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Wear Assessment in a Biodiesel Fueled Compression Ignition Engine

A. K. Agarwal
Department of Mechanical Engineering,
Indian Institute of Technology, Kanpur,
Kanpur 208016, India
e-mail: Akag@iitk.ac.in

J. Bijwe
ITTMEC,
Indian Institute of Technology, Delhi,
New Delhi 110016, India

L. M. Das
Centre for Energy Studies,
Indian Institute of Technology, Delhi,
New Delhi 110016, India

Biodiesel is prepared using linseed oil and methanol by the process of transesterification. Use of linseed oil methyl ester (LOME) in a compression ignition engine was found to develop a highly compatible engine-fuel system with low emission characteristics. Two similar engines were operated using optimum biodiesel blend and mineral diesel oil, respectively. These were subjected to long-term endurance tests. Lubricating oil samples drawn from both engines after a fixed interval were subjected to elemental analysis. Quantification of various metal debris concentrations was done by atomic absorption spectroscopy (AAS). Wear metals were found to be about 30% lower for a biodiesel-operated engine system. Lubricating oil samples were also subjected to ferrography indicating lower wear debris concentrations for a biodiesel-operated engine. The additional lubricating property of LOME present in the fuel resulted in lower wear and improved life of moving components in a biodiesel-fuelled engine. However, this needed experimental verification and quantification. A series of experiments were thus conducted to compare the lubricity of various concentrations of LOME in biodiesel blends. Long duration tests were conducted using reciprocating motion in an SRV optimol wear tester to evaluate the coefficient of friction, specific wear rates, etc. The extent of damage, coefficient of friction, and specific wear rates decreased with increase in the percentage of LOME in the biodiesel blend. Scanning electron microscopy was conducted on the surfaces exposed to wear. The disk and pin using 20% biodiesel blend as the lubricating oil showed lesser damage compared to the one subjected to diesel oil as the lubricating fluid, confirming additional lubricity of biodiesel. [DOI: 10.1115/1.1501079]

Introduction

The world's economy depends upon the burning of fossil fuel equivalent of some 180 million barrels of oil each day. The consumption rate is equivalent to an annual burning of what nature took about one million years to accumulate as fossil deposits. The world at present is confronted with the twin crises of fossil fuel depletion and environmental degradation. Indiscriminate extraction and lavish consumption of fossil fuels have lead to reduction in underground-based carbon resources. The search for an alternative fuel, which promises a harmonious correlation with sustainable development, energy conservation, management, efficiency, and environmental preservation, has become highly pronounced in the present context.

More than 6.5 million diesel engines are being used in the Indian agricultural sector for various activities. It is impossible to do away with these existing systems and hence alternative fuels are being expeditiously sought. As far as the application in rural agricultural sectors of a developing country like India is concerned, such internal combustion engines should preferably utilize alternative fuels of bio-origin, which are locally available. With agricultural conditions prevailing in India, the adaptation of the fuel to the existing engines has been more pronounced compared to developing a new engine for available alternative fuel. This allows the replacement of diesel fuel by vegetable oils, and for a short-term fuel as a blend.

Alternative fuels are generally referred as cleaner fuels in comparison with gasoline or diesel fuels. While using a new fuel, it is extremely important to strike a balance among many conflicting parameters involving not only the performance and emission characteristics of the engine, but also the overall life of the system. The combustion-related properties of vegetable oils are somewhat similar to diesel oil ([1]). 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-choking, injector deposits, injector pump failure, and lube oil dilution by crank-case polymerization. Such problems do not arise with short-term engine operations. Sometimes, the engine fails catastrophically, when operated on neat vegetable oils continuously for a longer period. The properties of vegetable oils such as high viscosity, low volatility, and polyunsaturated character are responsible for these problems ([2,3]). The deposits on the piston top are black, thick and hard, and at the edge, they fill the clearance in the top dead center position so that they will polish the bore at each stroke. A major problem using vegetable oil in engine operation is the deposits in the upper piston ring groove and on the piston ring. The piston ring gets stuck in the groove thereby weakening and decreasing the engine performance, as the combustion becomes erratic. The deposits grow, and the efficiency decreases. Another problem is that the vegetable oil and gases escapes through clearance into the engine crankcase as the sticking ring fails to seal adequately. As a result, it contaminates the lubrication oil, which leads to tough, rubber-like coating on the engine parts and the walls of the case, the fuel pump, and camshaft and push rods. The coatings on these parts can cause trouble or even breakdown. The build-up of carbon deposits is generally attributed to the large molecular size and resulting high viscosity of the medium-chain and long-chain triglycerides that constitute most commercial vegetable oils ([2,4]).

Keeping this in view, engine conditions were investigated using the newly developed biodiesel fuel. Transesterification is probably the most effective and widely used technique for formulating suitable fuel for Cl engines from vegetable oils in order to avoid these problems. Transesterification was known as early as 1864, when Rochleder described glycerol preparation through ethanolysis of

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castor oil. Transesterification is a chemical reaction that aims at substituting the glycerol of the glycerides with three molecules of mono-alcohols such as methanol thus leading to three molecules of methyl ester of the vegetable oil. The idea of chemically altering vegetable oils was noted even before World War II. Walton wrote in 1938 ‘‘to get the utmost value from vegetable oils as fuels, it is academically necessary to split the glycerides and to run on the residual fatty acid’’ because ‘‘the glycerides are likely to cause an excess of carbon in comparison’’ [5].

The stoichiometry of the overall transesterification reaction requires 1 mole of triglyceride for 3 moles of glycerol. This is a reversible reaction, which is acid or alkali catalyzed, involving stepwise conversions of triglycerides to diglycerides to monoglycerides to glycerol, thus producing 3 moles of ester in the process ([6]). A mixture of anhydrous alcohol and reagent (KOH) in desired proportions is combined with moisture-free vegetable oil. The materials are maintained at 65–70°C and allowed to settle by gravity for 24 hours. These esterified oils can be produced in a chemical laboratory by the above method. Some of the esters are commercially available. The molar ratio of the reagents, the presence of water, and free fatty acid determine the effectiveness of catalyst. Higher molar ratio (6:1) favors the use of potassium hydroxide (KOH) over potassium methoxide ($KOCH_3$), while lower molar ratio (3:1) favors the use of $KOCH_3$. Alkaline catalysts have the advantage of being less corrosive to industrial equipment than acid catalysts. Transesterification breaks the triglycerides in vegetable oils to two components, namely fatty acid esters and glycerol. Glycerol is a valuable byproduct, 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 ([7,8]).

Background Experiments

For the present work, linseed oil methyl ester (LOME) was prepared using methanol in the presence of potassium hydroxide as catalyst. Glycerol is the byproduct of the esterification reaction. Use of LOME in compression ignition engines was found to develop a highly compatible engine-fuel system with low emission characteristics. The physical and combustion related properties of the fuels were determined in the laboratory after esterification and most of them were found to be close to that of diesel oil ([9]).

Performance and emission test was carried out on one of the engines, which had been subjected to preliminary run-in. This test was aimed at optimizing the concentration of ester in the biodiesel blends. To achieve this, several blends of varying concentrations were prepared ranging from 0% (Neat diesel oil) to 100% (Neat biodiesel) through 5%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, and 75%. These blends were then subjected to performance and emission test on the engine. Performance data were analyzed from the graphs recording power output, torque, specific fuel consumption, and smoke density for all the blends of biodiesel. 20% biodiesel was found to be the optimum blend based on maximum thermal efficiency and smoke opacity considerations ([2,9]). Two similar engines were subjected to a long-term endurance test for 512 hours. The engine system selected is a portable diesel engine of 4 kW rating with an alternator coupled to it. This unit, manufactured by Perry & Co., India, is a compact, portable 4 kW genset run by diesel fuel. This is a single cylinder, four-stroke, vertical, water-cooled system having a bore of 86 mm and a stroke of 110 mm. At the rated speed of 1500 rpm, the engine develops 4 kW power output in pure diesel mode. The compression ratio is 16.7. 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. These engines were run for 32 cycles, each of 16 hours continuous running at rated speed and a fixed pattern of loading. The first engine operated on 20% biodiesel blend, and the second engine on neat mineral diesel oil. The engines had similar history and were rebuild with new liner, piston rings, bearings, etc. All metallic wear debris and corrosive wear debris generated during engine operation by wear of vital moving components were washed away by the lubricating oil and accumulated in the lubricating oil sump. Lube oil samples were drawn from the oil sump after intervals of every 128 hours of engine operation for conducting various tribological studies. Samples were taken after every 128 hours instead of industry standard of every 50 hours, in order to reduce the number of samples for the analysis. No major engine breakdown was observed during the entire range of engine operation of over 512 hours. The injector coking and deposition of carbon on cylinder head, piston top, was found to be significantly lower for biodiesel operated engine system ([10]). Since the engine used in this study are small engines, some of the fuel spray jets impinges upon linear walls in the combustion chamber and pass away to the oil sump along with the blow-by gases escaping through the piston rings. In the process, it affects the lubricating oil film present between the piston rings and liner wall. Though the engines are designed to minimize these losses, they can not be eliminated completely in small engines, thus leading to wear of various components.

Wear is defined as the progressive loss of substance from the operating surface of a body occurring as result of relative motion at the surface. It is a slow but a continuous process of removal of material from one or more elements. Wear depends on the load, speed, soot formation, temperature, hardness, surface finish, presence of foreign materials, corrosion and environmental conditions. During the process of wear, materials may deform or may be transferred from one element to another forming debris or the physical dimension may diminish. Wear particle analysis is a powerful technique for nonintrusive examination of the oil-wetted parts of a machine. The wear particles present in the lubricating oil provide a detailed information about the condition of the engine. A number of tests such as atomic absorption spectroscopy (AAS), ferrography, etc. were performed to estimate engine conditions indirectly through oil analysis. These tests provided information on the wear debris composition, wear debris size, type of wear, etc.

Atomic Absorption Spectroscopy

Atomic absorption spectroscopy was used for quantitative and qualitative analysis of wear debris of lubricating oils. The data was correlated with the extent of wear, the performance characteristics of either lubricating oils or diagnosis of failure of moving components. 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 concentration of various metals present in the lubricating oil samples from 20% biodiesel and neat diesel-fuelled Cl engines was evaluated to study the wear of different parts and material compatibility of the new fuel 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. Hence, various elements such as Fe, Cu, Zn, Cr, Mg, Co, and Pb were analyzed by following procedure.

Approximately 10 gms of lube oil was weighed in a silica crucible and burnt at 450°C for 4 hrs and at 650°C for 2 hrs. The residual ash was dissolved in concentrated HCl and the mixture was diluted with distilled water to make 100 ml of solution (Acid:

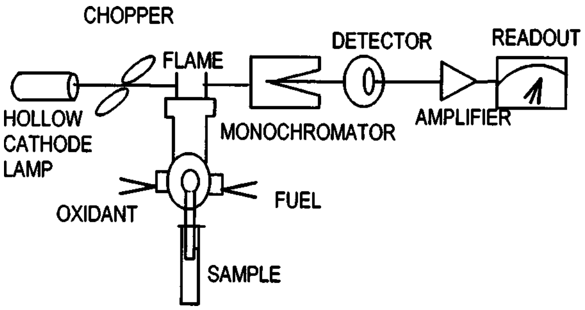

Fig. 1 Schematic diagram for atomic absorption spectroscopy

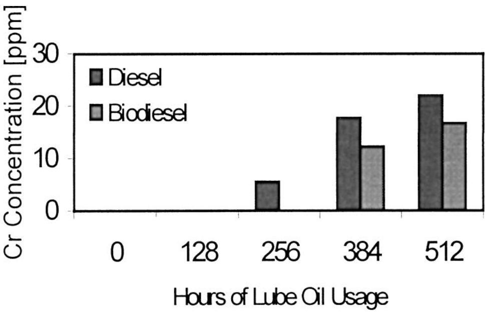

Fig. 5 Chromium concentration as a function of lube oil usage

Water: 1:100) standard solution of various metals with concentration ranging from 5 PPM to 20 PPM were prepared and subjected to AAS. The results are shown in Figs. 1–8.[10]

The wear metal concentration seems to be typical for this type of engines. AAS results for various wear metals shown in Figs. 2–8 conclude that the lubricating oil drawn from biodiesel-operated engine has lower absolute amount of wear metals and lower or nearly same rate of increase in concentration of wear metals. These results indicate that 20% amount of biodiesel present in significantly reduces wear of moving components.

To study the wear debris sizes, and concentration, ferrography was done on the lubricating oil samples drawn from both the engines after 128 and 512 hours of engine operation.

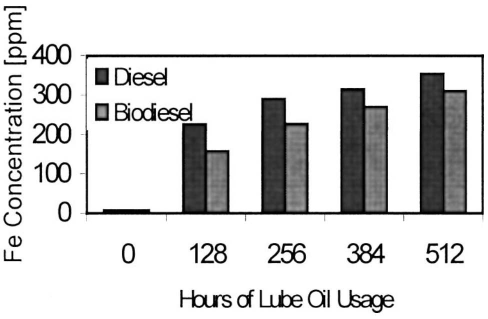

Fig. 2 Iron concentration as a function of lube oil usage

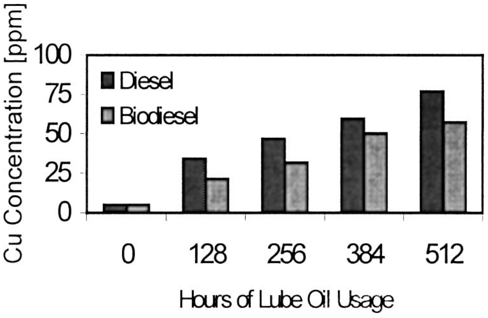

Fig. 3 Copper concentration as function of lube oil usage

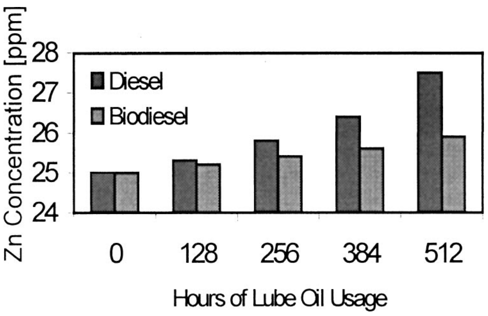

Fig. 4 Zinc concentration as a function of lube oil usage

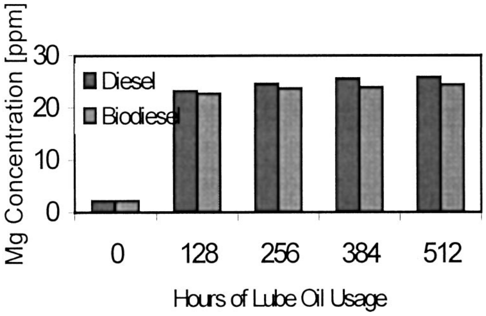

Fig. 6 Magnesium concentration as a function of lube oil usage

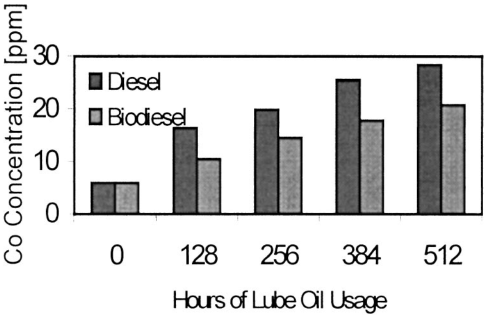

Fig. 7 Cobalt concentration as a function of hours of fuel usage

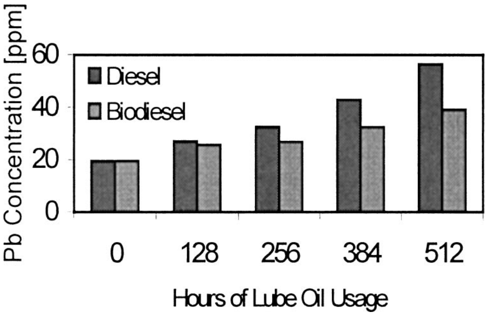

Fig. 8 Lead concentration as function of hours of lube oil usage

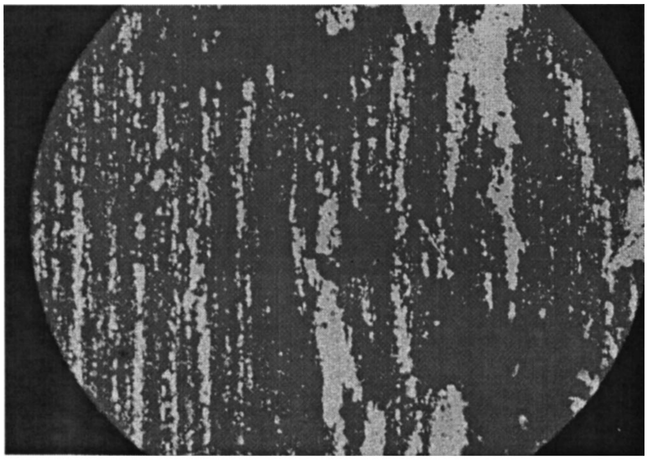

Fig. 9 Ferrogram of the lube oil drawn from 20% biodiesel operated engine after 128 hours of operation

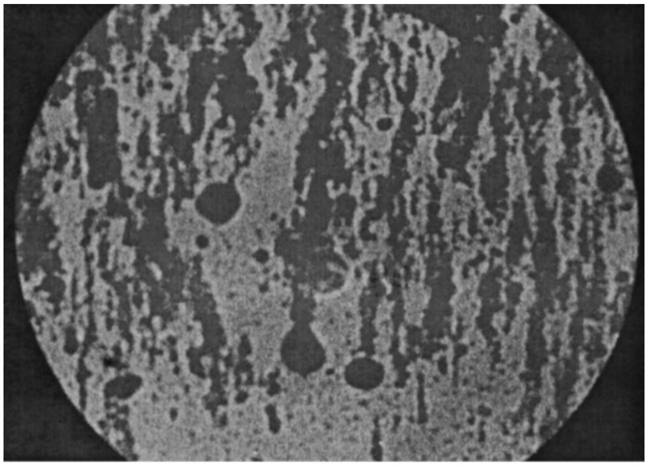

Fig. 11 Ferrogram of the lube oil drawn from 20% biodiesel operated engine after 512 hours of operation

Ferrography

During the life cycle of an IC engine, microscopic particles wear away from various moving parts. The size, distribution, number, and shape of the microscopic particle can provide information about the condition of the part they originate from, and the form of wear and wear mechanisms. Wear particle analyses in lube oil can therefore be used as a tool for monitoring not only the health of the engine oil but of the moving parts as well. Lube oil samples were subjected to ferrography to investigate the wear debris size and concentration in the oil samples. DR ferrograph by Fox Boro/Trans-Sonics Inc. was used for this study.

In the ferrogram, opaque objects appeared black, transparent objects appeared light gray and translucent materials appeared gray. Ferrography was done on the basis of classification of wear debris by color, texture, shape, concentration, and composition. Ferrography is a two-step process. The first step was of slide preparation and second step was of particle analysis. Bi-chrome microscope was used for particle analyses. Origin of the particle could be inferred from the composition of the particles, e.g., indications of bronze, copper or a special type of steel may be traced to specific bearings. Quantification of the ratio of sizes of large and small debris was not possible due to unavailability of dL/dS ratio sensor.

It is evident from Fig. 9 and 10 that the concentration of metallic wear debris is visibly lower for biodiesel-operated engines. Similarly, the ferrograms for 20% biodiesel and diesel-operated engines after 512 hours of engine operation in Fig. 11 and Fig. 12 indicate that the size of wear debris is smaller for biodiesel-operated engines. The type of wear identified is sliding wear, which is in conformity with the sliding motion of various engine parts. These results are in complete agreement with the AAS results, suggesting additional inherent lubricating properties for biodiesel present in fuel.

The different wear pattern can be due to the following reasons. The engines used in this study are small engines, and the engine walls possibly get some amount of fuel spray droplets in every injection cycle. These fuel droplets mix with the lubricating oil, which adheres to the cylinder liner wall surfaces, diluting it to some extent. The diluted lube oil gets swiped back into the crankcase due to the dynamics of the piston rings. In the process, the diluted lube oil acts as a lubricant between the cylinder liner and piston rings. It is expected that the lubricating properties of biodiesel and diesel fuel's play a predominant role at such a juncture and there is a need to investigate and quantify the lubricity of these fuels in order to find the difference in wear patterns. To investigate this explanation further, friction and wear patterns of

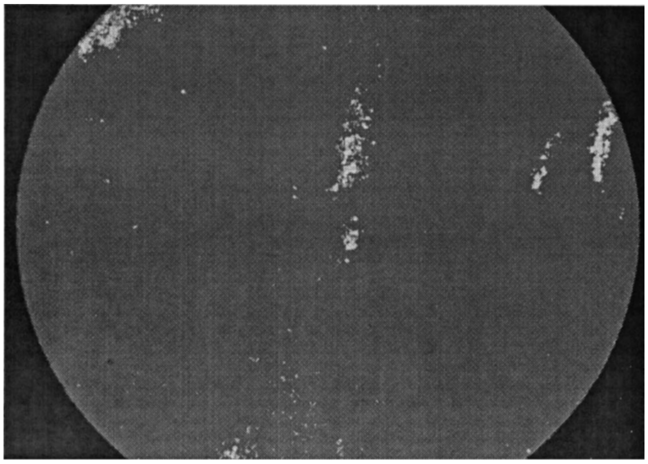

Fig. 10 Ferrogram of the lube oil drawn from diesel operated engine after 128 hours of operation

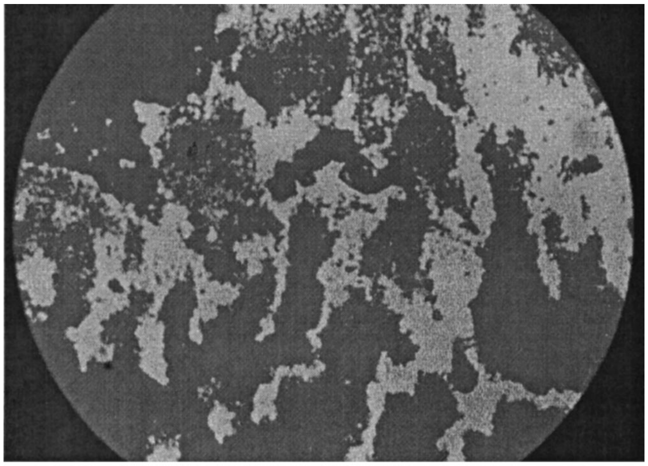

Fig. 12 Ferrogram of the lube oil drawn from diesel operated engine after 512 hours of operation

various combinations of these fuels were used as lubricating fluids in a SRV Optimol wear tester, which simulates the same type of motion as a real life diesel engine.

Experiments on Wear Tester

The SRV optimal wear tester was used for studying wear between rubbing surfaces. The machine (Fig. 13) used in this study allows a small section of piston ring to be moved relative to a small disk, made from the liner material. The device is such that the stroke of the ring piece and frequency can be varied to control the speed at which the ring piece moves. A force, that can be adjusted, pushes down the fixture holding the ring piece. Heating can control the temperature of the liner disk. Though, the machine is a wear tester, it does not completely match the characteristics of the piston ring in an engine, and also due to physical restriction, the ability to change the stroke on the tester was limited. However, fairly good results for the lubricity and specific wear rates of the surfaces for different lubricating fluids were achieved. For the present set of investigations, six pins were made from the top compression ring of the piston. The top ring was the hardest piston ring with hard chrome plating. Six disks were machined from the engine liner made of high phosphorous cast iron. A pin was held tightly in an aluminum holder provided in the SRV tester. The pin is slid in reciprocating motion against the disk made from the engine liner dipped in the lubricating fluid. Four different blends of LOME (0%, 20%, 40%, and 60%) with diesel oil were investigated. The following set of parameters given below was studied.

stroke length	1 mm
oscillation frequency	50 Hz
load	500 N
duration of runs	4 Hours

The engine used in the long duration tests has a stroke of 86 mm and operates at 1500 RPM with an oscillating frequency of 25 Hz. This can be noticed here that at this stroke and frequency, the maximum speed of the ring in the engine is much higher than in the wear tester. Lower speeds in the wear tester result in thin films of lubricating oil on the liner wall. In the fired engine used, the peak combustion chamber pressures that push on the back of the top ring can reach upto 9.4 MPa. This pressure, when applied to the ring piece, would be equivalent to 415 N. Since the speed of the pin was small, it was decided to go for higher load (500 N). It should also be noted that the peak pressure in the four-stroke engine does not last over the entire cycle of the engine. High pressures are present only for a part of each cycle. During low pressure in the cycle, only the ring tension exerts a force on the liner. This is approximately equivalent to a 14 N load on the ring piece ([11]). In the wear tester, the loading remains constant, and hence all the engine conditions are not simulated because of the constraints of the machine.

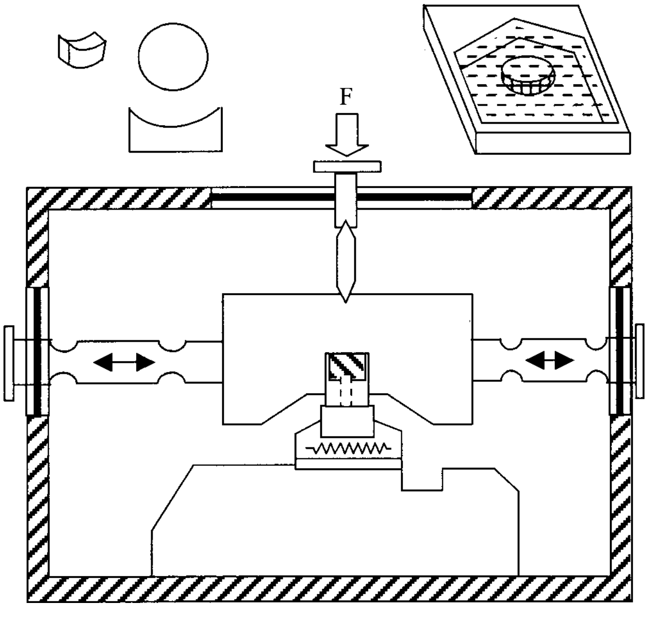

Fig. 13 SRV optimal wear tester, pin and disk arrangement

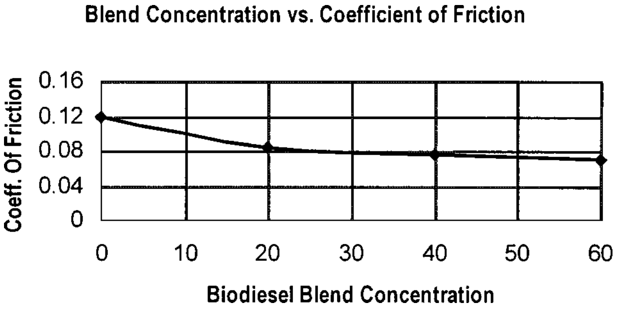

Fig. 14 Coefficient of friction of biodiesel blend concentration

In this study, friction coefficient was monitored continuously and then an average taken. The wear of pin and disk was measured by weighing the components before and after the tests. All the components were cleaned in ultrasonic bath with acetone, before and after the test, in order to remove foreign particle deposits.

Specific wear rates for the pin and the disk were calculated by the equation given below.

$$K_o = V/(LD)\,\text{m}^3/\text{Nm} \tag{1}$$

where

K_o = specific wear rate,
V = volume of the worn out material (m^3),
L = load in Newton and
D = total sliding distance (m).

The volume of worn out material is calculated using weight of worn out material and its density. The distance slid can be calculated by Eq. (2).

$$-D = 2A\nu t \tag{2}$$

where

A = Stroke length (m),
ν = oscillation frequency (Hz), and
t = the time period of run in seconds.

Efforts were also made to conduct the tests in 80% and 100% LOME blends but it was noticed that there is a sudden increase in noise after running the machine for more than an hour. The LOME gets completely blackened and thick due to oxidation and the oxidized particles formed increase the coefficient of friction in the contact zone. The coefficient of friction abruptly rises from the initial value (0.04). Hence, tests for higher percentages of LOME were abandoned. These results suggest that biodiesel leads to higher oxidation of the fuel, hence anti-oxidant additives are required in the biodiesel fuel to save it from deterioration with time.

The test results from the four lubricating fluid samples are represented in the following paragraphs. Figure 14 represents the average friction coefficient as a function of percentage of LOME in lubricating fluids. The figure shows that with increase in percentage of LOME in the lubricating fluid from 0 to 60, the coefficient of friction has continuously dropped from 0.12 to 0.07.

Figure 15 represents the specific wear rate for piston and disk as a function of percentage of LOME in the lubricating fluids. This figure also shows some interesting results in conformity with earlier observations. Specific wear rates for both pin and disk decreased with the increase in percentage of LOME in lubricating

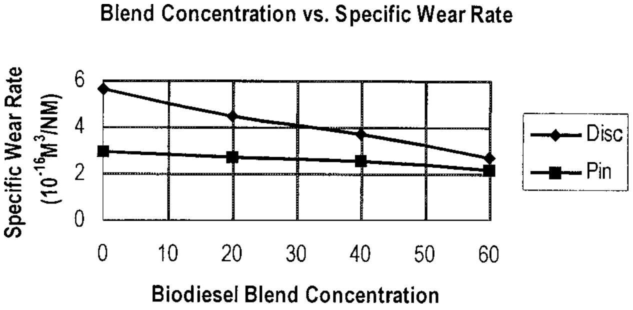

Fig. 15 Specific wear rates for disk and pin as a function of biodiesel blend concentration

fluids. Specific wear rates for disk submerged in diesel were maximum (5.6×10^{-16} m^3/Nm) and they were lowest for 60% LOME blend (2.7×10^{-16} m^3/Nm) with similar trends for pin material. Specific wear rates of disk material were higher than that for pin material because pin material was almost three times harder than the disk material. These tests clearly indicates that LOME has inherent lubricity properties, and this leads to lower wear of moving engine parts and thus longer life for the engine.

These disks were also subjected to scanning electronic microscopy. SEM micrographs show the surface topography with high magnifications.

Scanning Electron Microscopy

SEM was conducted on two disks, one subjected to neat diesel oil and the second subjected to 20% biodiesel blend as lubricating fluid. The micrographs for the two disks with different magnifications are shown in Fig. 16–19.

Micrographs 16 and 17, when compared to the micrographs 18 and 19, which are at the same magnifications indicate the difference in topography. In the case of disk subjected to 20% biodiesel blend, the overall surface appeared to be significantly smoother than the disc subjected to diesel indicating the reduction in wear. This also supports the fact that biodiesel is a better lubricant since it reduces the wear of the disk. The portion on the right side of micrographs 16 and 18 shows unworn surface of the disk when compared to the left side of the micrograph. High extent of grooving can be seen in the case of diesel-disk, which is due to body abrasive wear. The initial wear debris from the sliding surfaces get trapped in the contact zone and keep on abrading the surface till it is thrown out of the contact zone. Micrographs 17 and 19 (same

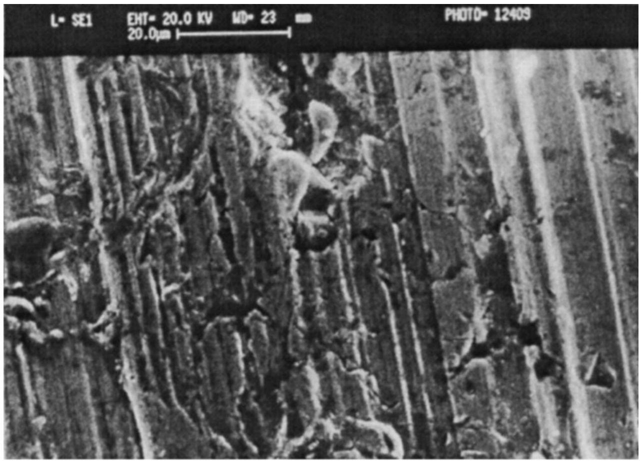

Fig. 17 High magnification micrograph of the disk subjected to diesel as lubricating fluid

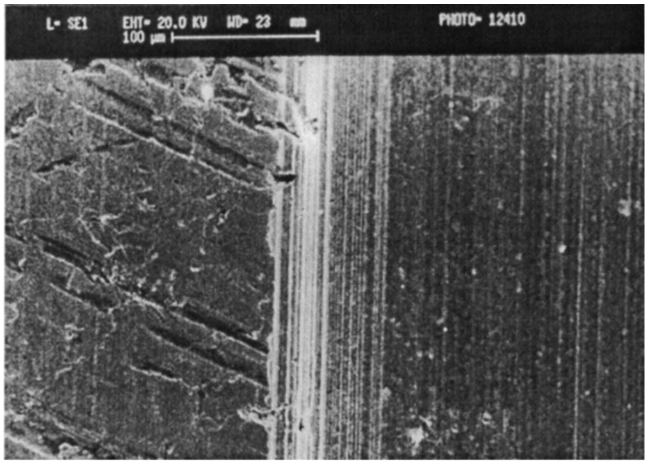

Fig. 18 Micrograph of the disk subjected to 20% biodiesel as lubricating fluid

Fig. 16 Mocrograph of the disk subjected to diesel as lubricating fluid

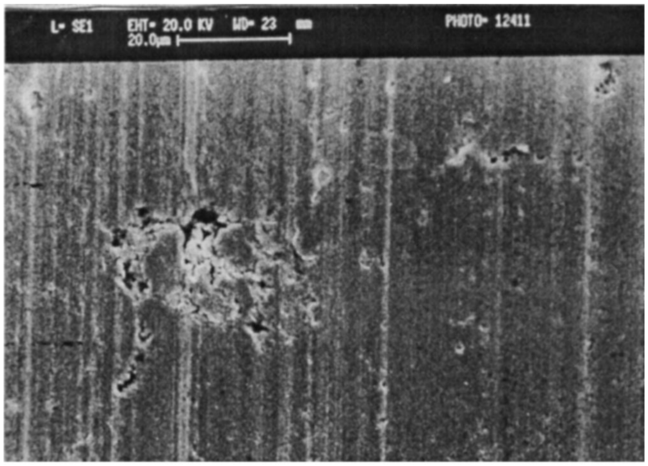

Fig. 19 High magnification micrograph of the disk subjected to 20% biodiesel as lubricating fluid

magnification) indicate a drastic difference in the topography of the surfaces. Disk surface subjected to diesel is extensively abraded at various places. It is evident from the above study that the self-lubricity of biodiesel results in reduced wear of engine parts.

Conclusions

Biodiesel can be readily adopted as a partial substitute for diesel in today's developing economies of the world. Transesterification is an appropriate method for the modification of vegetable oils, thus producing a suitable diesel fuel. Biodiesel is an environment-friendly fuel as it can be successfully used for long duration as none of the operational or durability problems were observed.

Atomic absorption spectroscopy tests conducted on lubricating oil samples drawn from biodiesel-operated engines suggested low concentration of wear metals. Ferrography tests showed smaller size and lower concentration of wear debris for biodiesel-operated engines. Though increase in wear debris concentrations was observed with usage of both biodiesel and diesel operated engine systems.

Additional tests conducted on SRV optimol wear tester to simulate the engine conditions partially for quantification of lubricity reflected that the lubricating fluids with biodiesel show lower coefficient of frictional low specific wear rates for moving components of the engines.

The scanning electron microscopy conducted on the disks subjected to wear tester reflected that biodiesel fuel is less damaging to the moving parts. These tests confirmed inherent additional lubricating properties of the LOME, i.e., biodiesel. Thus, it is apparently proved from the present investigation that biodiesel is not only a good choice for environmental reasons but it also keeps the engine in a better health, improving the life of its vital moving components.

Thus biodiesel fuel has proved to be a competent, engine friendly and environment friendly substitute for the mineral diesel oil.

Acknowledgments

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