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Article *in* Journal of Renewable and Sustainable Energy · November 2012

DOI: 10.1063/1.4771694

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AIP Journal of Renewable and Sustainable Energy

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Citation: J. Renewable Sustainable Energy **4**, 063138 (2012); doi: 10.1063/1.4771694
View online: http://dx.doi.org/10.1063/1.4771694
View Table of Contents: http://jrse.aip.org/resource/1/JRSEBH/v4/i6
Published by the American Institute of Physics.

JOURNAL OF RENEWABLE AND SUSTAINABLE ENERGY **4**, 063138 (2012)

Wear, durability, and lubricating oil performance of a straight vegetable oil (Karanja) blend fueled direct injection compression ignition engine

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(Received 24 August 2012; accepted 26 November 2012; published online 11 December 2012)

Depletion of fossil fuel resources and resulting associated environmental degradation has motivated search for alternative transportation fuels. Blending small quantity of Karanja oil (straight vegetable oil) with mineral diesel is one of the simplest available alternatives, which can be put into application immediately. Two identical direct injection compression ignition (DICI) engines were subjected to long-term endurance test for comparing long-term durability performance of 10% blend of Karanja oil with mineral diesel (K10) *vis-à-vis* mineral diesel. Carbon deposits, wear of vital engine components, and effect of new fuel (Karanja oil blend) on lubricating oil were analyzed in a long-term endurance test spanning over 512 h engine operation. Wear of liner, piston, piston rings, valves, gudgeon pin, crank pin, bearings, etc., of K10 fueled engine was found to be comparable to mineral diesel fueled engine. Iron, lead, chromium, zinc metal debris in the lubricating oil were found to be lower for K10 fueled engine compared to diesel fueled engine, however, aluminum content in the lubricating oil of K10 engine was slightly higher than diesel fueled engine. Karanja oil proved to be potential partial substitute for mineral diesel in DICI engine without substantial hardware modifications. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4771694]

I. INTRODUCTION

Depletion of fossil fuel resources and environmental pollution caused by their combustion has strongly motivated the search of alternative fuels for internal combustion engines. Plant based straight vegetable oils (SVOs) and fatty acid methyl esters derived from SVOs, animal fats and other triglyceride molecules are the new resources being considered in present scenario as potential alternative fuels for direct injection compression ignition (DICI) engines.[1] Biodiesel has already established itself as most suitable renewable fuel for CI engines. Biodiesel is produced by chemical processing of SVOs, which requires chemical and thermal energy input thus making the localized production of biodiesel in rural settings very difficult and challenging. Pradhan *et al*. showed that biodiesel produces higher amount of energy as a fuel than energy consumed in its cultivation/processing and production,[2] whereas Pimentel *et al*. claimed that biodiesel production process consumes more energy in its cultivation/processing and production than total energy it produces as a fuel.[3] Fore *et al*. concluded that on-form utilization of oilseed crops using SVO production route is the most economical method of biofuel production/utilization from biological renewable resources.[4] Life cycle impact assessment study of rapeseed oil was carried out for comparing the effect of SVO and biodiesel on the environment, which has indicated SVO route as more environment friendly with emphasis on its localised production and utilization.[5]

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TABLE I. 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

Several studies have indicated satisfactory performance of engines while using SVO as fuel in short-term tests.[6–16] Satisfactory operation of sunflower oil fueled engine was reported by Karaosmanoğlu *et al.* in a 50 h test.[17] Basinger *et al.* reported increased wear of waste vegetable oil fueled IDI engine in 500 h durability test.[18] Nwafor and Rice reported satisfactory lubricating oil performance with rapeseed oil blends.[19] Long-term endurance test of Karanja oil utilization by preheating in DICI engine has concluded that the utilization of Karanja oil is a viable option for stationary power generation engines.[20] Performance, emission, and combustion characteristics of different Karanja oil blends were thoroughly investigated and lower blends up to 20% were found suitable for engine operation without any hardware modifications.[21] In the present study, long-term endurance test (512 h) was performed on two identical DICI engines simultaneously, one fueled with 10% unheated Karanja oil blend (K10) and other with mineral diesel for investigating the comparative effect of Karanja oil utilization on engine upon long-term usage.

II. EXPERIMENTAL SETUP

Two four-stroke, single-cylinder, constant speed, water-cooled, DICI engines coupled with alternators of 7.4 kW (10 HP) rating (Kirloskar Oil Engines Ltd., DM-10) were used for comparative long-term durability investigations. One engine was fueled with mineral diesel while the other was fueled with K10. Experimental setup and detailed experimental procedure are described in earlier publications.[21,22] These two new engines were subjected to preliminary run-in and performance tests for verification of the identical condition of the new engines. After this, both the engines were dismantled and examined physically. During endurance test, engines were operated at constant speed of 1500 rpm as per the loading cycle prescribed by IS 10000:1980 (Table I) for constant speed engines.[22] Duration of each loading cycle was 16 h and each engine was subjected to 32 cycles during this test. Specified load on engine was monitored by measuring current and voltage output of the generator couples with the engine. After the execution of each 16 h cycle, necessary servicing and maintenance of both engines were done. Fuel injection pressure was kept fixed at 200 bars for both the engines as recommended by the manufacturer. Wear of various engine components was compared by measuring dimensions of cylinder liner, piston diameter, piston rings, bearings, connecting rods big and small end bore, etc., at the beginning and end of the 512 h long endurance test as specified in IS 10000:1980.[22] At the beginning of the endurance test, fresh lubricating oil was added to the engine sump and lubricating oil samples were drawn after every 128 h for comparing effect of 10% Karanja oil blending on lubricating oil degradation.

III. RESULTS AND DISCUSSIONS

Effect of K10 on the engine durability upon long-term usage is investigated by comparing its effect on carbon deposits, dimensional loss of important engine components, and lubricating oil degradation *vis-a-vis* mineral diesel. Carbon deposits and dimensional loss of the two engines were compared after 512 h endurance test and lubricating oil degradation was analysed by drawing lubricating oil samples at the interval of 128 h.

A. Carbon deposits and piston rating

Figure 1 shows the carbon deposits on the piston top, fuel injectors, and cylinder head of mineral diesel and K10 fueled engines after the endurance test. Both the engines completed 512 h of operation successfully and replacement/cleaning of injector tip was not required during the test for any of the engines. Erosion marks were noticed on the piston top of K10 fueled engine. Carbon deposits on the piston top of K10 fueled engine were seen to be higher as compared to mineral diesel fueled engine.

After completion of the endurance test, piston deposits of K10 fueled piston and mineral diesel fueled piston were analyzed separately according to Piston Rating IP/247/69 procedure.[23] Ring sticking was not observed in any of the engines.

Rating of diesel and K10 fueled engine piston's skirt was 8.28 and 7.745 merit points, respectively, on a scale of 10. This suggests that lubricating oil varnishing of K10 fueled piston skirt's cleanliness is comparable to mineral diesel fueled engine. Piston ring groove's carbon fillings are comparable for K10 and diesel fueled engines. Top ring groove of the diesel and K10 fueled engine was divided into ten sectors using a transparent grid. Results of carbon filling of top ring grooves the merit rating of the three ring lands (I, II, and III) carbon filling are shown in Table II. The inner walls of the piston, excluding under-crown area were rated as underskirt. Underskirt of the K10 fueled engine shows lower rating as compared to mineral diesel fueled engine (Table II). All these consolidated results in Table II suggest relatively inferior engine performance of K10 compared to mineral diesel.

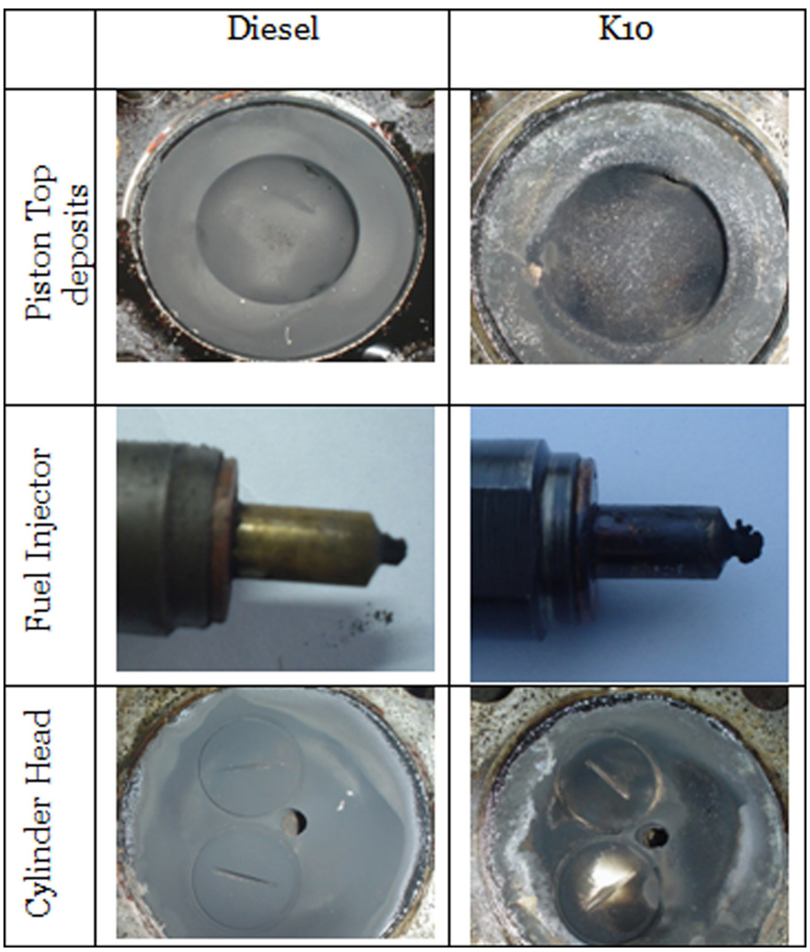


FIG. 1. Carbon deposits on piston top, injector and cylinder head after the endurance test.

TABLE II. Summary of rating at various areas on the piston surface.

Parameters rated	Diesel fueled engine	K10 fueled engine
Skirt	8.28	7.745
Ring groove (Overall)	(1) 1.37	(1) 0.00
	(2) 2.99	(2) 0.00
	(3) 6.83	(3) 0.24
	(4) 7.80	(4) 7.615
Top groove carbon filling %	55	74.12
Ring land	(1) 4.55	(1) 6.54
	(2) 7.45	(2) 5.76
	(3) 6.85	(3) 5.00
Under crown	10	9.00
Under skirt	10	5.8

After completion of the long-term endurance test, carbon deposits present on the top of the pistons was scraped carefully, collected, and weighed for the sake of comparison (Figure 2). K10 fueled engine showed relatively higher amount of carbon deposits on the piston top compared to mineral diesel fueled engine, however, it was not an order of magnitude higher as reported in the open literature.[20]

B. Physical wear measurements of vital parts

For comparison of the effect of 10% Karanja oil addition to mineral diesel on the engine wear, one engine was operated on mineral diesel and the other on K10 for 512 h in identical ambient conditions as well as engine identical loading cycles. The only variation in the engine operation was that the engines were operated using different fuels so that the effect of each fuel on the life of engine components could be compared directly. The dimensions of various vital engine components and physical condition were recorded before starting the endurance test and after the completion of endurance test according to Indian standard code: IS 10000.[22] The difference in the dimensions indicates the wear of these components in 512 h of engine operation. Comparison of wear of vital engine components for the two fuels is summarized in Table III.

Results given in Table III show that except the liner and big end bearing, wear of all other components is lower in K10 fueled engine compared to mineral diesel fueled engine. Addition of viscous, high density vegetable oil to mineral diesel increases the density of the blended fuel

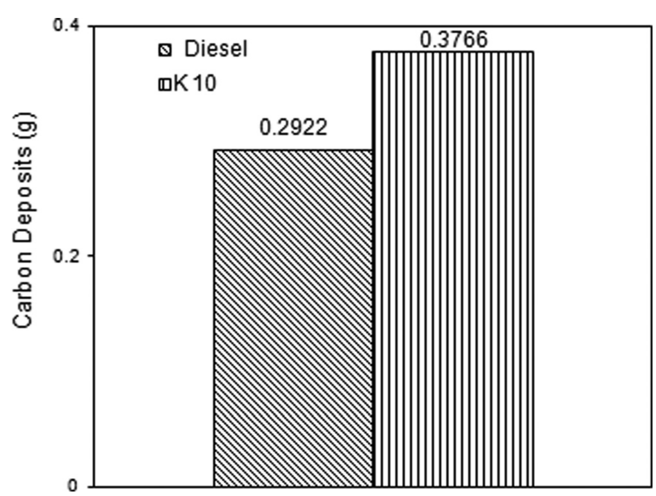
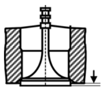
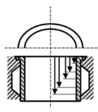
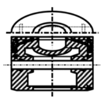
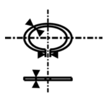
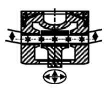
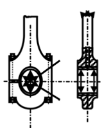
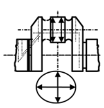


FIG. 2. Carbon deposits on the piston top after the endurance test.

TABLE III. Comparison of wear of K10 fueled engine with mineral diesel fueled engine after the endurance test.

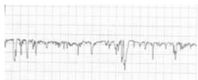
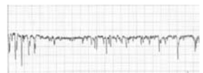
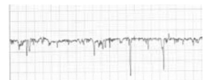
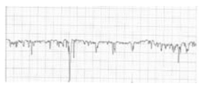
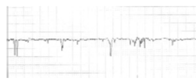
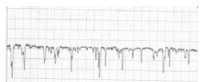
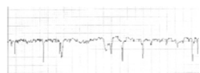
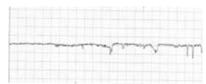
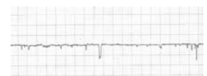
Component	% difference in wear of components from K10 fueled engine w.r.t. mineral diesel fueled engine (D: Lower; IN: Higher)
 Distance of valve head from mounting flange face	66.66 (D)
 Measurement of cylinder bore/ liner	17 (IN)
 Measurement of diameter of the piston	82 (D)
 Measurement of piston rings	33 (D)
 Measurement of gudgeon pin, pin bore, small end bush of connecting rod	22 (D)
 Measurement of big end bearing	112 (IN)
 Measurement of crank pin	79.4 (D)

while reducing its volatility. These property changes lead to increased spray penetration length and part of the fuel spray jet, possibly impinges on the combustion chamber walls, washing away the lubricating oil film present on the liner. The impinging fuel spray gets mixed with the lubricating oil present on the liner wall, and during piston's downward movement, this vegetable oil mixed lubricating oil reaches lubricating oil sump. This hypothesis can be confirmed by tests for verifying the fuel dilution of the lubricating oil. Lubricating oil forms a protective layer between the cylinder liner and piston ring interface, and change in its composition affects the cylinder lubrication mechanism directly, leading to increased wear of the liner. Hence, Table III above reflects mixed wear results with the wear of some components of K10 fueled engine higher than mineral diesel, however a large number of components show relatively lower wear.

C. Surface roughness for estimation of wear of liner

For estimating the wear of cylinder liner during the endurance test, surface profiles of the liner were measured before and after 512 h of engine operation at top dead center (TDC), mid stroke, and bottom dead center (BDC) using surface roughness profilometer (Mitutoyo, SJ 301). New liners were installed in the mineral diesel and K10 fueled engines before starting the

TABLE IV. Comparison of liner roughness profiles of K10 fueled engine with mineral diesel fueled engine.

	Diesel initial	Diesel 512 h	K 10 initial	K10 512 h
TDC				
MiD-Stroke				
BDC				

endurance test. Liner wear is caused by high in-cylinder pressure and high temperature gases, abrasive action of soot and dust particles, poor lubrication due to breakdown of the oil film between piston ring-liner interface, etc. Scuffing and abrasion take place due to three body dynamics of liner, piston rings, and soot particles.[20,24] Table IV shows comparative wear at anti-thrust side for diesel and K10 fueled engine liner at TDC, mid-stroke, and BDC positions. Differences in the initial roughness profiles and final roughness profiles after endurance test indicate extent of liner wear at these locations. From these roughness profiles, it can be observed that the wear of K10 fueled engine's liner is higher than the mineral diesel fueled engine's liner at all locations.

D. Effect of SVO on lubricating oil

Assessment of the effect of new fuel (K10) on tribological properties and residual useful life of lubricating oil upon long-term usage is extremely important. Density, viscosity, flash point, ash content, carbon residue, wear metal debris, cross linked polymer (insoluble), etc., are compared for the lubricating oil samples drawn from mineral diesel fueled and K10 fueled engines. The results are reported in the following sub-sections for comparison of lubricating oil degradation during the endurance test.

1. Density

The density of lubricating oil drawn from mineral diesel and K10 fueled engines increases with use (Fig. 3). Density of the lubricating oil increases mainly due to wear debris addition, chemical changes in the lubricating oil due to fuel dilution, and addition of moisture in the lubricating oil. Faster rate of change of density of K10 fueled engine indicates the possibility of higher wear rate and chemical degradation of lubricating oil in comparison to mineral diesel fueled engine, which needs to be verified by further testing and analysis of lubricating oil. Density of lubricating oil of mineral diesel fueled engine decreased after 384 h of engine operation possibly because rate of chemical change due to heating, and moisture addition is slower than lubricating oil's fuel dilution however in K10 fueled engine, changed in chemical properties are seen to be dominant upto 512 hours.

2. Viscosity

Viscosity of lubricating oil should be in acceptable limit for the entire life of lubricating oil because it affects the lubrication efficiency, engine efficiency, and engine durability. Inadequate oil viscosity affects interface oil film thickness, film formation, and load bearing capacity of the engine components leading to excessive wear of bearings and other components, low oil pressures, and finally poor oil economy and reduced engine durability. There are two main contributing factors responsible for the viscosity changes affecting the lubricating oil in mutually opposite directions. The viscosity of lubricating oil increases due to the formation of

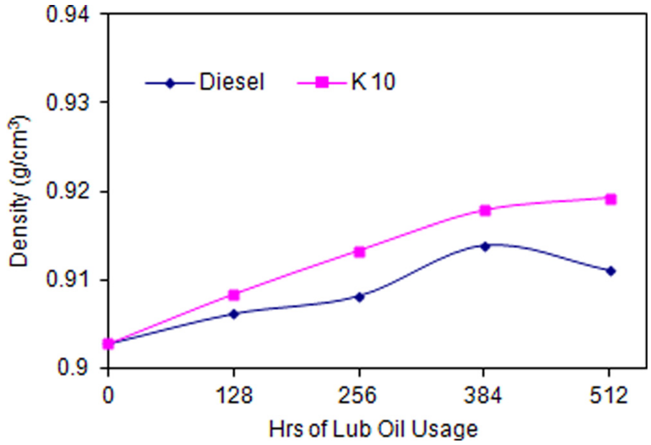


FIG. 3. Density of the lubricating oils during the endurance test.

resinous products due to oil's base-stock oxidation, evaporation of lighter fractions, depletion of anti-wear additives, and contamination by insoluble, while fuel dilution, moisture addition, and shearing of viscosity index improver additives tend to decrease its viscosity. The extent of dominance of these factors differ from system to system. Therefore, the net result can be in either direction. Hence, the viscosity of lubricating oil may either increase or decrease with usage.[20]

In the present case, an important observation is that the extent of lowering of viscosity of the lubricating oil is higher in case of K10 fueled engine compared to mineral diesel-fueled engine. This could be because of higher fuel dilution and oxidation of lubricating oil due to the presence of Karanja oil. Increased piston ring wear causes increased ring-liner clearance, hence higher fuel dilution. From Figures 4 and 5, it is amply clear that the fuel dilution is dominant for diesel fueled engines, whereas K10 fueled engine's lubricating oil also demonstrates higher extent of oxidation. Flash point test verify that the fuel dilution is higher in lubricating oil samples drawn from K10 fueled engine.

3. Flash point

Variation of flash point of lubricating oil for mineral diesel and K10 fueled engines is presented in Figure 6. Lowering of flash point of lubricating oil is an indicator of extent of fuel dilution. Fuel dilution of lubricating oil is undesirable because water and acids (such as sulfuric acid and free fatty acid (FFA)) often accompany fuel and these are responsible for lubricating

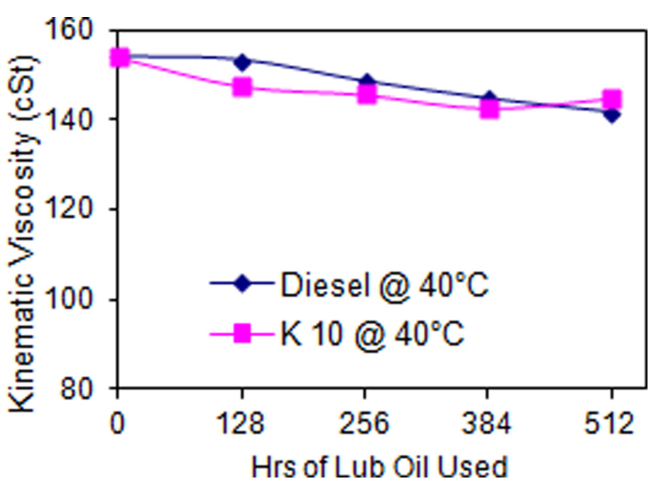


FIG. 4. Viscosity of the lubricating oils at 40 °C during the endurance test.

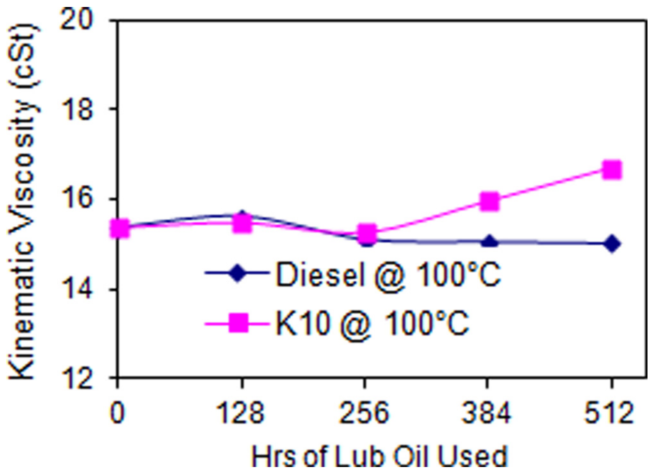


FIG. 5. Viscosity of the lubricating oils at 100 °C during the endurance test.

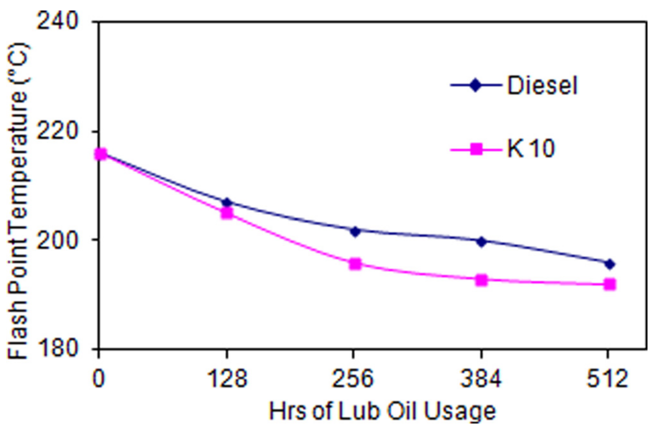


FIG. 6. Flash point of the lubricating oils during the endurance test.

oil degradation. The flash point of oils from both engine systems decreases with usage. However, the extent of reduction was higher for K10 fueled engine suggesting that the fuel dilution was possibly higher for this engine, verifying the observations made during viscosity tests.

4. Ash content

It is measured according to ASTM D482. Ash is the non-combustible part of the fuel/lubricating oil. It can be present as either solid or oil/water-soluble metallic compounds. These solid particles are often designated as sediments. Approximately 5 g of lubricating oil sample in a silica crucible is kept in the muffle furnace at 450 °C for 4 h and then 650 °C for 2 h and allowed to burn until only ash remains as final residue. This ash is cooled and weighed. The ash content of the lubricating oils from diesel and K10 fueled engines is shown in Figure 7.

The results suggest that the ash content is slightly higher in the lubricating oil samples drawn from diesel fueled engine. Since both the engines are operating under identical ambient conditions, the effect due to atmospheric dust will be essentially identical. Therefore, any difference in the ash content will be essentially due to difference in the wear of the engine components. These results (Figure 7) suggest that the wear of vital components in vegetable oil fueled engine is expected to be relatively lower than the mineral diesel fueled engine. These results can be further validated by physical wear measurements as well AAS tests conducted on the ash from the lubricating oil samples.

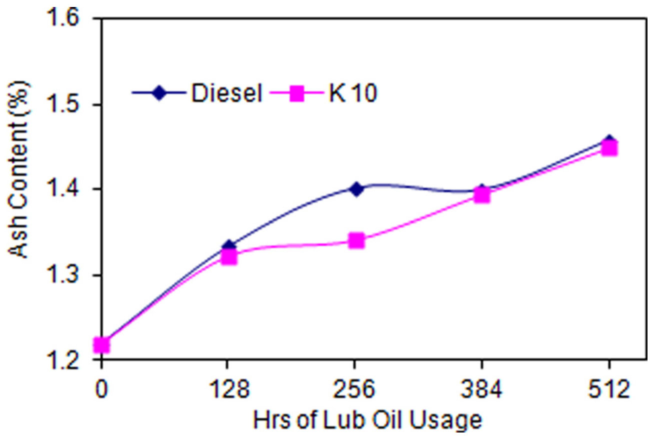


FIG. 7. Ash content of the lubricating oils during the endurance test.

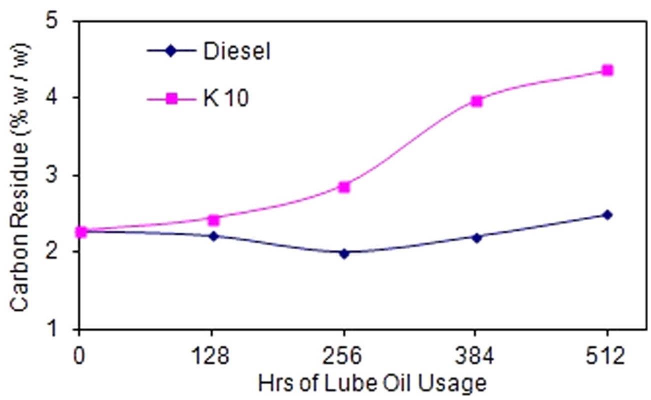


FIG. 8. Carbon residue of the lubricating oils during the endurance test.

5. Carbon residue

Carbon residue of all the lubricating oil samples was measured according to ASTM D189 by placing a weighed sample in a silica crucible in the furnace. Temperature of the furnace was maintained at 500 °C for 30 min under inert (nitrogen) atmosphere and then remaining residue was weighed. The carbon residue of the lubricating oils from the two engines is shown in Figure 8. The figure suggests that the K10 fueled engine shows relatively higher carbon residue compared to mineral diesel fueled engine. Carbon residue of fuels is higher than lubricating oil therefore this indicates towards possibly of higher fuel dilution for K10 fueled engine.

6. Atomic absorption spectroscopy

Concentration of wear metals present in the lubricating oil can be used as an indicator of wear of components containing those particular metals.[25] Trace concentrations of iron, aluminum, zinc, chromium, and lead in the lubricating oil samples drawn from both the engines were measured using atomic absorption spectroscopy technique (Figure 9).

Iron: Sources of iron in the lubricating oil are wear debris from cylinder liner, piston, rings, valves, gears, shafts, bearings, rust, and crankshaft.[26] It can be seen that wear of iron components in K10 fueled engine is relatively lower than mineral diesel fueled engine indicating possibly lower wear of iron containing components of K10 fueled engine.

Zinc: The zinc in the lubricating oil could be because of additive depletion, wear of bearings, brass components, and neoprene seals.[26] Zinc concentration in lubricating oil is found to be marginally lower for K10 fueled engine relative to mineral diesel fueled engine. Initial Zn

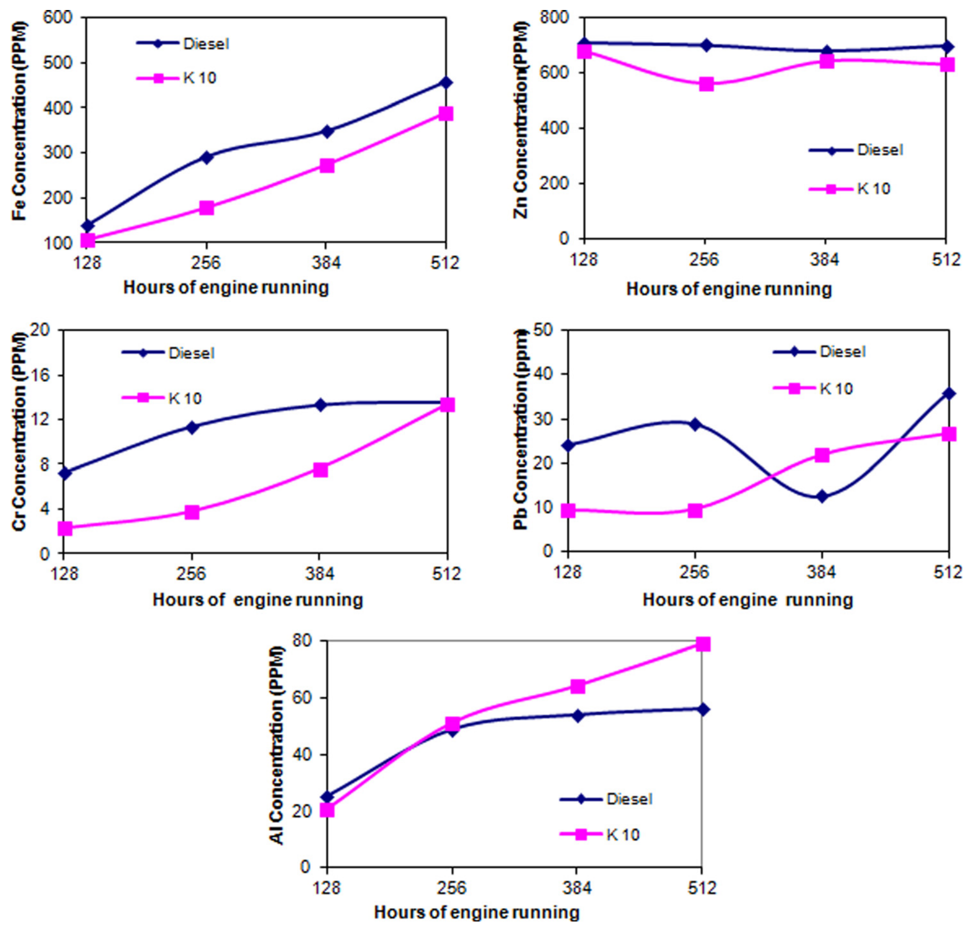


FIG. 9. Concentration of various trace metals in the lubricating oils during the endurance test.

concentration in the lubricating oil is significant in all the samples and it remains largely constant with time.

Chromium: Chromium in the lubricating oil could be because of wear of cylinder liner, compression rings, gears, crankshaft, and bearings.[26,27] Chromium concentration is quite small for the two fuels, however, the K10 fueled engine demonstrated lower increase in the chromium concentration in the lubricating oil. Hence, it can be inferred that the performance of K10 with respect to chromium debris addition in lubricating oil is relatively satisfactory.

Lead: The lead in the lubricating oil could be because of wear of bearings, paints, and grease addition.[25] Lead wear debris in the lubricating oil of K10 fueled engines are comparatively lower than lubricating oil from mineral diesel fueled engine. The Pb concentration is abnormally lower at 384 h. This might be possible because of some experimental errors, which might have occurred due to inhomogeneous nature of the lubricating oil.

Aluminum: Aluminum in the lubricating oil could be because of wear of piston, bearings, dirt, additives, and thrust washers.[26–28] Aluminum concentration in the lubricating oil of K10 fueled engine's lubricating oil is marginally higher than lubricating oil from mineral diesel fueled engine. This indicates that the wear of aluminum containing components is enhanced by the addition of 10% Karanja oil to the mineral diesel.

7. Copper corrosion test

Copper strip corrosion test of lubricating oil samples collected after every 128 h from mineral diesel and K10 fueled engines was performed to check corrosiveness of lubricating oil to

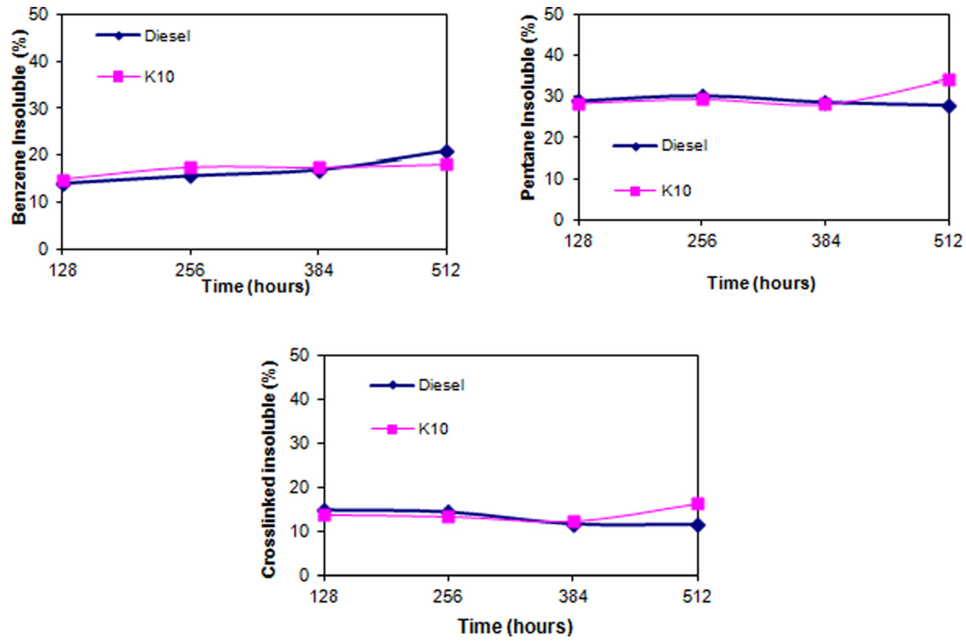


FIG. 10. (a) Benzene insoluble, (b) pentane insoluble, (c) cross-linked insoluble of the lubricating oils during the endurance test.

copper containing engine components using copper corrosion bath (Stanhope Seta, Setavis 11300) which conforms to ASTM D130. Fresh lubricating oil matches grade 1a standard, which is light orange, almost similar to freshly polished copper strip. Copper corrosiveness of all the lubricating oils is also grade 1a. Hence, it can be concluded that K10 doesn't cause any extra damage to the copper containing components of the engine.

8. Pentane and benzene insoluble

Insoluble content of the lubricating oil samples was measured according to ASTM D893. 10 g of used lubricating oil sample was dissolved in pentane and solution was centrifuged by maintaining centrifugal force between 600 and 700 RCF. After centrifuging, the solution is decanted and precipitate is dried and weighed. For estimating benzene insoluble, precipitate obtained after decanting pentane solution is dissolved first in alcohol followed by benzene and then centrifuged. This soluble material is decanted and remaining precipitate is dried and weighed. Measurement of insoluble assists in evaluating the performance characteristics of used lubricating oil and in determining the probable cause of equipment failure.[29] Higher difference between the pentane and benzene insoluble indicates higher extent of lubricating oil oxidation and polymerization of lubricating oil base-stock (Figure 10(c)).

Up to 256 h of lubricating oil usage, the cross-linked polymer formation in K10 fueled engine's lubricating oil is lower than mineral diesel fueled engine. Amount of benzene insoluble in K10 fueled engine is higher than mineral diesel fueled engine up to 384 h, however, after 512 h, benzene insoluble in mineral diesel fueled engine is higher. Pentane insoluble in the lubricating oil drawn from mineral diesel fueled engine remains almost constant with usage. After 512 h of engine operation, pentane insoluble in K10 fueled engine becomes higher than mineral diesel fueled engine. These observations suggest that even smaller concentration of vegetable oil in the fuel accelerates the oxidation/polymerization of lubricating oil base-stock; therefore, there is a need to develop specialty additive package/lubricants for Karanja oil utilization in DICI engines.

IV. CONCLUSIONS

In the long-term endurance test, the effect of use of 10% Karanja oil blend on wear of various engine components and lubricating oil properties *vis-à-vis* baseline mineral diesel was evaluated. The carbon deposits on the vital engine components were found to be slightly higher for K10 fueled engine and the traces of corrosion on piston and cylinder head were also noticed. Physical wear measurement of vital engine components indicates relatively higher wear of cylinder liner and big end bearings for K10 fueled engine whereas wear of piston rings, valve mountings, piston, gudgeon pin, and crank pin was found to be relatively lower. The piston rating indicates that the performance of K10 fueled engine was relatively slightly inferior to mineral diesel fueled engine. Viscosity, density, and ash content of the lubricating oil of K10 fueled engine were comparable to mineral diesel fueled engine throughout the endurance test. Carbon residue was, however, found to be slightly higher for K10 fueled engine. K10 was found to be as good as mineral diesel in terms of copper corrosion behavior. Fe, Pb, Cr, and Zn trace metals in the lubricating oil were found to be lower than mineral diesel for K10, however, Al content in the lubricating oil was slightly higher than mineral diesel.

Based on these comprehensive investigations, it can be concluded that K10 can be safely used as partial substitute of mineral diesel in DICI engines without any major engine modification; however, suitable changes in lubricating oil composition are required to offset some of the observations made in this investigation.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Technology Systems Group of the Department of Science and Technology, Government of India for their generous funding support to carry out this study.

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