et al*., 2006; Sinha, & Agarwal, 2006; Raheman & Ghadge, 2007; Lapuerta *et al*., 2008).

Purpose of study

In an agricultural country like India, the use of vegetable oils in diesel engines has to be widely investigated because of the large production capacity and possibility of producing it near the consumption points. Since vegetable oils have cetane numbers close to those of diesel fuel, they can be used in existing compression ignition engines with little or no modifications. The problems posed by the high viscosity of vegetable oil can be minimized by blending it with diesel. Another way to make vegetable oil suitable for diesel engines is converting it into bio-diesel by transesterification process. The vegetable oil–diesel blend is a simple way to reduce the viscosity of neat vegetable oil. This method does not require any chemical process. The vegetable oil transesterification represents another approach to overcome the problems associated with the high viscosity of neat vegetable oil. The transesterification process reduces the molecular size resulting in more volatile, less viscous liquids. In both the methods, the properties of vegetable oil have improved. In the present work both the methods have been adopted and the results are presented.

Potential and characterization of sea lemon oil

The scientific name of the sea lemon tree is Ximenia americana. Ximenia americana is a semi-scandent bush-forming shrub or small tree 2-7 m high. Trunk diameter seldom greater than 10 cm; bark dark brown to pale grey, smooth to scaly. The lax, usually divergent branching, forms a rounded or conical crown. Branchlets purple-red with a waxy bloom and the tree usually armed with straight slender spines. Fruits globose to ellipsoidal

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Table 1. Fatty acid composition for Sea lemon oil compared with Jatropha oil

Fatty acid	Sea lemon oil (% by weight)	Jatropha (% by weight)
Palmitic $C_{16}H_{32}O_2$	22.4	14.1-15.3
Stearic $C_{18}H_{36}O_2$	7.3	3.7-9.8
Oleic $C_{18}H_{34}O_2$	16.4	34.3-45.8
Linoleic $C_{18}H_{32}O_2$	45.9	29-44.2
Arachidic $C_{20}H_{40}O_2$	6.46	0.3

drupes about 3 cm long, 2.5 cm thick, glabrous, greenish when young, becoming yellowish (or, rarely, orange-red) when ripe, containing a juicy pulp and 1 seed. Seed woody, light yellow, up to 1.5 cm long, 1.2 cm thick with a fatty kernel and a brittle shell. The fruit yields up to 67.4% oil from the seed. A mostly solitary tree dispersed in open country, savannah, gallery forest, along coastal areas, in the under storey of dry forests, in dry woodlands, or on riverbanks. *Ximenia americana* is drought resistant. This tree is found in many parts of the world.

Preparation of oil from oil seeds

Sea lemon oil seeds collected from our area are dried in sunlight for a week and the dried seeds are peeled to obtain the kernel for extraction of sea lemon oil by using a mechanical expeller. Small traces of organic matter, water and other impurities were present in the sea lemon oil. These can be removed by adding 5% by volume of hexane to the raw oil and stirring it for 15 to 20min at 80° to 90 °C and allowing it to settle for 30min Since hexane is having low boiling point (68.7 °C), it gets evaporated on heating beyond the boiling point of hexane. The impurities and gum particles that settle down at the bottom can be removed. The remaining oil is the purified oil. The purified oil can be used for transesterification process.

Composition of sea lemon oil

Unlike diesel fuel, sea lemon oil consists mostly of saturated hydrocarbons and triglycerides consisting of glycerol esters of fatty acids. Sea lemon oil comprises 90% to 98% triglycerides and small amounts of mono and diglycerides. Triglycerides are esters of three fatty acids and glycerol. The fatty acids vary in their carbon chain length and in the number of double bonds. The fatty acid composition of sea lemon oil is given in Table1.

Transesterification process (Ghadge & Raheman, 2005; Leung & Guo; 2006; Meher *et al.*, 2006)

Sea lemon oil was converted into its methyl ester by transesterification process. This involves making the triglycerides of the sea lemon oil to react with methanol in the presence of a potassium hydroxide (KOH) catalyst to produce glycerol and fatty acid ester. The known amount of (1000 ml) sea lemon oil, 400 ml of methanol and 10 g potassium hydroxide were taken in a round bottom flask. The contents were stirred till ester formation began. The mixture was heated to 70 °C and held at that temperature without stirring for an hour, and then it was allowed to cool for 24 h without stirring. Two layers were formed. The bottom layer consisted of glycerol and the top layer was the ester. The bottom layer was removed and ester was collected for further analysis.

Experimental and test procedure

In the first phase of work the variable load tests were conducted at the rated speed of 1500 rev/min. at different injection timings. At each load, air flow rate, diesel/sea lemon oil/methyl ester of sea lemon oil flow rate, exhaust gas temperature, HC, CO, smoke and nitric oxide emissions were recorded. Based on the results, the optimum injection timing was fixed for diesel, sea lemon oil and methyl ester of sea lemon oil.

To obtain base line parameters, the engine was first operated on standard diesel. After taking the engine performance at all load conditions on standard diesel, similar experiments were conducted for sea lemon oil and its methyl ester extract.

The specification of the engine is given in Table 2. A single cylinder four-stroke water-cooled diesel engine developing 3.68 kW at a speed of 1500 rpm was used for this work. This engine was coupled to an eddy current

1. Engine, 2. Dynamometer, 3. Sea Lemon oil tank, 4. Diesel Tank, 5. Burette (Sea Lemon Oil), 6. Burette (Diesel), 7. Air tank, 8. Air filter, 9. Silencer, 10. Smoke Pump, 11. Exhaust gas analyzer, 12. Fuel flow rate Indicator, 13.RPM Indicator, 14. Air flow rate indicator, 15. Exhaust gas temp. Indicator, 16. Coolant temp. indicator, 17. Lube oil temp. Indicator, 18. Water flow rate indicator, 19. Pressure sensor, 20. Charge amplifier, 21. Digital data acquisition system

Layout 1. Experimental Setup

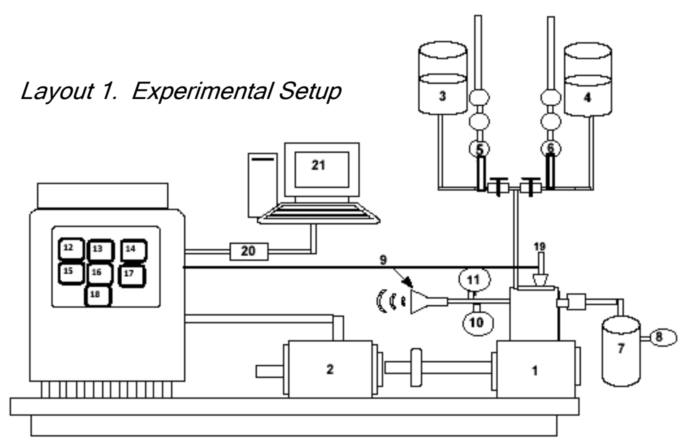

Table 2. Technical specifications of the engine

Manufacturer	Kirloskar engines Ltd, Pune, India
Engine type	Four stroke, single cylinder, constant speed, compression ignition engine
Rated power	3.68 kW at 1500 rpm
Bore & stroke	80 & 110 mm
BHP of engine	5
Swept volume	562cc
Compression ratio	16.5:1
Mode of injection	Direct Injection
Cooling system	Water
Dynamometer	Eddy current dynamometer

Indian Journal of Science and Technology Vol.2 No 4 (Apr. 2009) ISSN: 0974- 6846

dynamometer with a control system. The cylinder pressure was measured by piezoelectric pressure transducer (Kistler) fitted on the engine cylinder head and a crank angle encoder fitted on the flywheel. Exhaust gas analysis was performed using multi gas exhaust analyzer. A Bosch smoke pump attached to the exhaust pipe was used for measuring smoke levels. The total experimental setup is shown in Layout 1.

Performance analysis

Specific fuel consumption

The brake specific fuel consumption (BSFC) for neat sea lemon oil and its ester with diesel were calculated. These results are analyzed and represented graphically in fig1. Differences in BSFC are largely due to the lower heating value of the sea lemon oil and its ester resulting in required mass fuel flow increase needed to obtain equal fuel energy input. The brake specific fuel consumption of sea lemon oil and methyl ester of sea lemon oil was 14 to 21% and 13 to 16% respectively greater than that of standard diesel at all loads.

Brake thermal efficiency

The variation of brake thermal efficiency with power output for Sea lemon oil and methyl ester of Sea lemon oil is shown in Fig.2. The thermal efficiency is always lower with the Sea lemon oil as compared to diesel. This is due to poor mixture formation as a result of the low volatility, higher viscosity and density of the Sea lemon oil. The maximum thermal efficiency with Sea lemon oil is about 27.6 % at the peak power output where as it is 29.6 % with diesel. However, the thermal efficiency is higher with methyl ester of Sea lemon oil than the pure Sea lemon oil and it is about 28.8 % at peak load. The methyl ester of Sea lemon oil has a lower viscosity, which results in better atomization of the fuel as compared to pure Sea lemon oil. No drop in maximum power is observed with

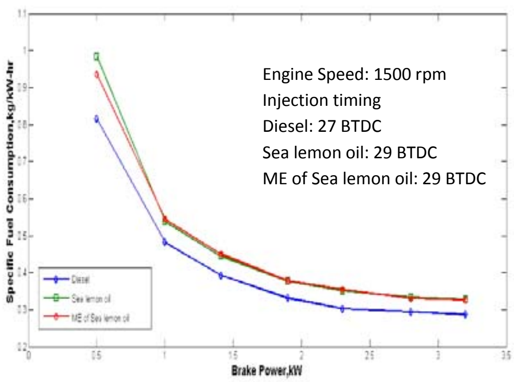

Fig.1 Variation of specific fuel consumption with brake power for various fuels

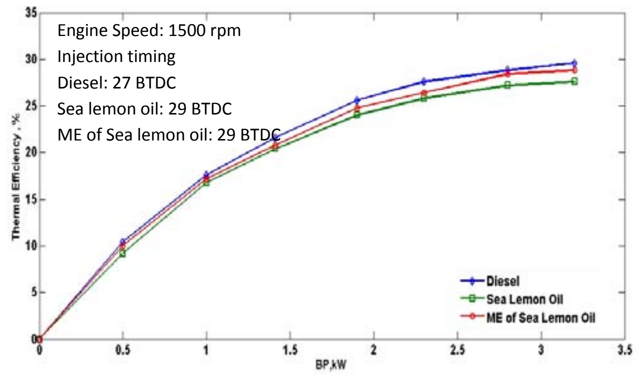

Fig.2. Variation of brake thermal efficiency with brake power for various fuels at optimum injection timings

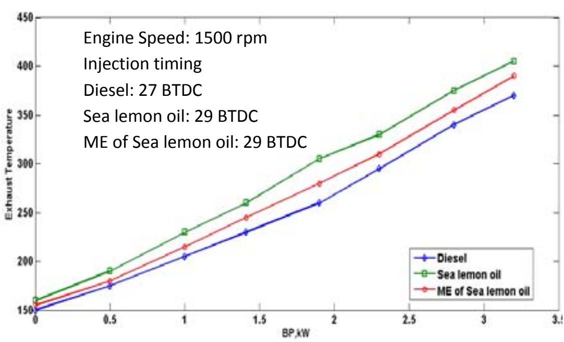

Fig.3. Variation of exhaust gas temperature with brake power for various fuels at optimum injection timings

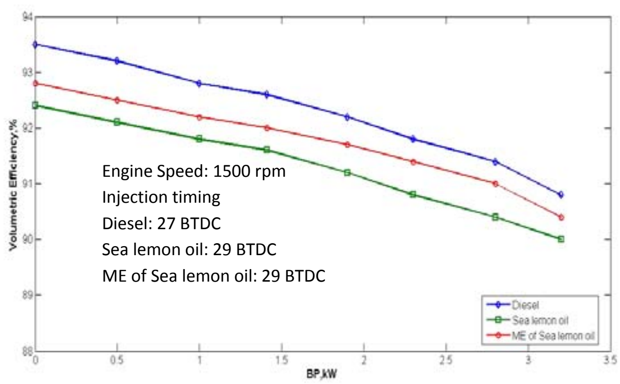

Fig.4 Variation of volumetric efficiency with brake power for various fuels at optimum injection timings

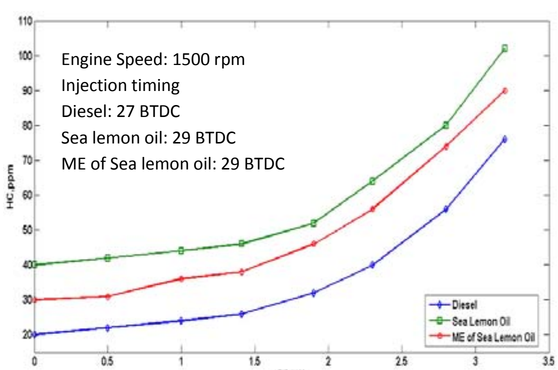

Fig.5. Variation of HC with brake power for various fuels at optimum injection timings

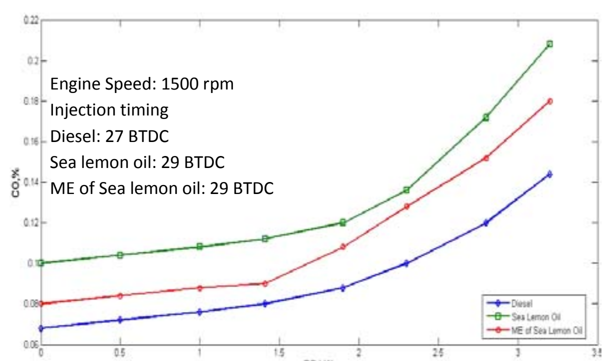

Fig.6. Variation of CO with brake power for various fuels at optimum injection timings

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Sea lemon oil and its methyl ester. This is because the reserve capacity of the fuel injection pump could take the small increase in the fuel delivery with Sea lemon oil and methyl ester of Sea lemon oil.

Exhaust gas temperature

Exhaust gas temperature shown in Fig.3 is higher when the load is increased and it is more for Sea lemon oil and the methyl ester of Sea lemon oil than diesel particularly at high loads. The poor volatility and high viscosity of the fuels lead to a more dominant diffusion combustion phase than diesel, which is responsible for this.

The maximum temperature of exhaust gas at peak load is 405^0 C with the Sea lemon oil and 390^0 C with the methyl ester of Sea lemon oil. The peak exhaust temperature is 370^0 C with diesel.

Volumetric efficiency

The variation of volumetric efficiency with Sea lemon oil and its methyl ester is shown in Fig.4. The volumetric efficiency with Sea lemon oil is lower than diesel. It may be noted that the volumetric efficiency curve is closely related to the exhaust temperature curves shown in Fig.3. A higher exhaust temperature leads to a lower volumetric efficiency. This is because the temperature of the retained exhaust gases will be higher when the exhaust gas temperature rises. A high-retained exhaust gas temperature will heat the incoming fresh air and lower the volumetric efficiency.

Emission analysis

The poor mixture formation tendency of Sea lemon oil oil leads to high hydrocarbon and carbon monoxide levels compared to standard diesel operation as seen in Figs.5&6. However, these emissions are lowered with the methyl ester of Sea lemon oil. In addition to the other factors, the lower thermal efficiency, with these oils also is responsible for this trend. It may be noted that a lower thermal efficiency with Sea lemon oil will lead to injection of higher quantities for the same load condition.

Fig. 7 indicates that Sea lemon oil and methyl ester of Sea lemon oil show lower NO (nitric oxide) emission compared to standard diesel. This reduction in NO emission may be due to the reduced rate of heat release as a result of reduced premixed combustion following the delay period. The premixed combustion phase of vegetable oil was less intense than that of diesel owing to the shorter ignition delay. The reason for this shorter ignition delay was due to the chemical reactions during the injection of vegetable oil at high temperature resulted in the breakdown of the unsaturated fatty acids of higher molecular weight, predominantly linoleic products of lower molecular weight.

The variation of smoke emission with power output with methyl ester of Sea lemon oil oil and diesel is shown in Fig.8. With neat Sea lemon oil, due to its heavier molecular structure and higher viscosity, atomization becomes poor and this leads to higher smoke emission. However, smoke emission is reduced with the use of methyl ester of Sea lemon oil, which is less viscous than the pure Sea lemon oil. Smoke level at maximum power is 3.5 BSU (Bosch Smoke Units) for the ester and 4.0 BSU for the pure Sea lemon oil.

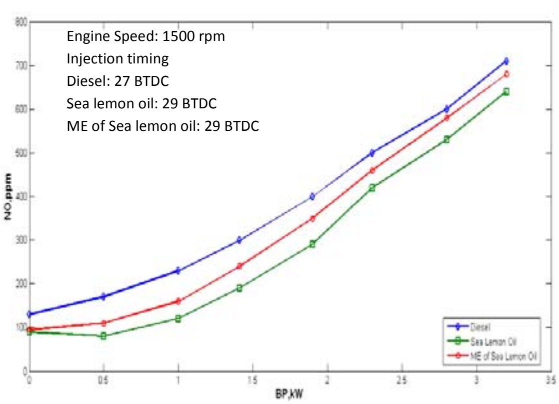

Fig.7. Variation of NO with brake power for various fuels at optimum injection timings

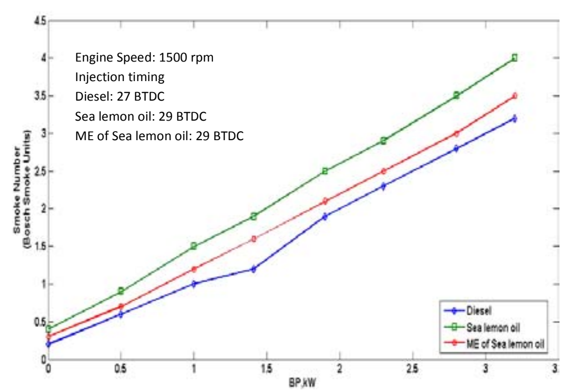

Fig. 8. Variation of smoke No. with brake power for various fuels at optimum injection timings

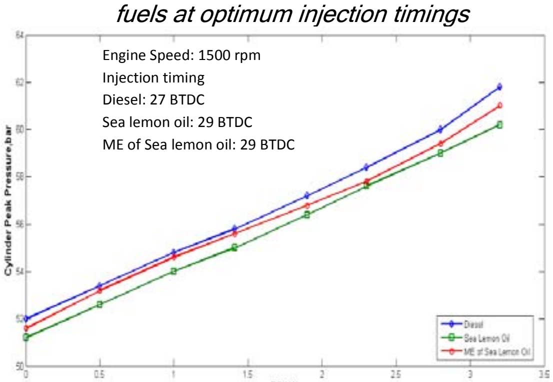

Fig.9. Variation of cylinder pressure with brake power for various fuels at optimum injection timings

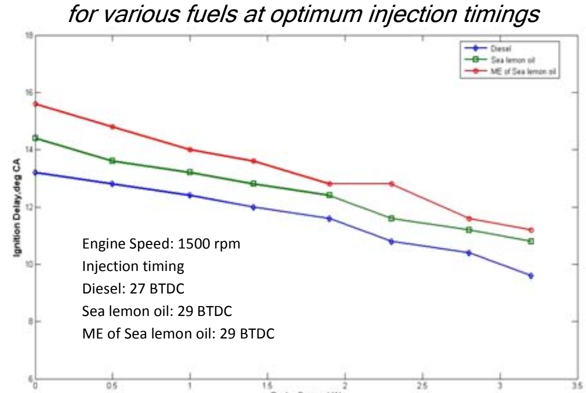

Fig. 10. Variation of ignition delay with brake power for various fuels at optimum injection timings

The smoke level with diesel is 3.2 BSU at maximum power output.

Combustion parameters

Peak pressure is highest for diesel followed by the methyl ester of Sea lemon oil and the pure Sea lemon oil as seen in Fig.9. The peak pressure with Sea lemon oil is about 60.2 bar and for diesel it is 61.8 bar at peak load. However, with the methyl ester of Sea lemon oil it is 61 bar, which is higher than that with pure Sea lemon oil. In a compression ignition engine, peak pressure depends on the combustion rate in the initial stages, which in turn is influenced by the amount of fuel taking part in the uncontrolled combustion phase. The uncontrolled or the premixed combustion phase is governed by the ignition delay period and by the mixture preparation during the delay period. Thus, higher viscosity and lower volatility of the Sea lemon oil which lead to poor atomization and mixture preparation with air during the ignition delay period are the reasons for this trend of peak pressure.

The variation of ignition delay is shown in Fig.10. The ignition delay was calculated based on the dynamic injection timing measured with an inductive needle lift transducer. Sea lemon oil and methyl ester of Sea lemon oil show longer ignition delays compared to diesel. Their cetane numbers are also lower than that of diesel. However, methyl ester of Sea lemon oil shows shorter ignition delay than neat Sea lemon oil.

Conclusions

The performance, emission and combustion characteristics of a 3.68 kW DI diesel engine fuelled with sea lemon oil based fuels have been analyzed and compared with those of standard diesel. The conclusions are summarized as follows:

The brake specific fuel consumption of sea lemon oil and methyl ester of sea lemon oil was 14 to 21% and 13 to 16% respectively greater than that of standard diesel at all loads

There was a reduction in brake thermal efficiency for Neat sea lemon oil by 6.8% and for methyl ester of sea lemon oil by 2.7% compared to standard diesel at full load.

There was a reduction in NOx emission for Neat sea lemon oil and its ester by 9.9% and 4.2% respectively at full load.

There was an increase in HC emissions for Neat sea lemon oil and its ester by 25.5% and 15.6% respectively at full load.

There was an increase in smoke emissions for Neat sea lemon oil and its ester by 25% and 9.4% respectively at full load.

On the whole it is seen that operation of the engine is smooth on Sea lemon oil and its methyl ester.

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