Impact of palm biodiesel blend on injector deposit formation

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HIGHLIGHTS

• 250 h Endurance test on 2 fuel samples; diesel fuel and PB20.
• Visual inspection of injectors running on DF and PB20 showed deposit accumulation.
• SEM and EDS analysis showed less injector deposits for DF compared to PB20 blend.
• Engine oil analysis showed higher value of wear particles for PB20 compared to DF.

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ABSTRACT

During short term engine operation, renewable fuels derived from vegetable oils, are capable of providing good engine performance. In more extended operations, some of the same fuels can cause degradation of engine performance, excessive carbon and lacquer deposits and actual damage to the engine. Moreover, temperatures in the area of the injector tip due to advanced diesel injection systems may lead to particularly stubborn deposits at and around the injector tip. In this research, an endurance test was carried out for 250 h on 2 fuel samples; DF (diesel fuel) as baseline and PB20 (20% palm biodiesel and 80% DF) in a single cylinder CI engine. The effects of DF and PB20 on injector nozzle deposits, engine lubricating oil, and fuel economy and exhaust emissions were investigated. According to the results of the investigation, visual inspection showed some deposit accumulation on injectors during running on both fuels. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analysis showed greater carbon deposits on and around the injector tip for PB20 compared to the engine running with DF. Similarly, lubricating oil analysis presented excessive wear metal concentrations, decreased viscosity and increased density values when the engine was fuelled with PB20. Finally, fuel economy and emission results during the endurance test showed higher brake specific fuel consumption (bsfc) and NOx emissions, and lower HC and CO emissions, for the PB20 blend compared to DF.

1. Introduction

In recent years, the use of biodiesel in modern CI engines with advanced injection systems has been widely tested [1]. However, diesel fuel injection equipment (FIE) systems are susceptible to the formation of a variety of deposits [2]. The formation of deposits within the holes of the injector nozzle or on the outside of the injector tip may have an adverse effect on overall system performance [3] because the injection pattern and fuel flow rate are affected by the nozzle deposits. It has been reported that deposit formation begins on the injector nose, which is the coldest part of the combustion chamber of a diesel engine, followed by the rings and the throat, the chamber walls, then the cylinder head, etc. [4]. Therefore, it is likely that fuel stored in the injector tip is heated during the combustion process and expands during the expansion stroke. A combination of evaporation of the lighter fractions of the fuel and degradation are considered responsible for sticky deposits. The process is affected by elemental fuel contaminants, reactive combustion products, soot and volatilized lubricating oil [5]. Moreover, recently the trend for smaller holes and high efficiency nozzles in direct injection (DI) and high speed direct injection (HSDI) engines has resulted in many more instances of injector spray-hole deposits causing problems. The reasons for this increase include [2]:

(i) Smaller holes which for a given deposit level will result in a proportionately larger reduction in flow area and therefore larger flow rate reduction, resulting in loss of torque and power.
(ii) High efficiency nozzles with honed entry to nozzle holes and/or tapered nozzle holes resulting in reduction or elimination of cavitating flow within the nozzle.

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(iii) Combustion and air management trends resulting in higher nozzle tip temperatures, which promote nozzle deposits.

According to Caprotti et al. [6], deposits in the injector can be developed in two separate locations:

(i) Inside the body of the injector like on plungers and internal valves. These types of deposits are called internal injector deposits (IID).

(ii) At the spray-hole, where the fuel leaves the injector and enters the combustion chamber. These are called spray hole deposits (SHD).

In the literature, different investigation reports can be found regarding deposit formation on the injector nozzle using biodiesels and their fuel blends. In short-term operations, renewable fuels derived from vegetable oils are capable of providing good engine performance. With more extended operation, some of the same fuels can cause degradation of engine performance, excessive carbon and lacquer deposits and actual damage to the engine [7]. It has been reported that some biodiesel properties such as higher viscosity, lower volatility [8], and the reactivity of unsaturated hydrocarbon chains can lead to injector coking and trumpet formation on the injectors, more carbon deposits, etc., after the engine has operated for a longer time period [9]. A comparative study of the effects of biodiesel and diesel fuel in two single-cylinder engines with the same injector specifications and fuel injection pump pistons was experimentally analyzed [10]. After the engines were run for 200 h at 2000 rpm, the injectors were examined and compared by performing scanning electron microscopy (SEM) and energy-dispersive X-ray (EDS) analysis. According to the results, SEM images showed greater shrinkage in the diameter of the injector nozzle of the engine using biodiesel. Metal cutting traces in the original, unused machined injector were covered with a layer and completely disappeared as a result of biodiesel use. Moreover, after the 200 h runs, the quantity of carbon (C) element on the fuel injector surface was greater when biodiesel was used compared to petroleum diesel. According to Richards et al. [3], biodiesel has been observed to lead to higher deposit formation in the injector nozzle. Injector deposits using rape methyl ester (RME) have been investigated in swirl chamber injection systems for: indirect fuel injection, current common rail, and future common rail systems [11]. The results showed moderate deposit formation and about 3% power loss when the engine was run on B10 RME for 16 h. A further test was also carried out for an extended period of 48 h. The result showed that deposit formation continued at approximately the same rate and probably beyond, causing a maximum drop in torque of 24%. On the contrary, according to Sinha and Agarwal [12], carbon deposits on the cylinder head, injector tip, and piston crown using a biodiesel blend (20% rice bran oil methyl ester blend with mineral diesel) in a 100 h endurance test were significantly lower compared to mineral diesel fuel. In order to investigate the coking of DI diesel engine injector nozzles, the effect of using neat rubber seed oil biodiesel (RSB) and blends with diesel fuel was studied [13]. It was found that deposit accumulation was greatest on the liners of injectors with B5 and B100 fuel. The surfaces of the injectors were dirtier after B5 and B100 use than with diesel fuel. However, more carbon deposits were observed around the injector tip of the diesel nozzle. Moreover, no significant difference was found in the degree of coking around the injector tips using B5 or B100.

In a lubrication system, wear particles remain in suspension in the lube oil. Sufficient information about wear rate, source of element and engine condition can be predicted after a certain running duration by analyzing and examining variations in the concentrations of the metallic particles available in the lubricant oil [14]. Particularly in diesel engines, the components that are normally subjected to wear are the cylinder liner, bearing, cam, tappet, crankshaft journals, pistons and piston pins, valve guides, valve systems, etc. [15]. Therefore, by analyzing the lubrication oil, direct indications of engine wear and health can be found [16].

The main objective of this work is to carry out the comparative study on the injector deposits, lubricating oil analysis and, engine fuel economy and emission results during 250 h endurance test on DF as baseline and PB20 blend respectively.

2. Materials and methods

For this study, a single-cylinder, four-stroke diesel engine was selected. Its major specifications including the fuel injector and pump can be found in Table 1. The engine was coupled to an eddy current dynamometer. The endurance test was carried out for 250 h at 2000 rpm and 10 N m load on 2 fuel samples: DF and PB20 respectively. The palm biodiesel used in this study was supplied by local company. The analysis report provided by the supplier is summarized in Table 2. The essential measured fuel
Main fuel properties.

Analysis report of palm biodiesel.

Test engine specifications.

Table 1
Test engine specifications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DF</th>
<th>PB20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine type</td>
<td>4-Stroke DI diesel engine</td>
<td></td>
</tr>
<tr>
<td>Number of cylinders</td>
<td>One</td>
<td></td>
</tr>
<tr>
<td>Aspiration</td>
<td>Natural aspiration</td>
<td></td>
</tr>
<tr>
<td>Cylinder bore x stroke (mm)</td>
<td>92 ± 96</td>
<td></td>
</tr>
<tr>
<td>Displacement (L)</td>
<td>0.638</td>
<td></td>
</tr>
<tr>
<td>Compression ratio</td>
<td>17.7:1</td>
<td></td>
</tr>
<tr>
<td>Max. engine speed (rpm)</td>
<td>2400</td>
<td></td>
</tr>
<tr>
<td>Maximum power (kW)</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>Injection timing (deg.)</td>
<td>bTDC 17.0</td>
<td></td>
</tr>
<tr>
<td>Injection pressure (kg/cm²)</td>
<td>200–210</td>
<td></td>
</tr>
<tr>
<td>Power take – off position</td>
<td>Flywheel side</td>
<td></td>
</tr>
<tr>
<td>Cooling system</td>
<td>Radiator cooling</td>
<td></td>
</tr>
<tr>
<td>Fuel injection pump</td>
<td>Bosch PFR type</td>
<td></td>
</tr>
<tr>
<td>Plunger diameter (µm)</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>Injection hole diameter (mm)</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>Number of holes</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Injection angle (deg.)</td>
<td>150</td>
<td></td>
</tr>
</tbody>
</table>

Table 2
Main fuel properties.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Method</th>
<th>Units</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 15 °C</td>
<td>EN ISO 12185</td>
<td>kg/m³</td>
<td>876</td>
</tr>
<tr>
<td>Viscosity at 40 °C</td>
<td>EN ISO 3104</td>
<td>mm²/s</td>
<td>4.63</td>
</tr>
<tr>
<td>Flash point</td>
<td>EN ISO 3679</td>
<td>°C</td>
<td>170</td>
</tr>
<tr>
<td>Cetane number</td>
<td>EN ISO 5165</td>
<td></td>
<td>64.7</td>
</tr>
<tr>
<td>Total ester content</td>
<td>EN 14103</td>
<td>% (m/m)</td>
<td>97.01</td>
</tr>
<tr>
<td>Moisture</td>
<td>EN ISO 12397</td>
<td>mg/kg</td>
<td>500</td>
</tr>
<tr>
<td>Acid value</td>
<td>EN 14104</td>
<td>mg KOH/g</td>
<td>0.57</td>
</tr>
<tr>
<td>Methanol content</td>
<td>EN 14110</td>
<td>% (m/m)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Monoglyceride</td>
<td>EN 14105</td>
<td>% (m/m)</td>
<td>0.49</td>
</tr>
<tr>
<td>Diglyceride</td>
<td>EN 14105</td>
<td>% (m/m)</td>
<td>0.05</td>
</tr>
<tr>
<td>Triglyceride</td>
<td>EN 14105</td>
<td>% (m/m)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Total glycerol</td>
<td>EN 14105</td>
<td>% (m/m)</td>
<td>0.10</td>
</tr>
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</table>

Table 3
Physochemical properties of biodiesel from different feedstocks [17].

<table>
<thead>
<tr>
<th>Properties</th>
<th>Biodiesel Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Palm</td>
</tr>
<tr>
<td>Kinematic viscosity (cst, at 40 °C)</td>
<td>4.42</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>860–900</td>
</tr>
<tr>
<td>Heating value (MJ/kg)</td>
<td>34</td>
</tr>
<tr>
<td>Cetane number</td>
<td>62</td>
</tr>
<tr>
<td>Iodine value</td>
<td>60.07</td>
</tr>
<tr>
<td>Acid value (mg KOH/g)</td>
<td>0.08</td>
</tr>
<tr>
<td>Saponification number</td>
<td>207</td>
</tr>
</tbody>
</table>

Table 4
Physochemical properties of biodiesel from different feedstocks [17].

Examine with the help of scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analysis. SEM permits the observation of materials in the macro and submicro ranges. When used in conjunction with EDS, it can perform an elemental analysis on microscopic sections of the material. Visual inspection of the injector nozzle was carried out by taking photographs at 0 h (new), 60 h, 125 h, 180 h, and 250 h, respectively. To investigate the effect of DF and the PB20 blend on the engine oil, oil samples were collected after every 20 h during the engine endurance test on each fuel. The engine oil was changed after 160 h for each fuel sample to avoid further degradation of the lubricating oil. The viscosities of engine oil samples were determined using an Anton Paar (SVM 3000) viscometer, whereas a multi-element oil analyzer (MOA) was used for quantitative and qualitative analysis of any increase in wear metal concentrations during the engine endurance test. In order to examine the emission characteristics, a portable BOSCH exhaust gas analyzer (model ETT 0.08.36) and Bacharach (Model CA300NSX) were used to measure the concentrations of exhaust gases from the test engine such as hydrocarbons (HC) and nitrogen oxide (NOₓ) in parts per million (ppm), while carbon monoxide (CO) was measured in percentage volume (%vol). Engine fuel consumption and exhaust emission measurements were taken at 0 h (during the first hour), 60 h, 125 h, 180 h and 250 h. Time taken for fuel consumption was determined by using a digital stopwatch.

3. Results and discussions

3.1. Injector visual inspection

As shown in Fig. 1, injector nozzles were photographed during a 250 h endurance test on DF and the PB20 blend. Visual inspection after different hours of operation revealed some deposit accumulation on the liners of the injectors and their tip surfaces for both fuel samples, as indicated in Fig. 1. However, the injector running on PB20 was dirtier than the injector running on DF. Similar results have been reported by Reksowardojo et al. [13]. Moreover, deposits on injectors run with DF were observed to be oily/greasy, whereas dry deposits were observed on nozzles run with the PB20 blend.

3.2. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analysis

Upon completion of the long-term 250 h endurance test on DF and the PB20 blend, the engine was partly disassembled and deposit formation on each injector tip was studied. Fig. 2 shows SEM micrographs at 17× magnification of deposits on injector tips fuelled with DF and PB20, respectively. It has been reported that advanced diesel injection systems are characterized by higher temperatures in the area of the injector tip that can lead to particularly stubborn deposits at and around the injector tip [18,19]. It can be clearly seen that deposits with DF are substantially reduced compared to with the PB20 blend.

Fig. 3a illustrates SEM of deposits at 30× magnification on an injector tip fuelled with diesel fuel (DF) and Fig. 3b–f shows elemental analysis by EDS of different locations (locations A–E) on deposited surfaces as seen in Fig. 3a. The location indicated by ‘A’ of the deposited layer seems to be on the top layer, which shows the highest amount of oxygen (O) (19.50%). Similarly, location E is another point on the top layer that shows a similar concentration of oxygen (18.68%). The concentration of carbon (C) in these locations is another point on the top layer that shows the highest amount of oxygen (O) (19.50%). Similarly, location E is another point on the top layer that shows a similar concentration of oxygen (18.68%).
of the deposited layer. On the other hand, location C shows the presence of base metal (67.42% Fe) rather than a higher amount of deposition (carbon: 12.82% and oxygen: 8.43%). This indicates that in case of DF, the formation of deposition does not present a uniformly thick layer of carbon. Generally, in baseline tests with DF, deposit accumulation at and around the injector tip did not significantly interfere with the nozzle holes. The elemental composition of the deposits predominantly consisted of carbon (C) and oxygen (O) and some trace amounts of different elements. At higher temperatures, carbon deposits are usually formed via two different routes: decomposition of hydrocarbons to elemental carbon and hydrogen; or polymerization/condensation of hydrocarbon species into larger polynuclear aromatic hydrocarbons (PAHs) that then nucleate and grow to become carbonaceous deposit. In the spectra, different metal elements were detected from the formed deposition. In fact, many engine parts such as: (i) static components: fuel tank, filter, fuel pump injector housing, fuel line, exhaust system, cylinder liner, etc. and (ii) dynamic components: piston, piston rings, inlet and exhaust valve, fuel pumps and filters plunger, connecting rod, etc. may directly come in contact with fuel and engine oil. The most common metallic elements found in deposit including aluminum (Al), chromium (Cr), copper (Cu), iron (Fe), zinc (Zn), lead (Pb), etc. could be due to wear, corrosion and tribo-corrosion of the engine components. These metal particles are washed away lubricating oil as well as fuel. As the high-pressure pump is lubricated by engine oil, a possible source of the lubricant was transport of trace amounts into the fuel. In this regard, the presence of zinc (Zn) and sulfur (S) at all locations except location B indicate that the deposit may be linked to potential contamination from the metal contaminated lubricant. The appearance of iron (Fe) and chromium (Cr) at location C is due to nozzle material, whereas at location E the appearance of iron (Fe) is an artifact of beam penetration to the metal surface. However, the origin of tungsten (W) at locations C and E, and nitrogen (N) at location C could not be clarified.

Fig. 4a shows a magnified SEM image of deposits on an injector tip fuelled with PB20 at 30× magnification and Fig. 4b–f shows elemental analysis by EDS at different locations (locations A–E) on the deposited surfaces shown in Fig. 4a. It can be seen in Fig. 4a that relatively thick and overlapping deposits are formed at tip and around the injection hole exit along with shrinkage in the diameter of the injector nozzle hole. Moreover some nozzle holes are completely closed by apparently the same deposits. All locations of the deposited layer indicated by locations A–E show higher concentration of carbon. In this regard, concentration of carbon at these locations is found as: 77.51% at location A, 69.73% at location B, 85.17% at C, 79.86% at location D and 74.32% at location E respectively. However, concentration of oxygen at these locations is...
found as: 18.22% at location A, 17.47% at location B, 14.83% at C,
16.14% at location D and 21.39% at location E respectively. More-
over, appearance of some other elements given below could not
be clarified such as: sodium (Na) and silicon (Si) at location A, so-
dium (Na) and silicon (Si) at location B, sodium (Na) and silicon (Si)
at locations D and E respectively. It is noted that few metal ele-
ments were found in diesel fuelled engine deposition while not
in BP20. This demonstrates that BP20 seems to provide better
lubricity as compared to DF. It has been reported that higher vis-
cosity and low volatility of biodiesel fuel result in poor fuel atom-
ization and air/fuel mixing due to the formation of the larger size of fuel droplets during fuel atomization in engines [20,21]. Ignition delay is one of the parameters that is effected due to bigger size of fuel droplets during the combustion process. The ignition delay increases for higher viscosity fuel compared to the lower viscosity fuel due to its droplets requiring more time to be vaporized. Thus

Fig. 4. Magnified SEM micrographs of the deposited injector tips fuelled by PB20 and related elemental analysis of the different locations (locations A–E).
the tendency of deposit formation rate may increase [20]. Decomposition of biodiesel occurs at higher temperatures, therefore the possibility exists for the biodiesel to be decomposed during the ignition delay period, resulting in injector tip deposits. It was reported that deposit of biodiesel was basically composed of volatile substances, high boiling point substances, oxidizing substances, carbonization substances, and residual ashes in different proportions [22]. These could be related to unstability of biodiesel at higher temperature. Further study should be done in order to understand the effect of temperature on thermal stability of palm biodiesel.

3.3. Lubricating oil analysis

Engine lubricating oil plays a very important role in IC engines. It consists of a complex mixture of hydrocarbons and is a combination of base oils and additives. Lubricants are used primarily to reduce friction and lessen the wear of various sliding and rotating components in the engine and to keep the different elements clean, acting as detergents, dispersant agents, anti-oxidants, viscosity modifiers, etc. [16,23]. In order to investigate its effect on the engine oil during the endurance tests carried out on DF and the PB20 blend, lubricating oil samples were collected after every 20 h of operation. However engine oil was changed after 160 h operation for each fuel sample to avoid further degradation of lubricating oils. Higher viscosity indicates that the lubricant is deteriorating from either oxidation or contamination, while a decrease usually indicates dilution of the lubrication oil [25]. Viscosity was determined at 40 °C and 100 °C whether the engine oil more in the case of the engine running with the PB20 blend than the run with DF.

3.3.1. Viscosity

Viscosity is one of the most important properties of engine lubricating oils. Higher viscosity indicates that the lubricant is deteriorating from either oxidation or contamination, while a decrease usually indicates dilution of the lubrication oil [25]. Viscosity was determined at 40 °C and 100 °C. Viscosity determined at 100 °C was thought to be close to the average oil temperature during engine operation [13]. It can be seen in Fig. 5a and b that there was a decrease in oil viscosity at both 40 °C and 100 °C whether the engine was fuelled with DF or PB20 during the endurance test. This decrease in lubricating oil viscosity can most likely be attributed to fuel dilution of the crankcase oil. However, the engine endurance test carried out with PB20 showed a more pronounced reduction in engine lubricating oil viscosity compared to DF. The reduction in viscosity of the engine oil samples during the endurance test might increase wear between the engine’s moving parts and reduce engine life [26]. It has been reported that un-burnt biodiesel blend passing into the crankcase may dilute lubricating oil viscosity over time, reducing lubricant film thickness and ultimately increasing component wear in the oil [13]. In addition, it has been also reported that higher viscosity of the fuel, decreases the cone angle of fuel spray and increases the diameter of fuel droplets and their penetration in the combustion chamber. Finally, the liquid of fuel spray can touch the combustion chamber wall and the piston surface, causing the engine oil dilution along with carbon deposits [27]. Moreover, excessive engine oil dilution has the potential to create several problems, such as reduced oil performance and durability and catalyst poisoning [28].

3.3.2. Density

Measurements of engine oil density during long term endurance test provide necessary information regarding contamination with wear metals and dilution of the engine oil with fuel. The density of the used engine oil increases mainly owing to the addition of wear debris, fuel dilution, and increased moisture content [29]. As shown in Fig. 6, the density of the engine oil samples presents an increasing trend with usage. First, the wear of engine parts is faster and dilution with fuel also starts. Thus, the combined effect of these factors influences the rate of increase in the density in the engine oil more in the case of the engine running with the PB20 blend than the run with DF.

3.3.3. Analysis of lubricating oil contamination

Engine oil is basically contaminated due to wear of different engine components. In diesel engines, the most critical wear components are cylinder liner, piston rings, piston and piston pins, bearing, cam, tappet, crankshaft journals, valve guides, valve systems, etc [15]. In an engine lubrication system, wear particles always remain in suspension in the engine oil. Therefore, wear debris originate from different components in engine and are washed away by lubricants and finally get accumulated in the oil sump. Moreover regarding the biodiesel fuels, it has been reported that oxygen available in fuels may decrease exhaust emissions but may also lead to more wear than fuels with high sulfur content. Biodiesel consisting of oxygen and unsaturated fatty acids enters into a chemical reaction with the metal surfaces they come in contact with; thus, oxidation and wear may occur on the metal surfaces [10]. Therefore, during engine endurance tests, the concentration of metallic particles available in the engine oil provides important information about wear rate and the source of ele-

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Fig. 5. Kinematic viscosity of the engine oil at (a) 40 °C and (b) 100 °C during the endurance test.
In wear, iron debris originates from various engine components. Hence metal analysis of lubricating oil gives a fair idea of the wear on vital components in the engine. Thus, the engine condition at that stage can be predicted [30,31]. Fig. 7 shows various wear particles available in the engine lubrication oil during the endurance tests, when the engine was fuelled with either DF or PB20. However, it was determined that no engine oil sample exceeded the warning level suggested in [7].

3.3.3.1. Iron (Fe). In wear, iron debris originates from various engine components such as the piston ring, cylinder head, piston, rings, valves, gears, shafts, rust and crankshaft [15]. In fact as shown in Fig. 7a, the iron concentration in engine oil samples was higher when the engine was fuelled with PB20 compared to DF. The highest level of iron concentration was obtained with PB20 (52 ppm) followed by DF (38 ppm).

3.3.3.2. Chromium (Cr). In IC engines, the chromium in wear debris could be because of wear to the cylinder liner, compression rings, gears, crankshaft and bearing [29]. Inside the cylinder, chromium is found in very small amounts but its strength is high; therefore, as can be seen in Fig. 7b, a very small amount was present in the engine oil. The maximum chromium concentration in the engine oil was 1.7 ppm with PB20 followed by 1.2 with DF.

3.3.3.3. Aluminum (Al). The aluminum concentration in the engine oil indicates piston wear or ingested dust [26]. In Fig. 7c, the diesel-fuelled engine showed less aluminum wear in comparison with PB20 run. The highest level of aluminum concentration was 4.3 ppm with PB20 followed by 3.7 ppm when the engine was run on DF.

3.3.3.4. Copper (Cu). Copper wear in engine oil samples is one of the most significant issues for biodiesel-run engines. Copper may be present because of wear on the bearings, bronze, and bushing [15]. Fig. 7d shows the copper concentrations in engine oil samples. The engine running on the PB20 blend showed higher concentrations of copper in the engine oil when compared to the engine run on DF. The maximum copper concentration in engine oil was 3.8 ppm when the engine was fuelled with PB20 but 2.9 with DF.

3.3.3.5. Lead (Pb). The most probable sources of lead in wear debris is due to wear on bearings and contributions from paints and grease [29]. Fig. 7e shows lead concentrations in the engine oil when the engine was running on either DF or PB20. During the endurance test carried out with the PB20 blend, it showed slightly higher wear debris than with DF. The highest level of lead was 5.1 ppm in the case of PB20 and 4.7 ppm when engine was run on DF.

3.3.3.6. Magnesium (Mg). The magnesium in wear debris may be due to wear on the bearing, gearbox housing and additive depletion [29]. Fig. 7f shows that the engine fuelled with the PB20 blend presented higher concentrations of magnesium in the engine oil compared to DF. The highest level of magnesium observed was 10.2 ppm when the engine was fuelled with PB20, followed by 6.71 ppm when it was fuelled with DF.

3.3.3.7. Molybdenum (Mo). Fig. 7g shows molybdenum concentrations in the engine oil. The concentrations of this element were found to be very low, indicating a very small influence of this element on engine materials and wear. However, it can clearly be seen from Fig. 7g that the molybdenum concentration in the engine oil was higher when the engine was run on PB20.

3.4. Engine fuel economy and exhaust gas emissions

During the 250 h endurance test, engine brake specific fuel consumption (bsfc) and exhaust gas emissions such as HC, CO and NO, shown in Fig. 8 were measured to investigate the effect of DF and PB20 blend due to deposit build up on injector nozzle. It has been reported that the formation of deposits within the holes of the injector nozzle or on the outside of the injector tip may have an adverse effect on overall system performance [3]. Deposits available present inside spray holes of diesel injector are known to reduce the flow of the fuel whereas deposits on the nozzle tip can lead to a distortion of the optimum spray pattern [10]. Thus the injector carbon deposits cause many operational problems, including excessive smoke emissions, loss of power, poor fuel economy, degraded emissions, excessive engine noise, rough engine operation, and poor drivability [32].

3.4.1. Brake-specific fuel consumption (bsfc)

   Engine bsfc with respect to engine run time during the endurance tests is shown in Fig. 8a. It can clearly be seen from Fig. 8a that bsfc with the PB20 blend was higher compared to DF. This increased fuel consumption for the PB20 blend is due to the oxygen content of the fuel, resulting in a lower heating value [33–35]. Therefore, in order to provide the same engine output, more fuel mass flow rate is required due to lower energy content of biodiesel which results in higher specific fuel consumption [36]. The average percentage increase in bsfc for PB20 compared to DF during the endurance tests was 3.88%. However, the percentage increase in bsfc after 250 h compared to 0 h (during the first hour) was 1.49% with DF and 2.22% with PB20.

3.4.2. Hydrocarbon (HC) emissions

   Fig. 8b shows HC emissions with respect to engine run time during the endurance tests. The values of unburned hydrocarbon emissions in the case of the PB20 blend were less than those with DF. The decreased trend in HC emissions from the CI engine compared to DF may be due to better combustion of biodiesel blend due to presence of oxygen [34,37,38]. Moreover, it has been reported that the higher cetane number of biodiesel reduces the combustion ignition delay, and such a reduction has also been related to decreases in HC emissions [39–41]. During the endurance tests, the average percentage decrease in HC emissions with PB20 compared to DF was 11.71%. However, the percentage increase in HC emissions after 250 h of the endurance test compared to 0 h (during the first hour) were 12.12% with DF and 15.52% with PB20. The increases in HC emissions after 250 h of the endurance test may be due to insufficient combustion caused by deposit build up and injector clogging [11].
Fig. 7. Wear concentration during the endurance test.
3.4.3. Carbon monoxide (CO) emissions

Fig. 8c illustrates the CO emissions during the endurance test with the PB20 blend and with DF with respect to engine run time. It can clearly be seen from Fig. 8c that CO emissions with PB20 were less than those with DF, because biodiesel mixture contains extra oxygen molecules that resulted in complete combustion of the fuel and supplied the necessary oxygen to convert CO to CO$_2$ [42,43]. Moreover, increased biodiesel cetane number lowers the probability of fuel-rich zones formation as well as advances injection and combustion, may also justify the CO reduction [44]. The average percentage decrease in CO emissions with PB20 compared to DF during the endurance tests was 11.0%. However, the percentage increases in CO emissions after 250 h of the endurance test compared to 0 h (during the first hour) was 8.17% with DF and 10.32% with PB20.

3.4.4. Nitrogen oxide (NO$_x$) emissions

Fig. 8d presents the NO$_x$ emissions with the PB20 blend and DF with respect to engine run time during the endurance test. Fig. 8d shows that the NO$_x$ emissions with PB20 were higher than with DF. A possible reason for the increase in NO$_x$ emissions may be the increased oxygen level in the blend, which increases local temperatures due to excess hydrocarbon oxidation, and thus it increases the maximum temperature during combustion and thereby increases NO$_x$ formation [45,46]. Therefore, the principal factor leading to the formation of NO$_x$ emissions is a high combustion temperature [47,48]. The average percentage increase in NO$_x$ emissions with PB20 compared with DF during the endurance test was 3.31%. However, the percentage increase in NO$_x$ emissions after 250 h of the endurance test compared to 0 h (during the first hour) was 7.89% with DF and 8.65% with PB20.

4. Conclusions

In this study, the effect of DF as a baseline fuel and the PB20 blend during a 250 h endurance test on injector deposits, lubricating oil, fuel economy and exhaust gas emissions were investigated. Based on the experimental results, the following conclusions can be drawn:

- Photographic views of injectors running on either fuel (DF and PB20) showed some deposit accumulation. However, the injector running with PB20 was found to be dirtier than the injector running with DF. Moreover, deposits on the injector nozzle running with DF were observed to be oily/greasy, whereas dry deposits were observed when engine was fuelled with PB20.
- SEM and EDS analysis at the end of the 250 h endurance test showed that injector deposits when the engine was run with DF were substantially less than when it was run with the PB20 blend. The deposition did not present a uniformly thick layer of carbon. Moreover, deposits on and around the injector tip did not interfere significantly with the nozzle holes. On the other hand, in case of engine fuelled with PB20 blend, it showed relatively thick and overlapping deposits at tip and
around the injection hole exit along with shrinkage in the diameter of the injector nozzle hole. Moreover some nozzle holes are completely closed by apparently the same deposits. All locations of the deposited layer showed higher concentration of carbon.

- During the endurance test, the viscosity of the lubricating oil with respect to engine operating time at 40 °C and 100 °C was decreased when the engine was fuelled with DF and PB20. However, when PB20 was used, it presented a greater reduction compared with DF.
- The density of the engine oil during the endurance tests showed increased with both fuels. However, the increase in the engine oil density was greater when the engine was fuelled with PB20 blend.
- Similarly, the concentrations of metallic particles available in the engine oil during the endurance test were higher when the engine was fuelled with PB20 compared to DF.
- Engine bsfc was higher with PB20 compared to DF. However, during the endurance tests, the percentage increase in bsfc after 250 h compared to 0 h (during the first hour) was 1.49% for DF and 2.22% for PB20.
- The average emissions of HC and CO were decreased with PB20 compared to DF. However, the percentage increases in HC emissions after 250 h compared to 0 h (during the first hour) were 12.12% for DF and 15.52% for PB20. Similarly, in the case of CO emissions, the percentage increase was 8.17% with DF and 10.32% with PB20.
- Average NOx emission increased with PB20 compared to DF. However, the percentage increase in NOx emissions after 250 h compared to 0 h (during the first hour) was 7.89% with DF and 8.65% with PB20.

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