Karanja oil utilization in a direct-injection engine by preheating. Part 2: experimental investigations of engine durability and lubricating oil properties

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The manuscript was received on 18 May 2009 and was accepted after revision for publication on 15 June 2009.

DOI: 10.1243/09544070JAUTO1267

Abstract: Straight vegetable oil utilization as a diesel engine fuel has the advantages of eliminating the energy, time, and cost involved in biodiesel production. Since straight vegetable oils have quite high viscosity compared with mineral diesel, they have to be modified to bring their combustion-related properties closer to mineral diesel. In this experimental study, a heat exchanger was designed and used to utilize the waste heat of exhaust gases for reducing the viscosity of Karanja oil by preheating. Carbon deposits, wear of vital engine components, and various effects of utilizing preheated Karanja oil on lubricating oil were analysed during a long-term endurance test executed for 512 h. Carbon deposits on various critical parts of the power cell were analysed by visual inspection. For pistons, the piston merit rating was determined. The effect on a lubricating oil because of heated Karanja oil *vis-à-vis* mineral diesel was evaluated by comparing the densities, viscosities, flash points, carbon residues, ash contents, copper corrosion effect and pentane, benzene insolubility measurements at intervals of every 128 h for 512 h. The wear of the cylinder liner, piston rings, gudgeon pin, and small- and big-end bearings for a Karanja-oil-fuelled engine were also measured and compared *vis-à-vis* mineral diesel-fuelled engine.

Keywords: biofuels, lubricating oil tribology, wear, piston rating, durability, atomic absorption spectroscopy

1 INTRODUCTION

Worldwide, there is a tremendous interest in utilizing non-edible vegetable oils and their derivatives as alternate fuels in diesel engines. South Asia is producing a host of non-edible oils such as linseed, castor, *Jatropha*, karanja (*Pongamia Pinnata*), neem (*Azadirachta indica*), palash (*Butea monosperma*), and kusum (*Schlelchera trijuga*). Some of these oils are not being adequately utilized, and it has been estimated that some plant-based forest-derived oils have a much higher production potential [**1**, **2**]. Much experimental work has been carried out in various countries on the utilization of vegetable oils in compression ignition (CI) engines. Vegetable oils and their derivatives in diesel engines lead to a substantial reduction in sulphur, carbon monoxide (CO), polycyclic aromatic hydrocarbons, smoke, noise, and particulate emissions [**3–5**]. Furthermore, the contribution of biofuels to the greenhouse effect is insignificant, since carbon dioxide (CO_2) emitted during combustion is recycled in the photosynthesis process in the plants. Vegetable oils have about 10 per cent lower heating value than mineral diesel owing to its higher oxygen content. The kinematic viscosity of vegetable oils is, however, several times higher than mineral diesel. The higher viscosities of vegetable oils (35–45 cSt at 40 °C) as against mineral diesel (3–4 cSt at 40 °C) lead to problems in fuel pumping and atomization, ring sticking, carbon deposits on the piston, cylinder head, ring grooves, etc. In addition, the higher viscosity is responsible for various undesirable combustion features of straight vegetable oils. Since straight vegetable oils

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(SVOs) are not suitable as fuels for diesel engines, they have to be modified to bring their combustion-related properties closer to mineral diesel. This fuel modification is mainly aimed at reducing the viscosity to eliminate flow- and atomization-related problems. Four well-known techniques are traditionally used to reduce the viscosity levels of vegetable oils, namely heating–pyrolysis, dilution–blending, microemulsion, and transesterification [**3–6**].

If the waste heat of the exhaust gas is utilized for the preheating of vegetable oils, this method of vegetable oil utilization in CI engines eliminates the material and cost requirements of fuel processing. However, there are various unresolved issues in using vegetable oils as substitute fuel for mineral diesel, such as the following.

1. The price of vegetable oil is dependent on the feedstock price.
2. Feedstock homogeneity, consistency, and reliability are questionable.
3. The homogeneity of the product depends on the supplier, feedstock, and production method used.
4. Storage and handling are difficult (particularly stability in long-term storage).
5. The flash point of blends is unreliable.
6. Compatibility with materials used in an internal combustion engine needs to be investigated.
7. Cold-weather operation of the engine is not easy with vegetable oils.
8. Acceptance by engine manufacturers is another major difficulty.
9. Continuous availability of the vegetable oils needs to be assured before embarking on the large-scale usage in combustion engines, etc.

Short-term engine performance tests have indicated good potential for most vegetable oils as fuel. The use of vegetable oil results in increased volumetric fuel consumption and brake specific fuel consumption. Emissions of CO and hydrocarbons were found to be higher, whereas nitrogen oxide (NO_x) and particulate emission levels were lower than mineral diesel [**7–11**].

Injector coking was investigated on a diesel engine running with cold-pressed rapeseed oil by considering various engine load conditions [**12**]. The results showed that coking of the injector nozzle depends on the engine performance mode. The injector nozzles that operated on neat rapeseed oil were more coated by carbonaceous deposits than injector nozzles that operated on the mineral diesel. Controlled studies of the valve lifting opening pressure and visual evaluation of fuel sprays confirmed that all injectors were still within the norm, suitable for further operation. Carbon deposits related to the usage of rubber-seed oil blend were investigated by Ramadhas *et al.* [**3**]. It was found that the deposits on the cylinder head were higher in a vegetable oil-fuelled engine than mineral diesel. A quick build-up of carbon deposits on the injector nozzles was also observed. Higher carbon deposits occurred because of incomplete combustion of the vegetable oil blends. It has been established by experiments that 50–80 per cent of rubber-seed oil can be substituted for mineral diesel without any major engine modifications and operational difficulties.

Carbon deposit accumulations in the injectors of a diesel generator fuelled with palm oil were investigated by de Almeida *et al.* [**13**]. It turned out that deposit accumulations in the injectors could lead to a higher exhaust gas temperature. The deposits on the cylinder head reached high levels when the engine operated with palm oil heated at 50 °C and acceptable levels when heated to 100 °C (almost similar to the operation with mineral diesel).

However, adequate engine modifications (increase in the injection pressure, installation of a turbocharger in order to increase the temperature and pressure inside the cylinders, usage of special lubricants with convenient additives, and adaptation of the injecting system to the particular use) are required to improve lubricating oil degradation, performance, and emissions and to achieve a more efficient combustion [**14**]. This study has been performed to evaluate the effect of preheated Karanja oil blends on long-term engine wear and lubricating oil degradation.

2 EXPERIMENTAL METHOD

Nearly all agricultural tractors, pump sets, farm machinery, and transport vehicles use direct-injection diesel engines. Keeping the specific features of diesel engines in mind, a typical engine widely used in the agricultural sector in developing countries has been selected for the present experimental investigations.

2.1 Engine

Four-stroke single-cylinder constant-speed water-cooled direct-injection diesel engines (Kirloskar Oil Engines Ltd, India, model DM-10) fitted with an a.c. alternator of 7.4 kW (10 hp) rating were procured (2

Nos., one for mineral diesel and the other for Karanja oil) to study the effect of preheating on the performance, emissions, durability, and lubricating oil of the Karanja-oil-fuelled-engine, *vis-à-vis* mineral diesel-fuelled engine. The engines were operated at a constant speed of 1500 r/min. The fuel injection pressure recommended by the manufacturer is in the range 200–205 bar at 1500 r/min. The oil sump was filled with fresh lubricating oil before beginning the experiments.

2.2 Fuel conditioning system

Fuel conditioning is essential because vegetable oil is highly viscous and contains impurities including dust particles and gums. Therefore, it is necessary to filter the vegetable oil adequately before it is supplied to the engine. If vegetable oil of poor quality is supplied to the engine, then it may generate higher particulate matter, leading to increased engine wear, as well as choking the fuel lines, fuel pumps, etc. In the experimental set-up, two filters in parallel are provided at the exit of the tank and one before the fuel pump. Two parallel fuel filters are provided next to the fuel tank because, if one filter is clogged, the supply of fuel can be switched to another filter while the clogged filter can be cleaned or replaced and engine operation during this procedure is not affected.

Two fuel tanks are given in the set-up. One fuel tank is for diesel and the other for vegetable oil. The engine is started with mineral diesel and, once the engine warms up, it is switched to vegetable oil. After concluding the tests with vegetable oil, the engine is again switched back to mineral diesel until the vegetable oil is purged from the fuel lines, injection pump, and injector in order to prevent deposits, and to avoid cold-starting problems. A shell-and-tube-type heat exchanger is designed to preheat the vegetable oil using the waste heat of the exhaust gases. One supply pipe connection is provided at each end plate of the heat exchanger for the inlet and outlet of the vegetable oil. A thermocouple was provided in the heat exchanger to measure the temperature of the preheated vegetable oil, close to the exit.

In the long-term endurance test, the effect of the use of heated Karanja oil on various engine parts *vis-à-vis* mineral diesel was studied. A comparison of the wear of various parts of Karanja- and diesel-fuelled engines was made in a long-term endurance test after dismantling various parts of the engine. Various tests on the engine systems are conducted as per the procedure specified in IS 10000: 1980 [**15**].

After the completion of the preliminary running-in and fuel consumption test, the engines were dismantled completely and examined physically with respect to the conditions of various critical parts before the endurance test was commenced. After physical examination, the dimensions of various vital moving parts were recorded, e.g. cylinder head, cylinder bore, cylinder liner, piston, piston rings, gudgeon pin, valves (inlet and exhaust), valve seats (inserts), valve guide, valve springs, connecting rod, big-end bearing, small-end bush, connecting rod bolts and nuts, crankshaft, crankshaft bearings and journals, and camshaft. The engines were reassembled and mounted on suitable test beds and again run-in for 12 h as recommended by the manufacturer. This was done in order to take care of any misalignments that occurred during dismantling and reassembling of the engine. This run-in included a continuous run of 11 h, at the rated full load at the rated speed followed by a 1 h run at 10 per cent overload at the rated speed.

During the running-in period, none of the critical components listed above was replaced. The lubricating oil from the oil sump was drained off and the engine was refilled with SAE 30 grade fresh lubricating oil as specified by the manufacturer. The engines were run for 32 cycles (each running for 16 h continuously) at rated speed. The test cycle followed is specified in Table 1.

3 CARBON DEPOSIT STUDY

3.1 Visual inspection of vital engine parts

Figure 1 shows the deposits on various in-cylinder parts after the completion of the long-term endurance test (i.e. after 512 h). An important observation during this test was that the injector tip (only) of the Karanja-fuelled engine was cleaned three times during the entire duration of 512 h. During the period of the endurance test; the injector tip of the mineral-diesel-fuelled engine were not cleaned throughout the test period. Hence no definite conclusion can be drawn from a comparison of the injector tip deposits of Karanja- and diesel-fuelled engines but heated

Table 1 Test cycle for long-term endurance test

Load (% of rated load)	Running time (h)
100	4
50	4
110	1
No load (idling)	0.5
100	3
50	3.5

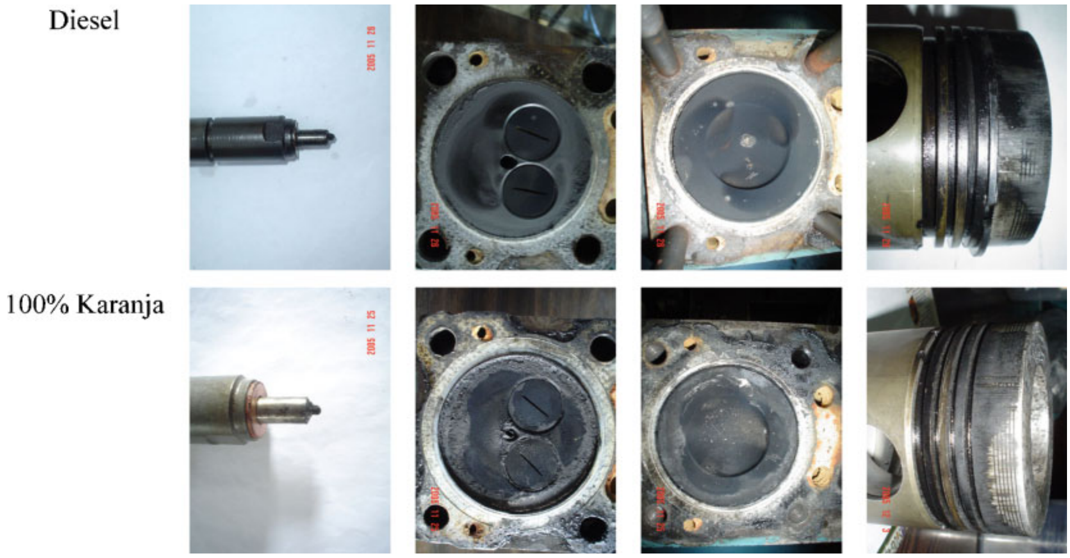


Fig. 1 Comparison of carbon deposits

Karanja oil was definitely problematic from an injector tip deposit viewpoint. The deposits of carbon were conclusively higher for preheated Karanja-oil-fuelled engine power-cell components than those from the mineral-diesel-fuelled engine.

However, it can be seen that the preheated Karanja-oil-fuelled engine does not demonstrate deposits which are an order of magnitude higher than mineral diesel and are expected (and also reported in the literature) from the SVO-fuelled engine. This indicates that the pre-heating technology is successful in using SVO as an alternate diesel engine fuel; however, a revised maintenance schedule needs to be drawn and followed for this purpose.

3.2 Carbon deposit rating

After completion of the long-term endurance test, the carbon present on the top of the piston was scraped off carefully, collected, and weighed for comparison purposes. The results are shown in Fig. 2. It can clearly be seen that the SVO-fuelled engines had a significantly higher amount of carbon deposits on the piston top.

3.3 Piston deposit rating

The piston deposit rating is useful to rate the varnish of the piston skirt for estimation of the engine performance and quality of the lubricating oil. For the exclusion of some defects, the rating includes an automatic quantitative varnish rating developed by using image processing. The varnished area of piston was extracted from the developed colour image by setting the two thresholds: the density and x value of the chromacity diagram. The nomenclature used for piston rating is given in Fig. 3.

After completion of the long-term endurance test, diesel-fuelled and Karanja-fuelled engine piston ratings were analysed separately by certified raters. The method of rating is given in IP/247/69 [**16**], the *CRC manual 16* [**17**], and the *CRC manual 17* [**18**]. Since colour charts and rating aids were not available, as recommended in the rating procedure, rating was carried out under daylight conditions. Under field conditions, such a rating is permitted. A 0.00 point scale is denoted as clean. In this test, piston portions such as the skirt, ring groove, ring land, under-crown, and under-skirt were analysed by comparing the colour of every 1 cm^2 area of the piston using a chromacity diagram. The color factors used for lacquer deposits are given in Table 2. Also

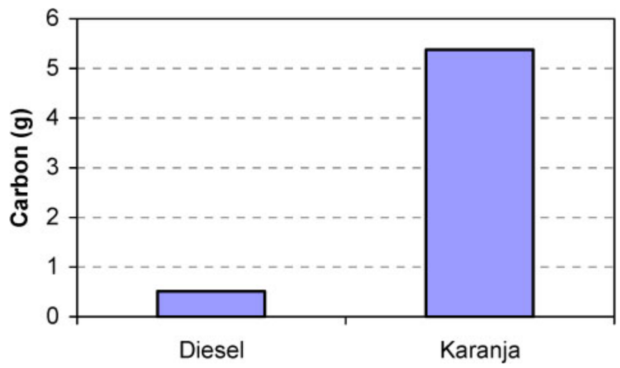


Fig. 2 Carbon deposits on the piston top

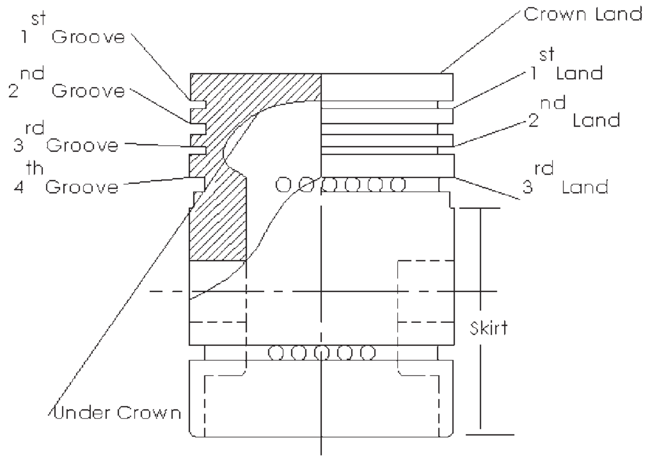


Fig. 3 Nomenclature of various engine parts: used for piston rating

Demerit rating =

$$\frac{\text{percentage of area covered by deposits} \times \text{colour factor}}{10}$$

Merit rating = 10 − demerit rating

The area below the last ring groove, excluding all recesses (the contacting area with the liner) was rated as the piston skirt. The skirt was rated by using colour factors as indicated in Table 2 and a transparent template was used for dividing the piston skirt into small sectors. The merit ratings of the pistons from the mineral-diesel-fuelled engine and Karanja-fuelled engine are shown in the Table 3.

4 EFFECT OF SVO ON THE LUBRICATING OIL

The lubricating oil samples were drawn from the two engines after every 128-h run, using the standard lubricating oil sampling procedure, and these samples were then analysed for various properties and parameters experimentally. The results of these tests are shown in the following sections.

Table 2 Colour factors for lacquer deposits for piston rating

Clean	0.00
Discolouration	0.10
Light brown	0.25
Red–brown	0.5
Dark brown	0.75
Black (carbon is to be considered as black lacquer)	1.00

Table 3 Consolidated results of piston merit rating

Parameter	Value for the following: Diesel	K100 (preheated)
Skirt	8.70	8.96
Ring groove (overall)		
Ring 1	*	0.00
Ring 2	0.00	0.00
Ring 3	0.00	0.00
Ring 4	2.75	0.00
Top groove carbon filling (%)	*	80
Ring land		
Ring land 1	0.18	0.19
Ring land 2	4.01	1.62
Ring land 3	5.51	0.19
Under crown	1.25	2.5
Under skirt	6.00	8.95
Ring sticking	Top ring merit rating, 3.00	—

*Ring stuck in the groove. This ring was not removed, and so no rating was assigned.

4.1 Density

Density measurements are important since they provide information on the addition of wear metals and fuel dilution of the lubricating oil. The density of lubricating oil from both engines shows an increasing trend with usage.

The density of the lubricating oil increases mainly owing to the addition of wear debris, fuel dilution, and increase in the moisture content. Initially, the wear of engine parts is faster and fuel dilution also starts. Because of the combined effect of these factors, the density of the Karanja-fuelled lubricating oil increases more rapidly than mineral diesel (Fig. 4). The rate of increase in the lubricating oil density decreases after engine operation for 384 h in the diesel-fuelled engine.

4.2 Ash content

The ash content reflects the non-carbonaceous matter in the lubricating oil since carbonaceous materials such as oil, soot, fuel, and non-metallic parts of organometallic additives are converted into CO_2 after thermal decomposition. The ash content mainly indicates metallic wear debris and abrasive foreign particles such as dust entering the system. Since both engines operated under similar conditions, the contribution of foreign particles is assumed to be similar and hence the variation in ash content of lubricating oils drawn from the engines primarily reflect wear debris. The ash content is measured according to ASTM D482 [**19**]. Ash is present as solid, oil-soluble, or water-soluble metallic compounds. These solid particles are often designated as sediments.

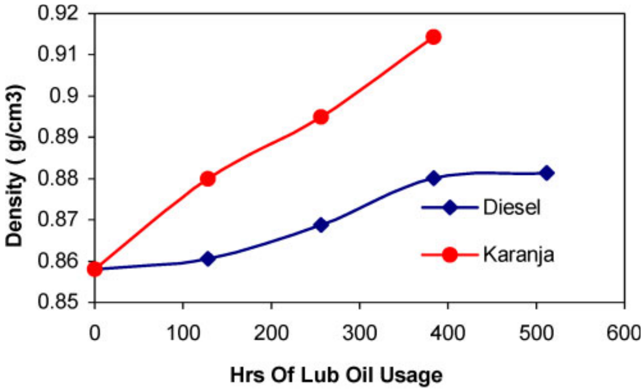


Fig. 4 Change in the density of lubricating oil with usage

Approximately 5 g of oil sample, contained in a silica crucible, was kept in the muffle furnace at 450 °C for 4 h and 650 °C for 2 h and allowed to burn until only ash was left. The ash was finally cooled and weighed.

Figure 5 indicates that the ash content initially decreases for the Karanja-fuelled engine, suggesting a higher amount of fuel dilution and moisture addition. Thereafter the ash content steadily increases, suggesting the addition of wear debris.

4.3 Viscosity

Any change in viscosity of the lubricating oil is undesirable in an engine as it affects the lubrication effectiveness. In fact, the criterion for replacing lubricating oil states 'change the lubricating oil if viscosity increases by 20 per cent or more, or decreases by 10 per cent or more'. The viscosity of lubricating oil may increase or decrease with usage. Inadequate oil viscosity affects the lubricating-oil-film thickness separating the metallic parts and load-bearing capacity leading to low oil pressure, poor oil efficiency, and excessive wear of mating parts, bearings, and other moving components.

Two factors are mainly responsible for lubricating oil viscosity changes in opposite directions. Formation of resinous products because of oil oxidation, evaporation of lighter fractions, depletion of anti-wear additives, and contamination by insoluble compounds tend to increase the oil viscosity while moisture addition, fuel dilution, and shearing of viscosity index improvers tend to reduce the oil viscosity. The extent of dominance of both mechanisms, however, differs from system to system. Hence, the net result can be in either direction. If the first factor is dominating and the feasibility of fuel dilution is almost insignificant, the net viscosity is higher than the original. However, the viscosity can decrease, if fuel dilution is a dominating mechanism. The viscosity of lubricating oil samples was evaluated at 40 °C and 100 °C using a kinematic viscometer (Figs 6 and 7).

These figures show that the viscosity of the SVO-fuelled engine first decreases and then increases rapidly, making the lubricating oil unfit for further use beyond 384 h.

The rate of change in viscosity is also controlled by oil oxidation. It is also possible that vegetable oil, which enters the lubricating oil through fuel dilution (in the initial period), might have accelerated the oxidation rate of the base stock, leading to an initial reduction in viscosity due to fuel dilution, followed by an increase in viscosity due to oxidation of the lubricating oil base stock. In the initial phase, the decrease in viscosity due to fuel dilution could have slowed down owing to base-stock oxidation.

Fuel dilution is a direct consequence of the clearance between the piston rings and the cylinder liner. The more the piston rings wear out, the higher

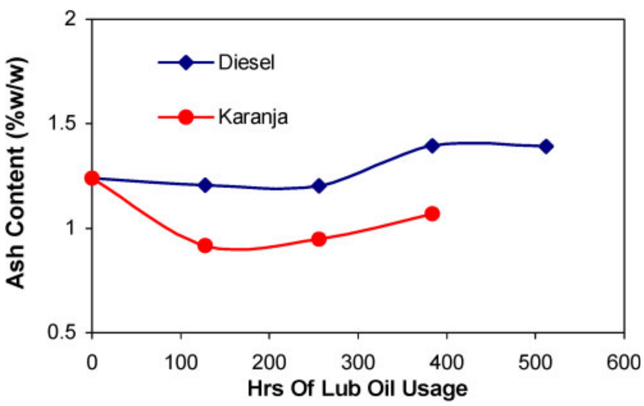


Fig. 5 Change in the ash content of lubricating oil with usage

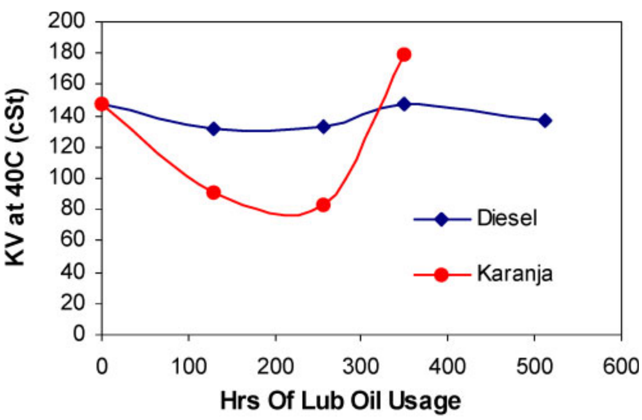


Fig. 6 Change in the lubricating oil viscosity at 40 °C with usage

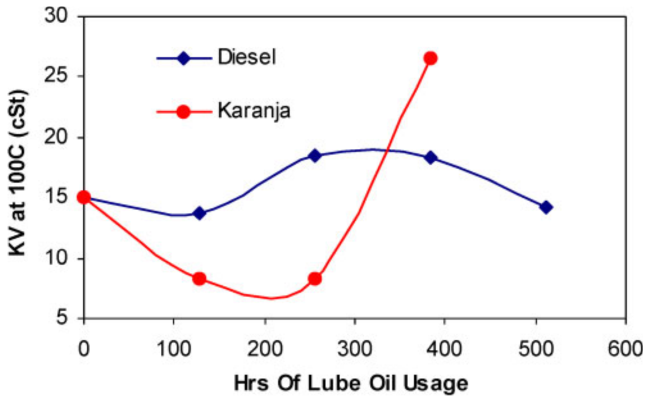


Fig. 7 Change in the lubricating oil viscosity at 100 °C with usage

will be the clearance, and hence there is more fuel dilution.

4.4 Flash point

The flash point temperature of all lubricating oil samples was evaluated using the Setaflash closed-cup flash point apparatus. On heating, the lubricating oil molecules experience van der Waals forces. The higher the van der Waals forces, the higher will be the energy required for vaporizing and the higher will be the flash point. Fuel dilution of the lubricating oil is undesirable because it will reduce the van der Waals forces to a greater extent, thus lowering the flash point.

As observed from Fig. 8, the flash point of oil from the diesel-fuelled engine is reduced first (possibly owing to dilution by mineral diesel, which has a flash point of approximately 70 °C), whereas the flash point of the Karanja-fuelled engine is reduced to a less extent because it has fuel dilution from a fuel that has a very high flash point (237 °C).

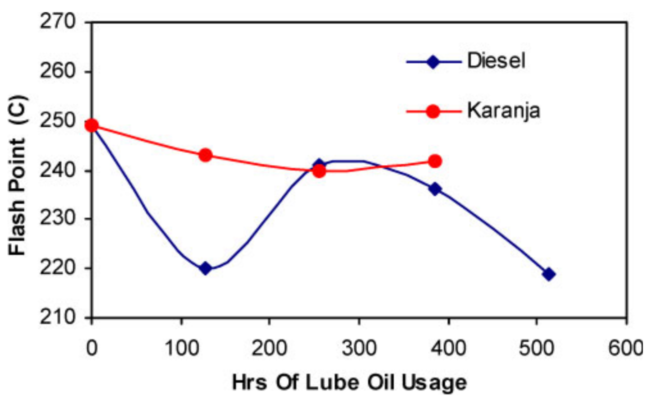


Fig. 8 Change in the flash point of lubricating oil with usage

4.5 Carbon residue

The carbon residue was measured according to ASTM D189 [**20**] and was determined by placing a weighed sample in a silica crucible. The crucible was heated in a muffle furnace at 500 °C for 30 min in an inert (nitrogen) atmosphere. The crucible was then cooled and weighed. The weight of tar remaining in the crucible in comparison with the original sample gives the carbon residue (in per cent w/w). The data on carbon residue in the lubricating oils for diesel-fuelled and Karanja-fuelled engines are shown in Fig. 9.

4.6 Atomic absorption spectroscopy

Atomic absorption spectroscopy (AAS) was used for quantitative and qualitative analysis of the wear debris of lubricating oils. The data were correlated with the extent of wear, the performance characteristics of the lubricating oils, and diagnosis of failure of moving components.

The concentration of various metals present in the lubricating oil samples from both engines was evaluated to study the wear of different parts and material compatibility of the new fuels with the existing engines. Since many sliding components were involved, it was anticipated that the wear debris originating from different metallic parts appeared in the lubricating oil. The results of AAS carried out on the lubricating oil samples for various metals are shown in Fig. 10.

4.6.1 Iron

The iron in wear debris could be because of the wear of cylinder liner, piston rings, valves, gears, shafts, bearing, rust, and crankshaft. For the Karanja-fuelled

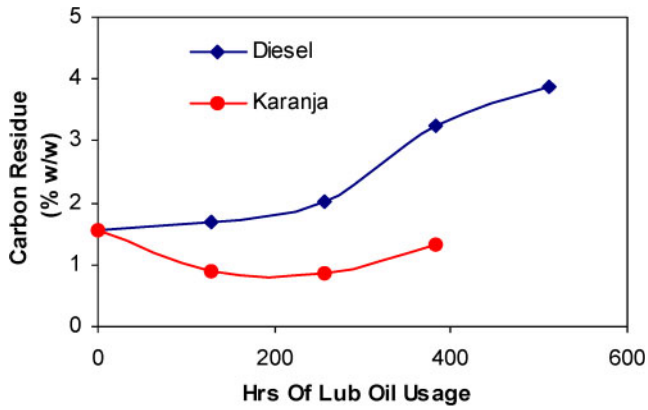


Fig. 9 Change in the carbon residue of lubricating oil with usage

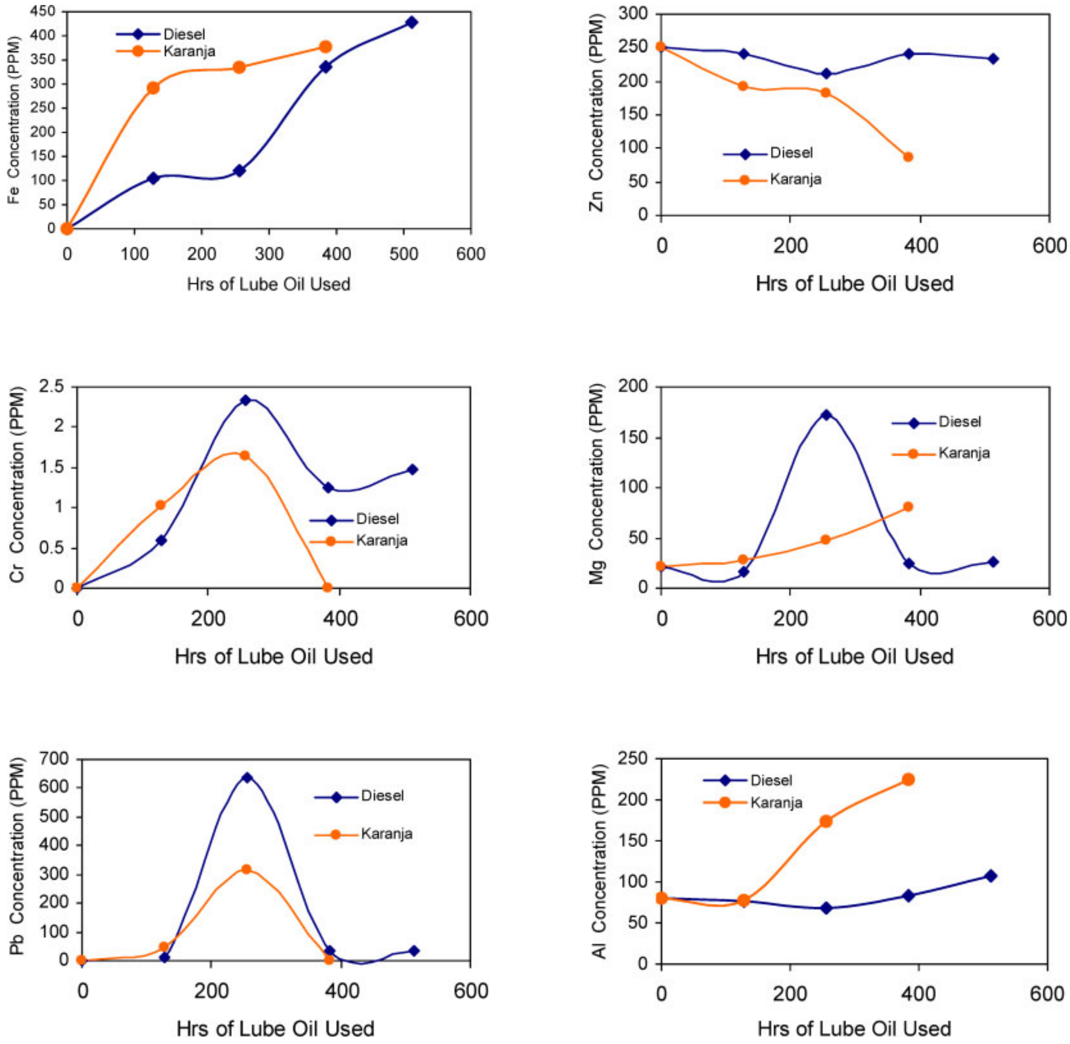


Fig. 10 AAS results of lubricating oils from the engine for various metals

engine, iron wear is substantially higher than for the mineral-diesel-fuelled engine.

4.6.2 Zinc

The zinc in wear debris could be because of additive depletion, wear of bearings, brass components, and neoprene seals. The amounts of zinc wear are almost the same in the Karanja-fuelled engine and the diesel-fuelled engine.

4.6.3 Chromium

The chromium in wear debris could be because of wear of the cylinder liner, compression rings, gears, crankshaft, and bearing. Since chromium is found in a very small amount inside the cylinder and its strength is high, therefore a very small amount is present in lubricating oil of both the engines.

4.6.4 Magnesium

The magnesium in wear debris could be because of additive depletion, wear of the bearing, and gearbox housing. The wear performance of the Karanja-fuelled engine is similar to that of the mineral-diesel-fuelled engine.

4.6.5 Lead

The lead in wear debris could be because of the wear of bearings, paints, and grease addition. The wear performance of the Karanja-fuelled engine is similar to that of the mineral-diesel-fuelled engine.

4.6.6 Aluminium

The aluminium in wear debris could be because of wear of the piston, bearings, dirt, additives, and thrust washers. The Karanja-fuelled engine showed slightly higher aluminium wear in comparison with the diesel-fuelled engine.

4.7 Copper corrosion test

The objective of the copper strip corrosion test was to find the corrosiveness of lubricating oil to copper-containing engine parts. This test monitors the presence of corrosive acids in the lubricating oil. The copper corrosion bath (Stanhope Seta, UK, model Setavis 11300) is a constant-temperature bath which conforms to ASTM D130–IP154 [**21**], ASTM D4048 [**22**], IP 112 [**23**], IP 227 [**24**], BS 2000 Part 112 [**25**], and BS 2000 Part 154 [**26**]. This is used for determining the copper corrosion potential of various lubricating oil samples drawn from the two engines. The copper corrosiveness of all the lubricating oils is of grade 1a. Hence, it can be concluded that heated Karanja oil does not cause any harm to the copper parts of the engine and also that the heated lubricating oil from the Karanja-oil-fuelled engine is as safe as lubricating oil from the diesel-fuelled engine from a copper corrosion viewpoint.

4.8 Pentane and benzene-insoluble test

The aim of the pentane- and benzene-insoluble test is to find the suspended contaminants in lubricating oil. These suspended contaminations can be oil-soluble resinous material formed as a result of degradation of oil, additives or both, fuel carbon or highly carbonized material, corrosion and wear particles from the engine, and dust particles entering from the environment.

The weight of the insoluble fraction in benzene (Fig. 11(a)) is lower than that in pentane (Fig. 11(b)). The difference between the pentane- and benzene-insoluble fractions indicates the extent of oil oxidation (Fig. 11(c)). The higher the difference, the higher is the oil oxidation. A significant change in the pentane-insoluble fraction, benzene-insoluble fraction, and insoluble resins indicates a change in oil properties, which could lead to lubrication system problems. The insoluble measured content can also assist in evaluating the performance characteristics of the used oil or in determining the cause of equipment failure.

The formation of cross-linked gels in the Karanja-fuelled engine is higher than in the mineral-diesel-

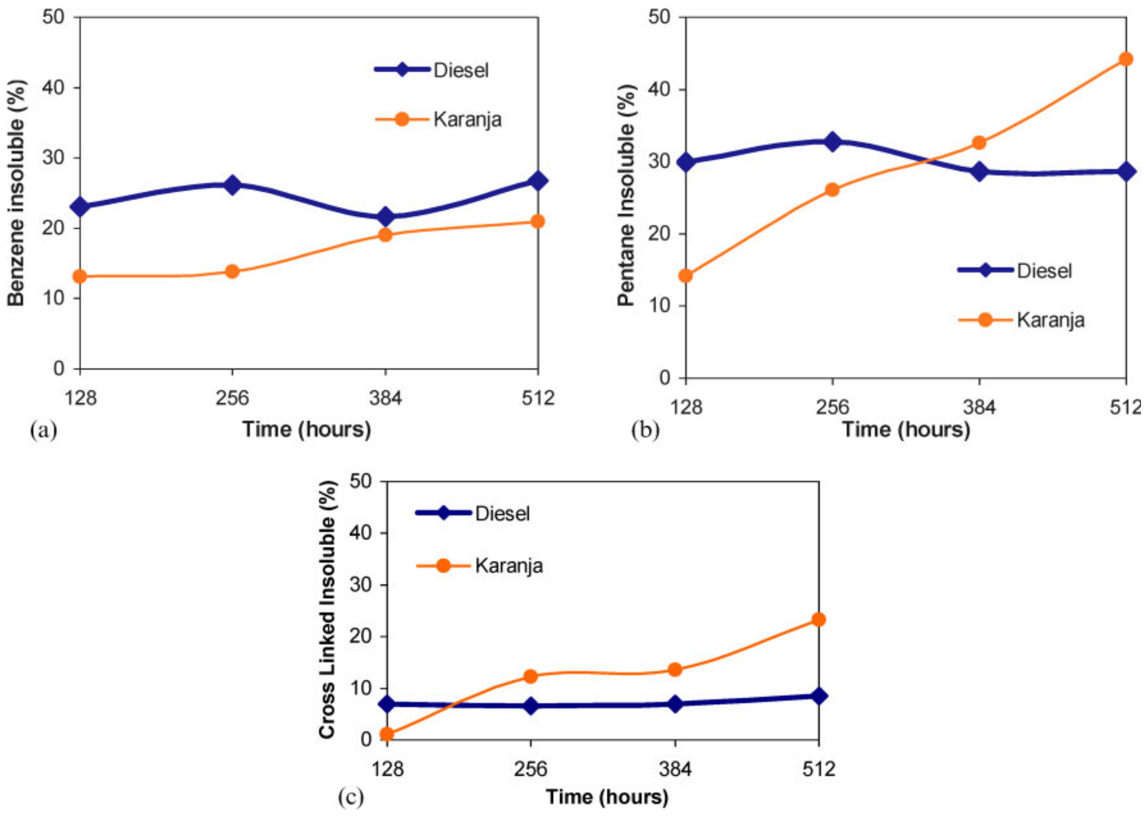


Fig. 11 Changes in (a) the benzene-insoluble content, (b) the pentane-insoluble content, and (c) the cross-linked insoluble content of lubricating oil with usage

fuelled engine (Fig. 11(c)). This is expected because of presence of oxygen in the vegetable oils, which cause oxidation of lubricating oil when it mixes with lubricating oil by the process of fuel dilution.

The pentane-insoluble fraction with the diesel fuel remains almost constant with hours of lubricating oil usage, but it tends to increase in the Karanja-fuelled engine (Fig. 11(b)). For a lubricating oil usage of 128 h, a comparatively small amount of pentane-insoluble compounds are formed in SVO-fuelled engines, but, with time, the pentane-insoluble content becomes higher in the Karanja-fuelled engine than in the mineral-diesel-fuelled engine.

Overall, it can be safely concluded that Karanja oil shows a higher tendency for polymerization (of the lubricating oil base stock) than does the mineral diesel.

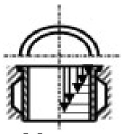
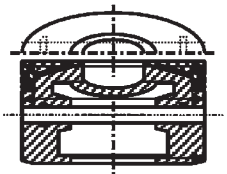
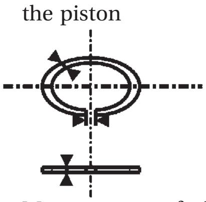
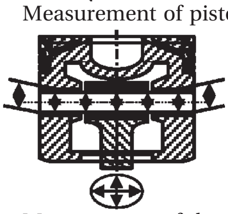
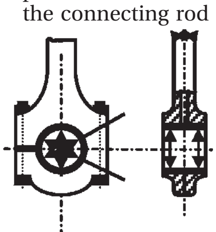
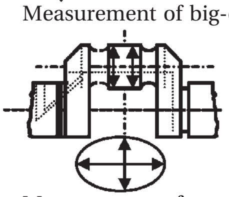
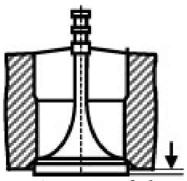
5 PHYSICAL WEAR MEASUREMENT OF VITAL PARTS

The wear of various moving parts took place because of prolonged engine operation. Both the engines were operated under identical conditions and the loading cycles of the engines were also similar. The only variation in the operation was that engines were operated using different fuel blends so that the effect of each fuel on the life of engine hardware could be compared directly. The dimensions of the vital parts and physical condition were recorded before the commencement of and after the completion of the long-term endurance test. The difference in these dimensions gave the wear of these parts in the given period of engine operation. After completion of the long-term endurance test, the engines were again dismantled completely, and the physical condition of various parts inspected carefully. Wear was estimated by accurate measurement of dimensions of various vital parts of the engine, before and after the long-term endurance test. These observations of wear were useful to compare the performance of the SVO *vis-à-vis* mineral diesel on the wear of the vital engine parts (Table 4). This table shows generally higher engine component wear with Karanja oil than in the mineral-diesel-fuelled engine, with some exceptions of lower component wear.

6 SURFACE ROUGHNESS PARAMETERS

In this experiment, new cylinder liners were used for both the engines. To check the wear of cylinder liner material during the course of the engine test, the

Table 4 Comparative performances of Karanja oil *vis-à-vis* mineral diesel with respect to the wear of the vital engine components

Component		Wear in a Karanja-oil-fuelled engine in comparison with a mineral-diesel-fuelled engine
 Measurement of the cylinder bore and liner		236 ↑
 Measurement of the diameter of the piston		53 ↓
 Measurement of piston rings	Ring 1	322 ↑
	Ring 2	22 ↓
	Ring 3	87 ↑
	Ring 4	—
 Measurement of the gudgeon pin, pin bore, and small-end bush of the connecting rod	Gudgeon pin	93 ↑
	Pin bore	1.8 ↓
	Small-end bush	92 ↑
 Measurement of big-end bearing		333 ↑
 Measurement of crank pin		18 ↓
 Distance of the valve head from the mounting flange face		49.4 ↓

surface profile of the liners was taken before and after operating the engine for 512 h. The surface profiles were taken at three locations: at top dead centre (TDC) (30 mm from top of the cylinder liner); at midstroke (78 mm from the top of the cylinder liner); at bottom dead centre (BDC) (128 mm from the top of the cylinder liner) on the thrust and anti-thrust side. TDC and BDC are the most important locations of the cylinder liner where maximum wear is expected to take place. The piston skirt touches the liner surface in the intake stroke towards the thrust side and, for the rest of the three strokes, it touches the anti-thrust side. Scuffing and abrasion takes place in the liners owing to the three-body relative motion of liner, piston rings, and soot particles. The major reasons for liner wear are high thrust due to high-pressure and high-temperature gases, abrasion due to soot and dust particles, poor lubrication, etc.

A surface roughness profilometer (Mitutoyo, Japan, model SJ 301) was used for surface profiling of the liner surfaces. The evaluation length of the surface profile was kept at 2.4 mm. The profiles were taken with ×10 magnification in the horizontal direction and ×2000 magnification in the vertical direction. The roughness parameters of cylinder liner 1 (engine operated by diesel fuel) on the thrust and anti-thrust side are shown in Table 5.

From the roughness parameters shown in Table 5, it can be observed that the wear of the liner at TDC is consistently higher than at BDC and in the midstroke position. The wear at TDC is more because this zone of cylinder liner faces the highest temperature due to combustion gases. TDC faces a high load and relatively lower piston speeds; because of this the boundary layer lubrication at TDC breaks down. At TDC, the lubricating-oil-film thickness is less than 0.025 μm which is less than normal size of soot particles, which act as abrasives and increase the wear of the liner surface at TDC.

It was also observed from Table 5 that the wear of the cylinder liner is higher on the anti-thrust side than on the thrust side. The possible reason for this may be that the piston touches the thrust side of the cylinder liner surface during intake strokes only, while the piston touches the anti-thrust side of the cylinder liner surface during the remaining three strokes; hence the wear at the anti-thrust side is higher than at the thrust side.

From roughness parameters, it can be observed that the wear of the liner at TDC is consistently higher than at BDC and midstroke positions. It can be concluded that the wear of Karanja-oil-fuelled engine liners is substantially higher than for the mineral-diesel-fuelled engine. This conforms with the results obtained from the physical wear measurements and AAS of the lubricating oil.

7 CONCLUSION

In the long-term endurance test, the effect of use of Karanja oil on various engine parts and lubricating oil *vis-à-vis* mineral diesel was evaluated. The assessment of wear of various parts of Karanja-oil-fuelled and diesel-fuelled engines was made where the Karanja oil is preheated using the waste heat of the engine exhaust. The deposits on the vital engine parts were found to be higher on Karanja-fuelled engine. The piston rating carried out on the pistons

Table 5 Roughness parameters of the mineral-diesel-fuelled engine

Roughness parameter (μm)	Value before the endurance test at the following positions			Value after the endurance test of 512 h at the following positions		
	TDC	Midstroke	BDC	TDC	Midstroke	BDC
Thrust side						
R_a	0.35	0.29	0.43	0.15	0.17	0.18
R_z	1.90	1.55	1.72	1.94	1.72	2.88
R_q	0.56	0.40	0.61	0.29	0.27	0.43
R_t	6.59	4.05	3.28	2.63	2.13	4.24
R_p	0.86	0.65	0.65	0.50	0.40	0.42
R_v	2.67	2.13	2.30	2.14	1.73	3.82
R_{sk}	−1.70	−2.02	−1.97	−4.00	−2.84	−5.58
Anti-thrust side						
R_a	0.17	0.14	0.32	0.14	0.21	0.26
R_z	1.11	1.14	1.64	1.95	2.59	2.22
R_q	0.29	0.24	0.48	0.28	0.37	0.41
R_t	2.46	2.55	3.26	3.47	3.01	3.32
R_p	0.30	0.36	0.53	0.43	0.51	1.37
R_v	1.72	1.57	2.12	3.04	2.50	1.96
R_{sk}	−3.29	−3.75	−2.22	−5.15	−3.20	−0.10

Table 6 Roughness parameters of the 100 per cent Karanja-oil-fuelled engine

Roughness parameter (μm)	Value before the endurance test at the following positions			Value after the endurance test of 512 h at the following positions		
	TDC	Midstroke	BDC	TDC	Midstroke	BDC
Thrust side						
R_a	0.62	0.14	0.24	0.18	0.19	0.23
R_z	3.67	0.60	1.25	3.41	2.41	2.94
R_q	1.05	0.19	0.38	0.40	0.36	0.37
R_t	10.63	1.35	3.38	5.73	4.07	3.50
R_p	0.80	0.49	0.58	1.12	0.75	0.76
R_v	4.92	0.60	1.59	4.61	3.32	2.74
R_{sk}	−2.77	−0.11	−1.68	−6.30	−4.49	−2.84
Anti-thrust side						
R_a	0.44	0.28	0.43	0.10	0.12	0.20
R_z	2.19	1.89	2.15	1.00	1.18	1.60
R_q	0.67	0.44	0.58	0.14	0.19	0.33
R_t	4.58	4.21	5.42	1.47	1.60	2.63
R_p	0.71	0.43	0.81	0.69	0.47	1.38
R_v	2.92	2.26	1.98	0.79	1.13	1.24
R_{sk}	−2.29	−2.72	−1.31	−0.01	−2.37	0.25

of the two engines reflect that the Karanja-fuelled engine has reasonable long-term performance in comparison with mineral-diesel-fuelled engine. The Karanja-oil-fuelled engine first underwent lowering of lubricating oil viscosity followed by severe vegetable-oil-initiated oxidation of the lubricating oil base stock; thus the life of the lubricating oil was over in approximately 400 h.

It was found that the wear of the Karanja-oil-fuelled engine liner is substantially higher than that of the mineral-diesel-fuelled engine. It can be concluded that Karanja oil can be safely used as a substitute for mineral diesel in a compression ignition engine by utilizing the waste heat of exhaust to lower the viscosity, with the use of additional anti-wear additives to the lubricating oil and a revised maintenance schedule.

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