Tribological Performance of Various Types of Biodiesel

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Lubricity is a critical property of diesel fuel because it affects engine performance. Current and future regulations are expected to reduce the sulfur content of diesel fuel. Low lubricity (i.e., low sulfur content) increases diesel engine wear and damages the fuel injection system. Alternative types of fuel have reduced diesel engine exhaust emissions and improved the friction and wear properties of engine parts.

Four types of diesel fuel, pure petrodiesel, soybean oil, palm oil, and waste edible oil (WEO), were compared for their fuel properties, engine performance, and emission characteristics. A series of tests was performed using various types of diesel fuel. The ball-on-ring wear testing method was used as an analytical tool for this purpose. The lubricating efficiency of the fuels was estimated using a photomicroscope to measure the average width of the wear scar produced on the test ring.

The wear experiments showed that the wear scar widths were 3.48 mm, 2.76 mm, 2.90 mm, and 2.93 mm for lubrication of the pure petrodiesel, soybean oil, palm oil, and WEO, respectively. Lubricities of this diesel are as follows: soybean oil > palm oil > WEO > pure petrodiesel. The ability of biodiesel to be highly biodegradable and its superior lubricating property when used in compression ignition engines make it an excellent fuel. This detailed experimental investigation confirms that biodiesel can substitute mineral diesel without any modification in the engine. The use of biofuels as diesel engine fuels can play a vital role in helping the developed and developing countries to reduce the environmental impact of fossil fuels. [do:10.2320/matertrans.M2015263]

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1. Introduction

It is believed that climate change is currently the most pressing global environmental problem; if the average global temperature increases by more than 3°C, as many as 1 million species could become extinct. Fossil fuel reserves are finite and highly concentrated in specific regions of the world; therefore, searching for renewable fuel is becoming increasingly critical to ensure energy security and environmental protection. Using fossil fuels, such as petroleum products and coal, causes several environmental problems, including reduced underground-based carbon energy sources, severe modifications in the surface layer of the earth, and subsidence of the ground surface after extraction of fuels and minerals.1-3)

Biodiesel is an alternative and environmentally friendly fuel that increases the supply of renewable energy. The higher cetane number of biodiesel improves engine performance, and its higher ignition temperature ensures fire safety during storage.4,5) The many other benefits of biofuel include increased employment and improved economic conditions, particularly in rural areas; enhanced energy security because of reduced dependence on oil imports; foreign exchange savings; reduced vehicle pollution; and practically no contribution to global warming.6-9)

Biodiesel as an alternative type of fuel is more attractive to various energy sectors, particularly the transportation sector. Biodiesel has an immense potential to be a part of a sustainable energy mix in the future. Biodiesel is primarily produced from rapeseed, canola, and palm oils. Although the trading price for soybean oil is subject to market speculation, broadening production alternatives may help the industry to reduce production costs when producing biofuel. The most effective method of using vegetable oil as fuel is to convert it to biodiesel. Biodiesel is a type of clean burning monoalkyl ester-based oxygenated fuel made from natural and renewable sources, such as new or used vegetable oils and animal fats. WEO, an oil-based substance, is vegetable matter that has already been used for cooking or preparing foods and is no longer suitable for human consumption. Using waste cooking oil in diesel engines is an alternative method of reducing the disposal of waste cooking oil, as well as an abatement of the fuel crisis.10-12)

Ejaz and Younis13) concluded that almost all types of vegetable oils can be used to replace petrodiesel; however, rapeseed oil and palm oil are the most suitable types of vegetable oil that can be used as diesel fuel. Biodiesel derived from these sources can generally be defined as monoalkyl esters of long chain fatty acids. Monoalkyl esters, which are the primary chemical species of biodiesel, have properties similar to those of petrodiesel. Biodiesel, a cleaner renewable fuel than petrodiesel fuel, has been considered the most efficient candidate for diesel fuel substitution because it can be used in any compression ignition engine without modification to the engine.

The conventional fossil fuel (pure petrodiesel) used in diesel engines contains higher amounts of aromatics and sulfur, which cause environmental pollution. As an example, higher amounts of particulate matter (PM), unburned HC, oxides of nitrogen (NOx), carbon dioxide (CO2), and oxides of sulfur (SOx) are produced from pure petrodiesel engine exhaust emissions. Moreover, NOx and CO2 are greenhouse gases and SOx causes acid rain. Because of the near absence of sulfur in biodiesel, this helps to reduce the problem of acid rain caused by transportation fuel. The lack of aromatic HC in biodiesel reduces unregulated emissions, as well as ketone and benzene. Inhaling PM is hazardous for human health, particularly in relation to respiratory system problems. Using biodiesel can help reduce global dependence on fossil fuels, and also has substantial environmental benefits. Researchers have reported that 100% biodiesel fuel emits lower tail pipe exhaust compared with petrodiesel fuel, nearly 50% lower
showed that polycyclic aromatic HC emissions were reduced
observed compared with using biodiesel fuel. The speci-
Substantial improvements in engine performance were
engine when using biodiesel and diesel fuel blends.

Huang
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viscosity of the biodiesel.

fuel consumption was reduced because of a decrease in the
emission was reduced in biodiesel engines compared with
35%

PM emissions, nearly 50% lower CO emissions, and
approximately 68% lower HC emissions.

Puhan Sukumar et al.\cite{14} showed that exhaust pollutant
emission was reduced in biodiesel engines compared with
petrodiesel. Carbon monoxide (CO), hydrocarbon (HC),
smoke, and nitrogen oxide (NOx) were reduced by 30%,
35%, 11%, and 35%, respectively. Suryawanshi\cite{15} showed
that smoke emissions are up to 35% lower in biodiesel
engines compared with petrodiesel engines. All blends
produce substantially reduced smoke at partial and full loads
because they burn soot-free and with complete combustion
because of the oxygenated fuel that comprises biodiesel
blends. Helwani et al.\cite{16} reported that combustion of neat
biodiesel reduced carbon monoxide (CO) emissions by
46.7%, PM emissions by 66.7%, and unburned HCs by
45.2%. Bettis\cite{17} demonstrated that B2 and B20 produced
by 2.7% and 17.2%, respectively, when used in a diesel
engine. Pramanik\cite{18} reported the performance of a diesel
engine when using biodiesel and diesel fuel blends.
Substantial improvements in engine performance were
observed compared with using biodiesel fuel. The specific
fuel consumption was reduced because of a decrease in the
viscosity of the biodiesel.

An experimental study of the performances and emissions
in a diesel engine using biodiesel oil was conducted by
Huang et al.\cite{19} The engine performance and thermal
efficiency of biodiesel were comparable with petrodiesel
fuel. However, the fuel consumption of engine was slightly
higher when fuelled with biodiesel. The biodiesel exhibits
improved load capacity wear resistance. Analysis of lubricity
characteristics of the biodiesel fuel blends showed a
nonlinear relationship between biodiesel concentration and
wear loads. Bettis\cite{17} showed that using biodiesel in diesel
engines slightly increases fuel consumption. However,
the lubricant properties of biodiesel were more effective than
those of petrodiesel and increased engine life. Knothe and
Steidley,\cite{20} Holser and Harry-O’Kuru\cite{21} reported that bio-
diesel regularly provides more efficient lubricity than that
of petrodiesel. Trace components found in biodiesel fuels,
including free fatty acids and diglycerides, have been
reported to improve the lubricity of biodiesel. Demirbas\cite{22}
concluded that biodiesel improves the lubrication properties
of the petrodiesel fuel blend. Biodiesel reduced long term
eengine wear in diesel engines, and was an effective lubricant,
demonstrating a superior performance compared with
petrodiesel. The possible uses of other types of biodiesel
and their effects on human health and the environment
warrant large-scale studies. Other types of biodiesel must be
examined for lubricity properties, engine performance, and
emission characteristics.

2. Experimental Procedure

Four types of diesel, pure petrodiesel, soybean oil, palm
oil, and waste edible oil (WEO), were used as lubricants in
this study. The essential fuel properties are given in the
Table 1. All diesels were reinjected without burning process
after a filtering treatment (Fig. 1). The fuel feed sub-system
helps to draw fuel from the tank and to deliver it to the
injectors of various cylinders. The fuel feed sub-system
consists of a tank, preliminary filter, pump, filter, an injector
pump, injectors and connecting lines. The injection pump
feeds high-pressure lines to the fuel nozzles for injection into
the cylinders. In-line pumps and injectors do not rely on fuel
for lubrication. However, in some sliding components, the
fuel itself provides lubricity (Haseeb et al., 2011).\cite{23} The
system simulates injector motion and operates in the range
of 50 Hz. The reciprocating motion covers 4 mm. The first
tests compared petroleum diesel and a biodiesel in terms of
friction produced in a fuel-injector operating for 400 hours.
The fuel injection plunger was made of bearing steel SUJ2
(composition: 0.95–1.10% C, 0.15–0.35% Si, 1.3–1.6% Cr,
≤0.50% Mn, ≤0.025% P, ≤0.025% S) with 6 mm diameter
and length of 35 mm. The injector plunger surfaces were
also evaluated in terms of wear and surface roughness. The
average roughness (Ra) of the needle surface was measured
to evaluate the tribological behavior of testing in various

![Fig. 1 Experimental set-up of the injection system of a diesel engine testing system; (a) injector, (b) injection plunger, (c) injection system.](image-url)
biodiesel. The roughness of the needle was measured before and after testing using a surface profiler.

The common sliding components in diesel engine are cylinder liner, bearing, cam, tappet, crankshaft journals, pistons and piston pins, valve guides, valve systems etc. Lubricity of these components is normally provided by the fuel itself. To understand the comparative wear in diesel and biodiesel, several laboratory investigations with four ball wear machine, pin-on-disk wearing machine, reciprocating wear tester etc. have been performed by some researchers. This test was developed to simulate wear in hydraulic pump components and correlated well with both pump stand and vehicle field tests. All these laboratory tests basically have been conducted in order to simulate the wear in engine parts that are in contact with biodiesel (Fazal, et al., Kimbry, et al.,). The tribology wear tests used the ball-on-ring contact method with four different fuels forcing a stationary ball against a rotating ring, forming the tribocounter (Fig. 2). Typical measurement parameters defined in the ISO standard were applied. This included the fuel temperature maintained at 30°C and the volume of the diesel sample used, set at 300 mL. The relative humidity was kept between 50% and 55% while the mean ambient temperature in the laboratory was maintained at an approximate temperature of 20°C. The ring was made of bearing steel (AISI 52100 steel with HRc of 60-62, of composition: 0.95 C, 0.15-0.35% Si, 0.2-0.4% Mn, <0.027% P, <0.020% S, 1.3-1.65% Cr, <0.3% Ni, and <0.25% Cu) with 70 mm diameter and thickness of 17 mm. The steel ball used in this study was made of bearing steel GCr15 (composition: 0.95-1.05% C, 0.15-0.35% Si, 0.25-0.45% Mn, 1.40-1.65% Cr, <0.10% Mo, <0.025% P, <0.025% S, <0.30% Ni, <0.25% Cu, <0.50% Ni+Cu) with hardness of HRc 59-61 and diameter of 12.7 mm. Both surfaces were polished to roughness Ra = 0.05 µm for ball and Ra = 0.20 µm for ring. During the test, the ball and ring was fully submerged in the tested fuels at a rotating speed of 500 rpm lasting 2 hours (Fig. 3). Table 2 lists the wear test conditions. The mean width of wear scar on the ring was then measured from five identical tests using a digital-reading microscope with accuracy of 0.01 mm. The friction forces were measured by performing sliding tests on an identical tester and recorded using the strain gauge in the tester. A data acquisition system with an AD converter was used for continuous monitoring and measurement of frictional force. The friction coefficient µ was calculated using the expression µ = M/R², where M is the friction moment, R is the ring radius, and P is the normal load on the ball specimen. The steel balls were rinsed in ethanol immediately and then the topography of the scar surfaces after the wear test was observed by OM.

3. Results and Discussion

The study was performed in the following two steps.

3.1 Injection system simulation

The lubricity of the diesel fuel had a direct effect on the service life of the fuel injection equipment, and when alternative fuel was specified, it was of vital importance. The first tests compared pure petro-diesel and a biodiesel in terms of friction produced in a fuel-injector operating for 400 hours. Figure 4 show the injector plunger surface roughness analysis results. The injector plunger surfaces were also evaluated in terms of wear and surface roughness. Average roughness (Ra) determined through a surface profiler decreased from 0.412 µm to 0.259 µm after biodiesel usage, which indicated improved lubrication. It was observed that biodiesel has the greatest lubricating ability for protecting the sliding surfaces in fuel injection equipment.

Figure 5 shows that the injector plunger surface had no corrosion, scuffing or high wear. The findings indicate that the biodiesel obtained a normal rate of wear on the engine injector plunger. A possible reason is that the additional lubricity properties of the biodiesel reduced friction. Because of the oxygen-containing compounds and the mixture of several fatty acids in methyl esters, which were adsorbed onto the rubbing surface to reduce friction and to improve the film thickness of the boundary lubrication regime. This lubrication property helped to improve the fuel injectors and fuel pump lubrication capacity.

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**Table 2 Wear test conditions.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent load (N)</td>
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<tr>
<td>Maximum Hertzian pressures (GPa)</td>
<td>1.56</td>
</tr>
<tr>
<td>Sliding speed (rpm)</td>
<td>500</td>
</tr>
<tr>
<td>Sliding distance (m)</td>
<td>52752</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>28-30</td>
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</tbody>
</table>
3.2 Ball-on-ring test

The results of the lubricity tests are shown in Fig. 6. Biodiesel considerably reduced the width of a wear scar compared with pure petrodiesel. The average wear scar widths on the ring specimen were 3.48 mm, 2.76 mm, 2.90 mm and 2.93 mm for pure petrodiesel, soybean oil, palm oil, and WEO, respectively. All types of biodiesels, including soybean oil, palm oil, and WEO, distinctly improved the lubricity of pure petrodiesel. The wear scar width was lowest for soybean oil. The minimum value was approximately two-thirds lower than that for pure petrodiesel. The fatty acid composition of biodiesel mixtures may affect their effectiveness as lubricity enhancers. As carbon chain length increases, the wear scar width generally decreases. This trend is also seen in the incremental viscosity as the chain length increases.

Figure 7 demonstrates the lubricating properties of pure petrodiesel and biodiesels. To improve the lubricity of pure petrodiesel, the tribological properties of biodiesels were investigated. A statistical analysis of these results is shown in Fig. 7. It was observed that biodiesel dramatically improved the lubricating properties of pure petrodiesel. The low friction coefficient of biodiesel may result from fatty compounds. Biodiesel components, such as fatty acid methyl esters, free fatty acids, and monoglycerides, reportedly improve the lubricity of biodiesel.

![Fig. 4 Roughness of the injector plunger surface after injection test (injection system, 50 Hz, 400 hour); (a) profiles across the new injector, (b) rubbed surface lubricated by pure petro-diesel, (c) rubbed surface lubricated by soybean oil, (d) rubbed surface lubricated by palm oil, (e) rubbed surface lubricated by waste edible oil.](image)

![Fig. 5 Optical microscopy micrographs of injector plunger surface (injection system, 50 Hz, 400 hour); (a) new injector, (b) pure petroleum diesel, (c) soybean oil, (d) palm oil, (e) waste edible oil.](image)
Figures 8(a)–(d) show the typical frictional behaviors of the ball-on-ring wear tests for pure petrodiesel, soybean oil, palm oil and WEO lubricants, indicating that the coefficient of friction tested in biodiesel was the most low. In addition, biodiesel fuel appeared to reduce the negative effects on friction resistance, thus reducing wear volume, partly as a result of the presence of fatty acid methyl esters in the biodiesel, which display superior tribological properties compared with petrodiesel. The primary reason for this reduction may be an increase in the stability of the lubrication film, as shown in Fig. 8, as a result of polar compounds present in the biodiesels.

3.3 Analysis of worn surface

Figures 9(a)–(d) show the worn surfaces of the ball specimens tested at room temperature with various types of diesel. The worn surfaces of the ball specimen tested in petrodiesel show wear mechanisms, including abrasive wear and delamination (Fig. 9(a)). The wear mechanisms of the worn surface tested in biodiesel are similar to those found in petrodiesel; as shown in Figs. 9(b)–(d), the ball specimen tested in soybean oil, palm oil, and WEO is characterized by minor abrasive wear. Among the various types of biodiesel oil, biodiesel was found to have the strongest antiwear performance. Comparing Fig. 9(a) with Figs. 9(b)–(d), the worn surfaces of biodiesel were smoother than those of petrodiesel. This difference was also attributable to the presence of aliphatic fatty acids in biodiesel, such as stearic acid, which could enhance lubrication properties by controlling friction and wear between contact surfaces by developing lubrication films.

The wear scar profiles perpendicular to sliding direction on worn surfaces were analyzed using a Talysurf-120 profilometer. For the analysis of the surface roughness of the rubbed surface, a 1.25-mm evaluation length and Gaussian filter were used. The 3D worn surfaces taken from the profilometer are shown in Fig. 10. The results show that the average surface roughness was 0.565 μm, 0.249 μm,
0.304 µm and 0.491 µm when lubricated with the pure petro-diesel soybean oil, palm oil, and WEO, respectively. The average roughness of the biodiesel decreased by 56%. However, fatty acids containing biodiesel typically have thicker molecular layers than mineral pure petro-diesel, and thus can reduce the wear rate of the sliding metals. This improved the boundary lubrication conditions and the lubricity of the fuel. Biodiesel fuels are effective lubricity enhancers and have greater lubricity enhancing properties than petro-diesel.

4. Conclusions

The following conclusions can be drawn from the present investigation.

The wear experiments showed that the wear scar widths were 3.48 mm, 2.76 mm, 2.90 mm, and 2.93 mm for lubrication of the pure petro-diesel, soybean oil, palm oil, and WEO, respectively. Lubricities of this diesel are as follows: soybean oil > palm oil > WEO > pure petro-diesel. The ability of biodiesel to be highly biodegradable and its superior
lubricating property when used in compression ignition engines make it an excellent fuel.

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