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Effect of Biodiesel Utilization of Wear of Vital Parts in Compression Ignition Engine

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The combustion related properties of vegetable oils are somewhat similar to diesel oil. Neat vegetable oils or their blends with diesel, however, pose various long-term problems in compression ignition engines, e.g., poor atomization characteristics, ring-sticking, injector coking, injector deposits, injector pump failure, and lube oil dilution by crank-case polymerization. These undesirable features of vegetable oils are because of their inherent properties like high viscosity, low volatility, and polyunsaturated character. Linseed oil methyl ester (LOME) was prepared using methanol for long-term engine operations. The physical and combustion-related properties of the fuels thus developed were found to be closer to that of the diesel oil. A blend of 20 percent was selected as optimum biodiesel blend. Two similar new engines were completely disassembled and subjected to dimensioning of various vital moving parts and then subjected to long-term endurance tests on 20 percent biodiesel blend and diesel oil, respectively. After completion of the test, both the engines were again disassembled for physical inspection and wear measurement of various vital parts. The physical wear of various vital parts, injector coking, carbon deposits on piston, and ring sticking were found to be substantially lower in case of 20 percent biodiesel-fuelled engine. The lubricating oil samples drawn from both engines were subjected to atomic absorption spectroscopy for measurement of various wear metal traces present. AAS tests confirmed substantially lower wear and thus improved life for biodiesel operated engines. [DOI: 10.1115/1.1454114]

Introduction

The world is presently confronted with the twin crises of fossil fuel depletion and environmental degradation. Indiscriminate extraction and lavish consumption of fossil fuels have led to reduction in underground carbon-based resources. The need to exploit bio-origin-based alternative fuels to quench the world's energy thirst has long been realized. By now, it has been conclusively realized that internal combustion engines form an indispensable part of modern life style. They play a vital role in transportation and modern mechanized agricultural sector. Ever since the advent of the IC engines, vegetable oils have been tried as an alternative to the diesel fuel. The inventor of the diesel engine, Rudolf Diesel, in 1885, used peanut oil as a diesel fuel for demonstration at the 1900 world exhibition in Paris. Speaking to the Engineering Society of St. Louis, Missouri, in 1912, Diesel said, ''The use of vegetable oils for engine fuels may seem insignificant today, but such oils may become in course of time as important as petroleum and the coal tar products of the present times.'' The same petroleum-based fuel used in Diesel's days is still the fuel of choice in modern motorized society ([1]).

It is only in recent years that systematic efforts have been made to utilize vegetable oils as fuels in engines. A review of literature shows that European countries and the U.S.A. have mainly concentrated on saffola, sunflower, peanut oils, etc. as alternative fuels for diesel engines, which are essentially edible in nature. But, in the Indian context, only nonedible vegetable oils can be seriously considered as a fuel for CI engines as the edible oils are in great demand and are far too expensive at present. Moreover, there is a vast forest resource from which oil can be derived and formulated to give combustion-related properties close to that of diesel oil. Broadly speaking, due to the wide variations in climate, soil conditions, and competing use of land, different nations and researchers look upon different vegetable oils, which are locally available, as potential fuels. For example, Malaysia is pursuing research and development programmes on the use of palm oil and its derivatives as fuels for engines. There is no doubt that the production of oil seeds can be stepped up once they are being adopted for regular use in diesel engines. Considering the huge rates of consumption of petroleum fuels at present, it is clear that vegetable oils can, at best, provide only a partial replacement ([2]).

Kaltschmitt et al. conducted a study, which shows that bioenergy carriers offer some clear ecological advantages over fossil fuels such as conserving fossil energy resources or reducing the green house effect ([3]). Therefore, the process of utilizing biodiesel in the IC engines for transport as well as other applications, is gaining momentum. The international energy agency has recognized biodiesel as an alternative fuel for the transportation sector. The European Commission proposed a 12 percent market share for biofuels by the year 2020 ([4]).

The combustion-related properties of vegetable oils are somewhat similar to diesel oil. Neat vegetable oils or their blends with diesel pose various long-term problems in compression ignition engines, e.g., poor atomization characteristics, ring-sticking, injector-coking, injector deposits, injector pump failure, and lube oil dilution by crank-case polymerization. Such problems are not usually experienced with short-term engine operations. Sometimes the engine fails catastrophically, if run on neat vegetable oils continuously for a longer period. The properties of vegetable oils, responsible for these problems are high viscosity, low volatility, and polyunsaturated character ([5,6]).

In the majority of short-term tests employing vegetable oil as the fuel, peak power outputs ranged from 91 percent to 109 percent of those when equivalent engines were operated with mineral diesel fuel. The thermal efficiencies of the engines were generally

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reported to improve with vegetable oils. However, due to its lower energy content, vegetable oil consumption was higher than that of mineral diesel fuel ([7]). Hemmerlein et al. established that all of the engines run on rapeseed oil passed the ECE R49 regulation relating to CO, HC, NO_x, and soot emissions in the 13-mode test. However, some measured emissions increased while others decreased when rapeseed oil was used as a substitute for diesel fuel. Further, higher emissions levels resulted from combustion of rapeseed oil in direct injection (DI) and small-cylinder indirect injection (IDI) engines than combustion in larger-cylinder IDI engines. Emissions of CO and HC increased by up to 100 percent and 290 percent, respectively, compared with those for diesel fuel, but it is likely that these levels could be reduced if the injector timing is advanced. Emissions of NO_x were up to 25 percent lower, due to slower combustion and low maximum combustion temperatures resulting from the use of rapeseed oil. Generally, soot and particulate emissions were also reduced by up to 0.4 Bosch number and 50 percent, respectively, although particulate emissions were up to 140 percent higher, when combustion occurred in DI engines. The emissions of aromatics, aldehydes, ketones, and particulate matter were higher when rapeseed oil was used. PAH emissions were reduced in larger cylinder IDI engines and increased in other engine types ([8]). Freedman et al. experimentally evaluated CNs of vegetable oils and their derivatives by using constant volume combustion bomb ([9]). They also evaluated heat of combustion of various triglycerides, and attempted to find out the relationship between their heats of combustion and molecular properties of vegetable oils ([10]).

The process of transesterification yields vegetable oil esters. Vegetable oil esters have better fuel properties compared to neat vegetable oils. Their viscosity reduces, volatility increases, and they lose their polyunsaturated character after transesterification. The stoichiometry of the overall transesterification reaction requires 1 mole of triglyceride for 3 moles of glycerol. This is a reversible reaction, either acid or alkali catalyzed, and involves stepwise conversions of triglycerides to diglycerides to monoglycerides to glycerol producing 3 moles of ester in the process ([11]). Alkaline catalysts have the advantage of being less corrosive to industrial equipment than acid catalysts. Transesterification process breaks the triglycerides present in vegetable oils into two components, fatty acid esters, and glycerol. Glycerine is a valuable by-product, which is used in pharmaceuticals, cosmetics, toothpaste, and many other commercial products. Biodiesel is often blended with petroleum diesel to offset its high production cost ([12,13]). Pure 100 percent ''neat'' methyl esters of rapeseed, soybean, sunflower, tallow, and other fats and oils can be used as diesel fuel with little or no modifications of the engine. According to Alan Weber, ''Many fleets, however, utilize biodiesel blends called B20, which is a mixture of 20 percent biodiesel and 80 percent petroleum diesel'' ([1,14]).

System Selection

As far as the application in rural agricultural sector of a developing country like India is concerned, internal combustion engines should preferably utilize alternative fuels of bio-origin, which are locally available. The present work is carried out using a typical vegetable oil by formulating its properties and bringing them closer to the conventional diesel. System design approach has taken care to see that these modified fuels can be utilized in existing diesel engines without any substantial hardware modifications. India is producing around 6.7 million tons of nonedible oils such as, linseed, castor, karanji (*Pongamia glabra*), neem (*Azadirachta indica*), palash (*Butea monosperma*), and kusum (*Schlelchera trijuga*). Some of these oils produced even now are not being properly utilized, and it has been estimated that some other plant-based forest derived oils have a much higher production potential. From among the large number of vegetable oils produced in the country, linseed oil was chosen for the present investigation because India has the largest acreage under linseed cultivation, and it is the fourth largest producer of linseed oil in the world ([6,15]). The process of transesterification was selected to prepare suitable fuels for long-term engine operation. The molecular structure of the fatty acid molecules present in the vegetable oil gets modified by way of transesterification. For the present work, linseed oil methyl ester was prepared using methanol in the presence of potassium hydroxide as catalyst, and then separating by-product glycerol formed in the esterification reaction. The use of linseed oil methyl ester (LOME) in compression ignition engines was found to develop a very compatible engine-fuel system with low emission characteristics. The physical and combustion related properties of the fuels thus developed by the process of esterification were determined in the laboratory and most of them were found very close to that of diesel oil. Tests were conducted for determination of properties like density, viscosity, flash point, aniline point /cetane number, calorific value, etc. Some specific tests like infrared spectroscopy, carbon, hydrogen, nitrogen, oxygen analysis, and nuclear magnetic resonance spectroscopy were carried on biodiesel and linseed oil in order to study the effect of transesterification at molecular level.

The constant speed experimental test unit, manufactured by Perry & Co., India, is a compact, portable captive 4 kWh gen-set run by diesel fuel. It is widely used in the country mostly for agricultural purposes and in many small and medium scale commercial purposes. This is a single-cylinder four-stroke vertical water-cooled system that develops 4 kW power output in pure diesel mode. It has a provision of loading electrically, and is flexibly coupled with a single-phase alternator. Detailed specifications of the engines used in present investigations are given in Table 1.

The engine can be started by hand cranking. The engine is provided with a centrifugal speed governor. The inlet valve opens 4.5 deg BTDC and closes 35.5 deg ABDC. The exhaust valve opens 35.5 deg BBDC and closes 4.5 deg ATDC. The test engine is directly coupled to a 220 volts AC generator of sufficient capacity to absorb the maximum power produced by the engine.

Engine Tests

After developing the appropriate fuel, it was tested on the engine, first for its performance and emission characteristics and then through a series of other engine tests. In the long-term endurance test, the effect due to the use of biodiesel on various parts of the engine vis-à-vis diesel fuel was studied. For this purpose, two similar new engines were subjected to similar loading cycles and operating conditions. The assessment of wear of various parts of 20 percent biodiesel and diesel-fueled engines was done after dismantling the various parts of the engine. The various tests on the two-engine systems are conducted as per the procedure specified in IS10000, 1980 ([16]).

Preliminary Runs. The purpose of preliminary run for both the engines is that they should be made trouble free, by operating both the engines for their running-in period. Under the preliminary run, constant speed engines are subjected to a preliminary run of 49 hours at the rated speed under the operating temperature specified by the manufacturer, in nonstop cycles of seven hours each, conforming to the following cycle pattern. The engine loading cycle for the preliminary run is shown in Table 2.

During the preliminary run, attention was paid to engine vibration and quietness. Oil pressure was checked time to time.

Fuel Consumption Test. A fuel consumption test is essential for evaluating the fuel consumption pattern of an engine. This test was used to certify that both the engines are going to perform exactly similar, when subjected to the same fuel. When different fuels are used for running the similar engines under similar operating conditions, any marked difference in their performance is due to the characteristics of the fuel alone. This test was carried out only after the preliminary run, i.e., after stable operating conditions were achieved. The engines were subjected to similar loading conditions, starting from no load, observations were recorded

Table 1 Technical specifications of the test engine

Manufacturers	Perry Engines Ltd, India
Model	Single cylinder CI engine
Bore	87.5 mm
Stroke	110 mm
Displacement	661.7 cm^3
Length	531 mm
Width	356 mm
Height	546 mm
Weight	165 Kg
Rated speed	1500 rpm
Maximum speed	2000 rpm
Minimum speed	1200 rpm
Minimum idling speed	750 rpm
Nozzle pressure	200 bar
Compression ratio	17: 1

at 20 percent, 40 percent, 60 percent, 80 percent, 100 percent, and 110 percent of the rated load. During the fuel consumption test (loop test), observations were recorded after every 30 minutes and a graph was plotted for each engine. Further tests were undertaken, after ensuring that fuel consumption patterns observed were same within measurable accuracy for both the engines.

Performance and Emission Test: Selection of Optimum Blend. This test was carried out on one of the engines, which has already been subjected to preliminary run-in. The period of running in and the test cycles have already been discussed earlier. This test is aimed at optimizing the concentration of ester in the biodiesel blends. To achieve this, several blends of varying concentrations were prepared ranging from 0 percent (neat diesel oil) to 100 percent (neat biodiesel) through 5 percent, 10 percent, 15 percent, 20 percent, 25 percent, 30 percent, 40 percent, 50 percent, and 75 percent. These blends were then subjected to performance and emission tests on the engine. The performance data was then analyzed from the graphs recording power output, torque, specific fuel consumption, and smoke density, etc., for all the blends of biodiesel. The 20 percent biodiesel was found to be the optimum blend from the graphs based on maximum thermal efficiency and smoke opacity considerations ([5]).

Long-Term Endurance Test. After the completion of all these tests, both the engines were dismantled completely and examined physically for the conditions of the various critical parts before endurance test was commenced. After physical examination, the dimensions of various moving, vital 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 a suitable test beds and again run-in for 12 hours in the manner recommended by the manufacturer. This test was carried out to take care of any misalignments occurring during dismantling and re-assembling of the engine. This test included 11 hours of continuous run, at rated full load at the rated speed followed by one hour run at 10 percent overload. During the running-in period, none of the critical components listed above were replaced. The lubricating oil from the oil sump was drained off and the engines were refilled with SAE 30 grade of fresh lubricating oil as specified by the manufacturer and the engines were then ready for long-term endurance test.

Table 2 Loading cycle for preliminary runs of constant speed engine ([16])

Load (% of rated load)	Running time (Hours)
25	1.5
50	2
75	1.5
100	2

Table 3 Test cycle for long-term endurance test ([16])

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

Then both the engines were run for 32 cycles (each of 16 hours continuous running) at rated speed. The test cycle followed is specified in the Table 3.

The first engine was using 20 percent biodiesel blend, and the second engine was using neat diesel oil as fuel. At the end of each 16-hour cycle, both the engines were stopped and necessary servicing, and minor adjustments were carried out in accordance with the manufacturer's schedule, e.g., tappet settings, make up oil addition, etc. Before starting the next cycle, it was ensured that the temperature of the engine sump oil had reached within 5 K of the room temperature. The engines were then topped up with engine oil, if required and the quantity consumed recorded. The lubricating oil samples were collected from the engines after every 128 hours for conducting various tribological studies. In the entire range of engine operation spread over 512 hours, there was no major breakdown.

Comparison of Carbon Deposits. After completion of the long-term endurance test, the engines were completely disassembled and the deposit formations on cylinder head, piston top, and injector tip were investigated. The photographs for all these parts are shown in Figs. 1–6.

Figure 1 shows the carbon deposits on the cylinder head of the diesel-fueled engine and Fig. 2 shows carbon deposits on the cylinder head of the 20 percent biodiesel fueled engine. It can be clearly noticed that the deposits on the cylinder head of 20 percent biodiesel-fueled system are substantially lesser compared to the diesel-fueled system.

Figure 3 shows the carbon deposits on the piston-top of the diesel fueled system and Fig. 4 shows the carbon deposits on the piston top of 20 percent biodiesel-fueled engine. The pistons were weighed and the amount of carbon deposits formed was found

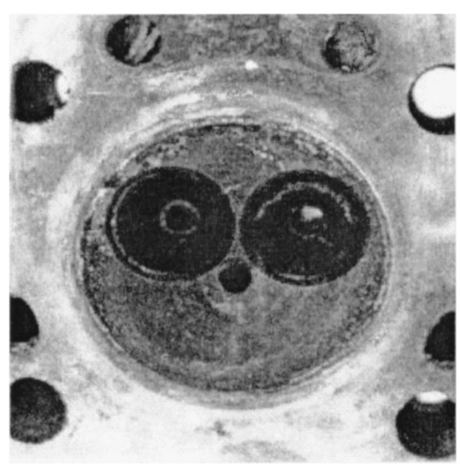


Fig. 1 Carbon deposits on cylinder head of diesel-fueled engine after 512 hours of engine operation

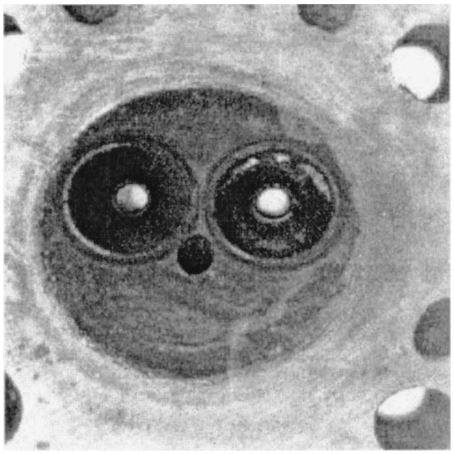


Fig. 2 Carbon deposits on cylinder head of 20 percent biodiesel-fueled engine after 512 hours of engine operation

out. The amount of carbon deposited on biodiesel system was found be to be about 40 percent lower compared to the diesel-fueled system. Figure 5 shows the injector tip of the diesel-fueled system after 200 hours of engine operation and Fig. 6 shows the injector tip of 20 percent biodiesel-fueled engine after 512 hours of engine operation. The carbonization of biodiesel injector after 512 hours of operation was far less than the diesel injector after 200 hours of engine operation. There were hardly any carbon deposits noticed on biodiesel fueled injector. This proved that the problem of carbon deposits and coking of injector tip have not only completely disappeared after the esterification of vegetable oils but also these have improved compared to conventional diesel fuel. Similar results were also noticed in the figures for deposits on piston ring grooves, intake and exhaust valves.

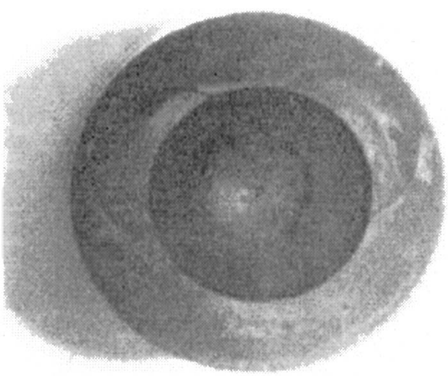


Fig. 3 Carbon deposits on piston top of diesel-fueled engine after 512 hours of engine operation

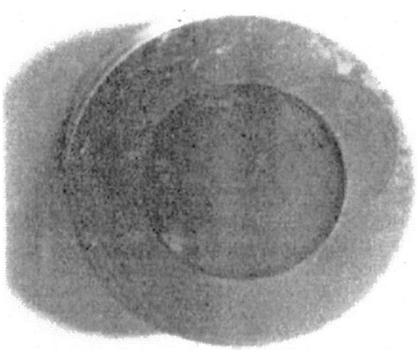


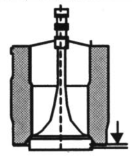
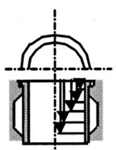
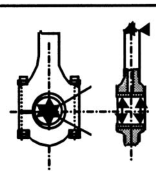
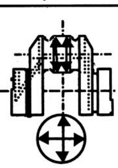
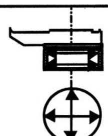
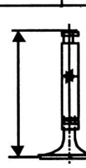
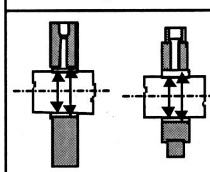
Fig. 4 Carbon deposits on piston top of 20 percent biodiesel-fueled engine after 512 hours of engine operation

Fig. 5 Carbon deposits on injector tip of diesel-fueled engine after 200 hours of engine operation

It is also observed that both diesel and biodiesel followed the same trend of cylinder pressure variation except that the 20 percent biodiesel-fueled engine showed a slightly lower peak cylinder pressure. This may be because of a bit slower rate of combustion of biodiesel fuel compared to diesel fuel. This slow rate of pressure rise leads to relatively smoother engine operation and also affects the wear of engine parts. It is noticed that with the increase in the load of the engine, the peak cylinder pressure increased. Addition of biodiesel decreases the reaction rate and mixture temperature at the end of compression, resulting in a drop in the overall flame temperature with a consequent decrease in flame speed. The addition of biodiesel plays an important role in reducing the maximum rate of pressure rise and peak pressure considerably. Combustion duration is almost similar for both the fuels.

Fig. 6 Carbon deposits on injector tip of 20 percent biodiesel-fueled engine after 512 hours of engine operation

Table 4 Comparative physical wear measurements of vital parts for 20 percent biodiesel-fueled engine via-à-vis diesel-fueled engine parts

Figure of the moving part	Dimensions	% lower wear for biodiesel
	Distance of valve head from mounting flange face	30
	Diameter of piston at position	33
	Measurements of cylinder bore/ cylinder liner	31
	Measurements for piston rings	34
	Measurements Of gudgeon pin, pin bore, and small end bush of connecting rod	40
	Measurements of connecting rod bearing bore	36
	Measurements of big end bearing (crank pin diameter	35
	Measurements of end float	25
	Measurements for inlet and exhaust valves	22
	Measurements of cam shaft bearings	28

Wear Measurement

Sliding contact between metallic components of any mechanical system is always accompanied by wear, which results in the generation of minute particles of metal. In diesel engines, the components normally subjected to wear process are the piston, piston rings, cylinder liner, bearings, crankshaft, cam, tappet, and valves. In a lubricated diesel engine system, wear particles are washed away by lubricating oil and remain in suspension in the lubricating oil. By analyzing and examining the variation in the concentration of the metallic particle in the lubricating oil after certain running duration, sufficient information about wear rate, source of wear metals, and engine conditions were predicted.

Physical Wear Measurement of Vital Parts. The wear of various moving parts took place due to 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 both the engines were operated using two different fuels so that the effect of new fuel on the life of engine hardware could be compared directly. This was thought to be an acid test to analyze the material compatibility of the newly developed fuels vis-à-vis diesel oil. The dimensions of the vital parts and physical condition were noted before the commencement of and after the completion of long-term endurance test. The difference of these two 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 measurements 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 biodiesel vis-à-vis diesel oil on the wear of the vital engine parts. Observations are summarized in the Table 4.

It is glaringly evident from the table that the wear of vital moving parts of the 20 percent biodiesel operated engine was substantially lower (of the order of about 30 percent lower) compared to the neat diesel operated engine. In small and midsized engines, part of the fuel spray jet impinges on combustion chamber walls, thus wetting the cylinder walls. The fuel thus gets mixed with the lubricating oil present on the liner wall. During the piston's reciprocating motion, this biodiesel dilutes lubricating oil and forms a layer between the cylinder liner and piston rings, thus affecting the cylinder lubrication mechanism directly. A series of experiments was planned to investigate this phenomenon through lubricating oils analysis from biodiesel and diesel operated engines.

Wear Debris Transport and Analysis. Oil used for lubrication of the IC engine picks up the wear debris of various metals depending on the origin. The quantitative evaluation of wear particles present in oil gives the magnitude of engine component deterioration and while qualitative analysis indicates its origin, i.e., wearing component. This ultimately provides adequate information about the components that are being deteriorated and the incipient failure of the machine.

A careful look at the literature reveals that the various contaminant metals present in lube oil might have various possible sources in the engines. Table 5 lists the typical sources of metallic elements in wear debris of the lubricating oil.

Ash Content. The lubricating oil samples were kept in the furnace at 450°C for 4 hours and then 600°C for 2 hours to produce ash. The residual ash contains the wear debris of metal primarily. The data on ash content in the lubricating oils for biodiesel and diesel-fueled compression engines have been presented graphically in Fig. 7. It was observed that the ash content for 20 percent biodiesel-operated engine oil was approximately 15 percent lower than that of diesel-operated engine oil.

The 20 percent biodiesel-operated engine has a lower amount

Table 5 Typical sources of metallic elements in wear debris ([14])

Element	Typical sources
Aluminum (Al)	Pistons, Bearings, Dirt, Additives, Turbo chargers
Antimony (Sb)	Greases, Bearings
Barium (Ba)	Additives, Water, Grease
Boron (B)	Coolant, Oil additives, Anti-freeze agents
Cadmium (Cd)	Bearings, Plating
Calcium (Ca)	Additives, Water, Greases
Chromium (Cr)	Compression rings, Coolant, Crankshaft, Gears, Bearings, Plating of cylinder liner
Cobalt (Co)	Bearings
Copper (cu)	Bearings, Bronze bushings
Indium (In)	Synthetic oils, Solder
Iron (Fe)	Cylinder liner, Piston, Rings, Valves, Valve guides, Gears, Shafts, Anti-friction bearings, Rust, Crankshaft.
Lead (Pb)	Bearings, Greases, and Paint
Magnesium (Mg)	Bearings, Additives, Supercharger, Gear box
Manganese (Mn)	Steel shafts, Valves
Molybdenum (Mo)	Additives, Piston rings
Nickel (Ni)	Shafts, Gears, Piston rings
Phosphorus (P)	Additives, Gears
Potassium (K)	Coolant, Additives
Silicon (Si)	Defoamants, Dirt, Lubricants
Silver (Ag)	Bearings
Sodium (Na)	Coolant, Additives
Tin (Sn)	Bearings, Solder
Titanium (Ti)	Springs, Valves
Vanadium (V)	Valves
Zinc (Zn)	Additives, Bearings, Plating, Brass components, Neoprene seals

of ash content in its lubricating oil. Hence, it is clear that biodiesel-fueled engine produced a lesser amount of wear debris thus indicating its better performance.

Atomic Absorption Spectroscopy. AAS works on the principle of absorption interaction, where atoms in the vapor-state absorb radiation at a certain wavelength that are well defined and show the characteristics of a particular atomic element. In this process, the source of radiation projects a beam of a specific wavelength through a pure flame (air-acetylene) on to a sensor and the amount of radiation arriving at the photo sensor is recorded. The fluid sample is introduced into the flame and vaporized. The amount of radiation arriving at the photo sensor is reduced in proportion to the quantity of the specific element present in the sample. The schematic diagram of AAS is shown in Fig. 8.

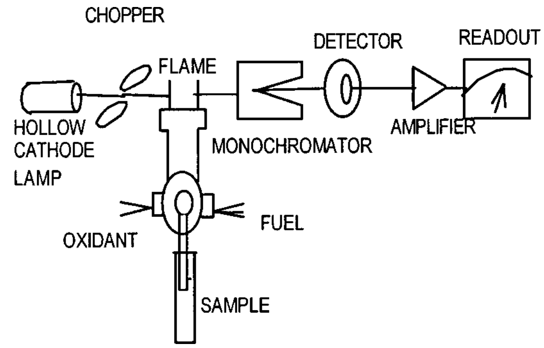


Fig. 8 Schematic diagram for atomic absorption spectroscopy

This technique can be used for quantitative and qualitative analysis of wear debris in lubricating oils. The data can be correlated with the extent in wear and hence, the performance characteristics of either lubricating oils or diagnosis of failure of moving components.

The procedure followed is explained in the following steps:

(a) Approximately 10 grams of oil sample was weighed in the silica crucible and burnt at 450°C for 4 hours and at 650°C for 2 hours.

(b) The ash was dissolved in concentrated HCl acid.

(c) The mixture was diluted with distilled water to make 100 ml solution (Acid: Water: 1:100)

(d) Standard solutions of various metals (concentrations ranging from 5 PPM to 20 PPM) were prepared.

This test of AAS was done to evaluate the concentration of various metals present in the lubricating oil samples from 20 percent biodiesel and diesel-fueled CI engines. This gave a fair idea about the wear of different parts, material compatibility of the new fuel with the existing engines. In the present study, since many sliding components were involved, it was anticipated that the wear debris originating from different metallic parts appeared in the lubricating oil. Hence, various elements such as Fe, Cu, Zn, Cr, Mg, Co, and Pb were analyzed by AAS and the results are shown in figures given below.

Iron. The iron in wear debris could be because of wear of the cylinder liner, piston, rings, valves, valve guides, gears, shafts, bearing, rust, and crankshaft. The results on concentration of iron as a function of oil usage are shown in Fig. 9. It is clearly seen that for both the systems, iron increased at a higher rate initially up to 128 hours followed by a slower increase. The most important observation was that lubricants from 20 percent biodiesel-fueled system indicated a lower increase in iron content and hence lesser wear, which is because of improved lubricating efficiency of biodiesel fuel.

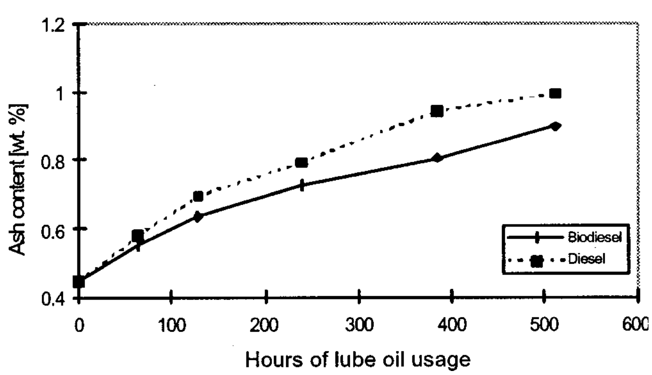


Fig. 7 Ash content versus hours of lube oil usage

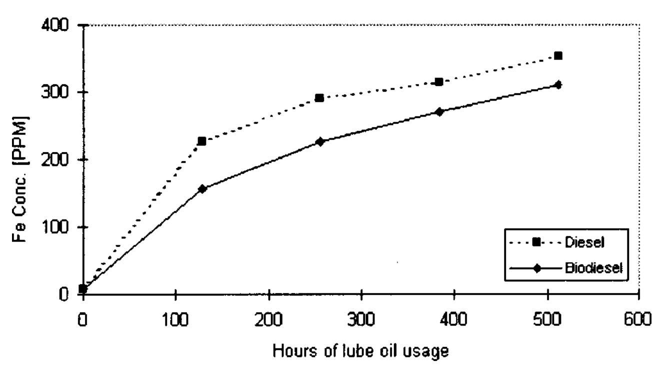


Fig. 9 Iron concentration as a function of lube oil usage

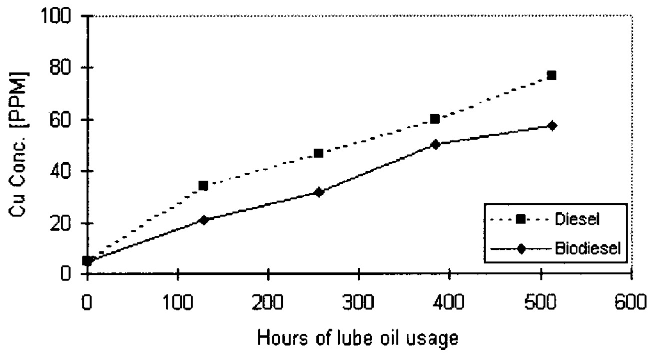


Fig. 10 Copper concentration as a function of lube oil usage

Copper. The copper in wear debris comes from wear of bearings, and bushings. The results on concentration of copper as a function of oil usage are shown in Fig. 10. It is evident that for both the systems, copper increases at a constant rate. An important observation is that lubricant from 20 percent biodiesel-fueled system indicates approximately 25 percent lower copper content and hence lower wear.

Zinc. The zinc in wear debris could be because of additive depletion, extra additives being added due to addition of make-up oil, wear of bearings, brass components, neoprene seals, etc. The results on concentration of zinc as a function of oil usage are shown in Fig. 11. It is observed that for both the systems, zinc increased at a slower rate initially followed by a faster increase in case of diesel-fueled system while the 20 percent biodiesel-fueled system showed steady wear of these components. The main zinc source in the engine is ZDDP, an additive in lubricating oil. An important observation is that lubricant from 20 percent biodiesel-fueled system indicated approximately 65 percent lower zinc content increases, hence lower wear of zinc containing components and lower lubricating oil consumption.

Chromium. The chromium in lubricating oil comes from wear of a cylinder liner, compression rings, gears, crankshaft, and bearings. The results on concentration of chromium as a function of oil usage are shown in Fig. 12. It is glaringly evident that for both the systems, chromium concentration shoots up beyond 128 hours in case of diesel-fueled system, while in the case of a 20 percent biodiesel-fueled system, it happened beyond 256 hours of engine operation. The lubricant from 20 percent biodiesel-fueled system indicated approximately 20 percent lower chromium content increase.

Magnesium. The magnesium in wear debris originates from additive depletion, wear of bearings, and gearbox housing. The results on concentration of magnesium as a function of oil usage are shown in Fig. 13. It can be noticed that for both the systems, magnesium concentration increased at a higher rate initially up to 128 hours followed by a slow increase. The lubricant from 20 percent biodiesel-fueled system indicated approximately 10 percent lower magnesium content increase.

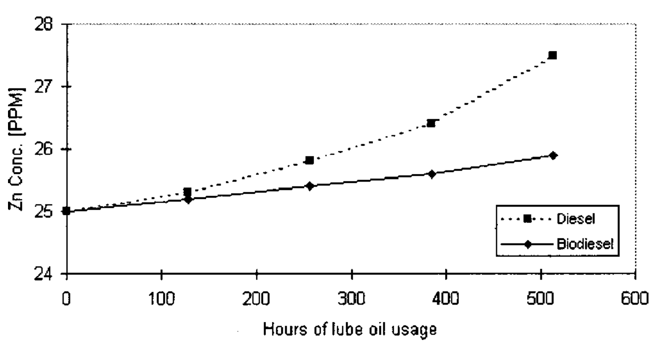


Fig. 11 Zinc concentration as a function of lube oil usage

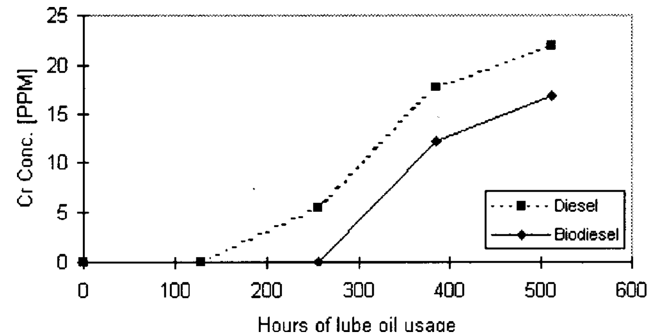


Fig. 12 Chromium concentration as a function of lube oil usage

Cobalt. The cobalt in wear debris originates from wear of bearings. The results on concentration of cobalt as a function of oil usage are shown in Fig. 14. It is seen that for both the systems, cobalt increased at a steady rate. Lubricant from 20 percent biodiesel-fueled system indicated approximately 40 percent lower increase in cobalt content compared to its diesel engine counterpart.

Lead. The lead in wear debris could be because of wear of bearings, paints, and grease addition. The concentration of lead as a function of oil usage is shown in Fig. 15. For both the systems, lead increased at a steady rate. Lubricant from the 20 percent

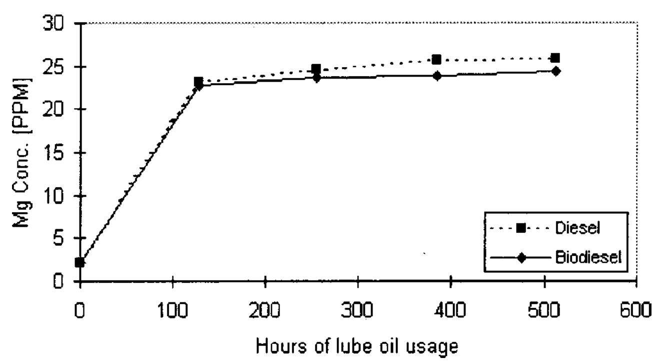


Fig. 13 Magnesium concentration as a function of lube oil usage

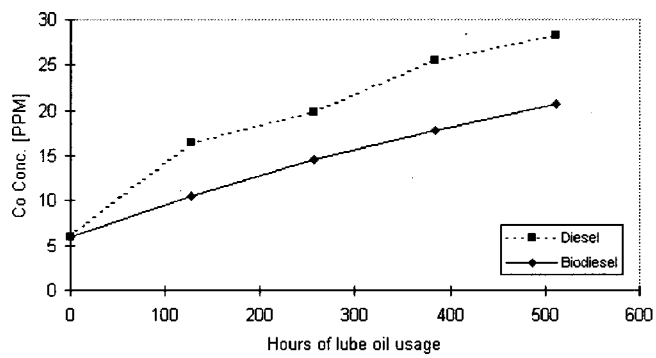


Fig. 14 Cobalt concentration as function of lube oil usage

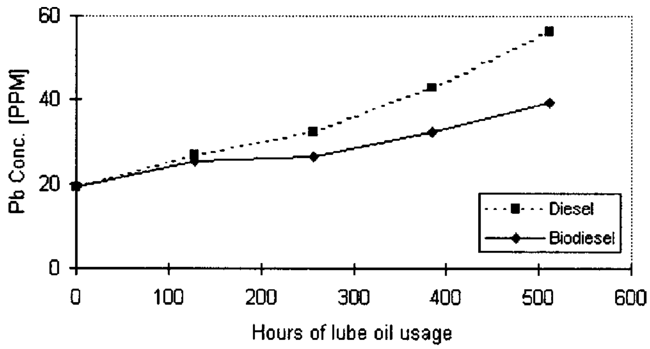


Fig. 15 Lead concentration as a function of lube oil usage

biodiesel-fueled system indicated approximately a 50 percent lower increase in lead content and hence lower wear of lead containing components.

All these observations suggested better additional lubricity properties of biodiesel fuel apart from fuel value, confirming the results of physical wear measurements.

Conclusions

A diesel engine can perform satisfactorily on biodiesel fuel without any engine hardware modifications. Esterification has been found to be an effective technique to prevent all long-term usage problems associated with utilization of vegetable oils such as fuel filter plugging, injector coking, formation of carbon deposits in the combustion chamber, ring sticking, and contamination of lubricating oils. The carbon deposits on piston top and injector coking substantially reduced in 20 percent biodiesel-fueled system.

The wear of various vital parts reduced up to 30 percent because of additional lubricity properties of biodiesel. These results of wear measurements by physical methods were also confirmed by atomic absorption spectroscopy. Oil analysis studies proved to be a powerful tool to estimate not only the condition of the engines, but of other moving parts as well. Moreover, these tests provided valuable and relevant information on the effect of fuel chemistry on the lubricating oil system. Ash content, which mainly represents wear debris, was found to be lesser in the case of a 20 percent biodiesel-fueled system. One of the most interesting studies conducted on the lube oils was for the estimation of individual wear of engine vital parts such as piston, piston rings, cylinder liner, etc. Atomic absorption spectroscopy studies on lube oils indicated that biodiesel fuel led to lesser wear of engine moving parts in terms of lesser amount of metallic debris (such as Fe, Cu, Zn, Mg, Cr, Pb, and Co) present in lube oil samples. Each element, which is present in oil in the form of wear debris, originated from a different moving part. Such an analysis strongly demonstrated that not only the performance characteristics but also wear characteristics of moving parts are better for a 20 percent biodiesel-fueled engine system.

Based on the studies presented, it is concluded that the fuels of bio-origin are superior in wear performance to conventional fuels, environment-friendly, biodegradable, and do not add to global warming problems. Biodiesel can be readily adopted as a substitute fuel to the existing diesel engines, which are widely used in the rural agricultural sector of the country.

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