Impact of biodiesel on injector deposit formation

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Abstract

Reducing exhaust emissions from CI engines through continued legislative pressure has resulted in the development of advanced fuel injection equipment. This advanced injection system produces higher temperature and pressure at the injector tip which initiates deposit formation at and around the injector. However, in the short term operation, there are many acceptable studies showing good performance results for engines operating with biofuels in literature. In more extended operations, some of the same fuels can cause degradation of engine performance, excessive carbon deposits and actual damage to the engine. In this research work, the endurance test was carried out for 250 h on 2 fuel samples; DF (diesel fuel) as baseline fuel and JB20 (20% jatropha biodiesel and 80% DF) in a single cylinder CI engine to investigate the effects of JB20 on the injector nozzle deposits and engine lubricating oil. According to the results of the investigations, visual inspection shows that some deposit accumulation appeared on liners of injectors for both fuel samples (DF and JB20). However using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray spectroscopy (EDX), greater carbon deposits at and around the injector tip were observed in case of JB20. Moreover, the lubricating oil analysis showed excessive wear metal concentrations for JB20 when compared to the engine running with diesel fuel. Viscosity decreased very soon to values below the minimum recommended due to dilution with both fuel samples, but especially more with JB20.

Keywords: *injector deposit, jatropha biodiesel, lubrication oil, CI engine*

1. Introduction

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 [1,2]. 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 deposit. 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]. In the literature, different investigation reports have been found regarding the deposit formation on the injector nozzle using biodiesels and their blend fuels. In the short term 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 [5]. It has been reported that some biodiesel properties such as higher viscosity, lower volatility, 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 been operated on for a longer time period [6]. On the contrary, according to Sinha and Agarwal [7], carbon deposits on the cylinder head, injector tip, and piston crown of biodiesel blend (20% rice bran oil methyl ester blend with mineral diesel) with 100 h endurance test was found 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 [8]. It was found that deposit accumulation on liners of injector of B5 and B100 fuel was the greatest. The surfaces of the injectors were dirtier after B5 and B100 use than for diesel fuel. However, greater carbon deposits were observed around the injector tip of the diesel nozzle. Moreover, there was no significant difference found in the degree of coking around the injector tips of B5 and B100. According to Richards et al. [3], biodiesel has been observed to lead to higher deposit formation in the injector nozzle.
The main objective of this study is to carry out 250 h endurance test on diesel fuel (DF) as baseline and JB20 blend, to investigate the injector deposits and lubricating oil analysis.

2. Materials and Methods

A single-cylinder, four-stroke diesel engine is selected for this study. Its major specifications are shown in Table 1. The engine is coupled to an eddy current dynamometer. The endurance test was carried out for 250 h at 2000 rpm and 10 Nm load on 2 fuel samples: DF (diesel fuel) as baseline and JB20 (20% jatropha biodiesel and 80% DF) respectively. The essential fuel properties are given in the Table 2. During endurance test, every day the engine was started for warming up, then the engine was run for 8 h. To investigate the effect of using DF and JB20 after 250 h endurance test, deposit formation at and around the injector tip at various locations were examined with the help of Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray spectroscopy (EDX). The SEM permits the observation of materials in macro and submicron ranges. The instrument is capable of generating three-dimensional images for analysis of topographic features (e.g nozzle tip). When used in conjunction with EDX, it can perform an elemental analysis on microscopic sections of the material. The visual inspection was carried out at 0 h (initial point, new one before inserting), 125 h (mid point) and 250 h (end point). To investigate the effect of DF and JB20 blend on the engine oil, lubricating oil samples were collected after every 20 hours of operation during engine endurance test on each fuels samples. Engine oil was changed after 160 hours operation for each fuel sample to avoid further degradation of lubricating oil. However, according to the engine manufacturer's information, engine oil was supposed to be changed after 200 hours. In this regard, viscosity of engine oil samples was determined according to the ASTM D7042 test method using Anton Paar (SVM 3000) viscometer. Whereas, Multi-element Oil Analyzer (MOA) was used for quantitative and qualitative analysis of any increase in wear metal concentrations caused by an abnormal wear rate during engine endurance test.

Table 1 Specifications of the engine

Engine Type	4-Stroke DI Diesel Engine
Number of cylinders	One
Aspiration	Natural aspiration
Cylinder bore x stroke (mm)	92 x 96
Displacement (L)	0.638
Compression ratio	17.7
Max. engine speed (rpm)	2400
Maximum power (kW)	7.7
Injection timing (deg.)	bDTC 17.0
Injection pressure (kg/cm^2)	200
Power take – off position	Flywheel side
Cooling system	Radiator cooling

Table 2 Main fuel properties

Parameters	DF	JB20
Kinematic viscosity @ 40^{0}C (cSt)	3.317	3.533
Heating value (MJ/kg)	45.5475	43.7385
Density @ 40^{0}C (gm/cm^3)	0.822	0.834
Cetane number (CN)	51	51.9

3. Results and Discussions

3.1 Injector Visual Inspection

During 250 h endurance test on DF and JB20 blend, injector nozzle was photographed at 0 h (initial point), 125 h (mid point) and 250 h (end point). From the visual inspection, it was observed that some deposit accumulation was appeared on liners of injectors for both fuel samples (DF and JB20) at 125 h and 250 h run. However surfaces of the injectors running with JB20 were dirtier than that of injectors running with DF at 125 h. Similar results have been reported by Reksowardojo et al. [8]. In another study, according to Richards et al. [3], biodiesel has been observed to lead to higher deposit formation in the injector nozzle. Moreover, deposits on nozzle running with DF at 125 h and 250 h were observed to be oily/greasy whereas deposits on nozzle running with JB20 at 125 hours and 250 hours were found to be harder.

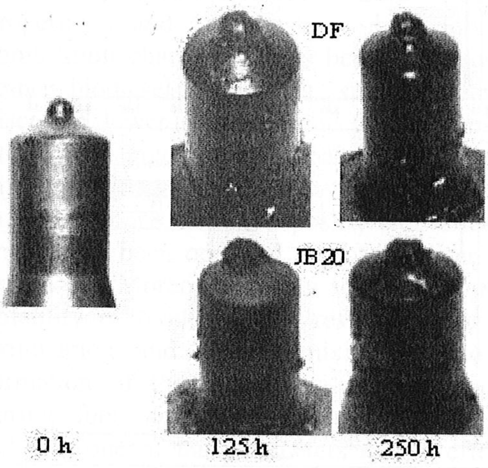

Fig. 1 Appearance of injector nozzle

3.2 SEM-EDX Analysis

This section presents the results of deposit analysis of fuel injectors running on DF (baseline fuel) and JB20 blend respectively. In this regard, deposits at and around the injector tip at various locations were examined with the help of Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray spectroscopy (EDX).

The locations (labeled A to E) indicated on the SEM images in Figs. 2(a) and 3(a) for DF and JB20 are correlated with the areas in which the EDX-spectra are taken along with their quantitative results which are shown in Figs. 2(b) and 3(b) respectively.

Fig. 2(a) and 2(b) showed SEM/EDX elemental analysis including nozzle material as well as deposits of injector tip of CI single cylinder engine running with DF (baseline fuel). Baseline tests with diesel fuel showed dry and hard deposits at and around the injector tip which didn't interfere much with the nozzle holes. It was observed that the elemental composition of the deposits predominantly consisted of carbon and oxygen and some trace amount of different elements. Therefore, oxygen (O) and carbon (C) are generally found to be the main peaks in EDX spectrum in Fig. 2(b). However percentage illustration has been only given to the predominant elements. Deposit analysis at different locations revealed that the carbon and oxygen by percentage weight (wt.%) found to be as: 74.85% and 19.50% at location A, 93.14% and 6.86% at location B, 82.53% and 13.04% at location D and, 67.34% and 18.68% at location E respectively. However at location C, higher percentage of iron (Fe) (67.42%) due to nozzle base material with overall less deposit can clearly be seen in Fig. 2(a) labeled C. 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 to larger polynuclear aromatic hydrocarbons (PAHs) which then nucleate and grow to become carbonaceous deposit. In the spectra, elements originating out of lubricant were also present. As the high-pressure pump is lubricated by engine oil, therefore, a possible source of the lubricant was the transport of these traces from the engine oil 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 lubricant. Another source of Zn may also be from the engine fuel system hardware. The appearance of iron (Fe) and chromium (Cr) at location C is due to nozzle material whereas at location E the appearance of Fe is an artefact of beam penetration to the metal surface. However, the origin of tungsten (W) at location C and E, and nitrogen (N) at location C could not be clarified.

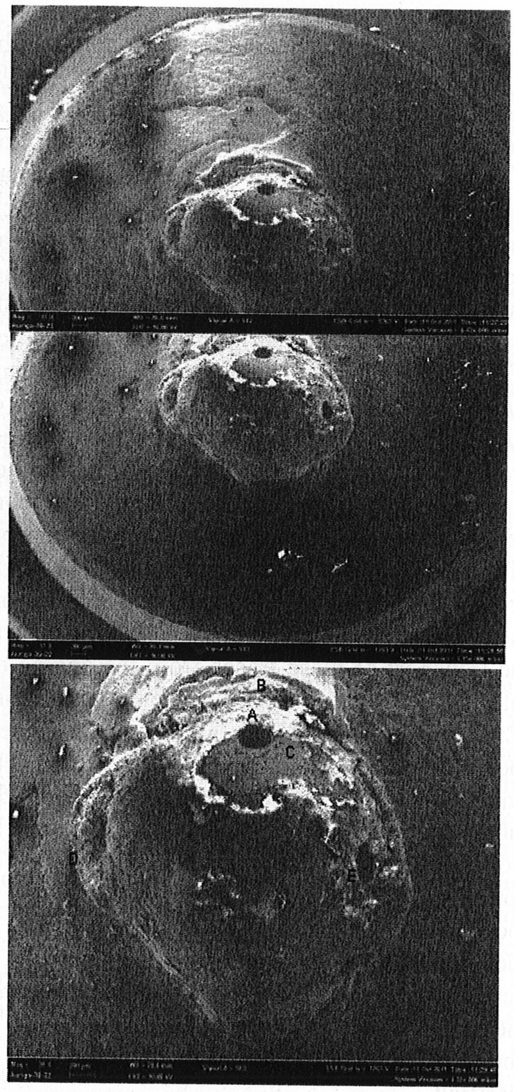

Fig. 2(a) SEM images when nozzle running with DF

In case of JB20, the deposits shown in SEM images in Fig. 3(a) have been observed to be nonuniformly distributed at and around the nozzle tip. Compared to the baseline DF, the deposition has increased amount and thickness at and around the injector nozzle tip when the engine was fuelled with JB20. It can be observed in Fig. 3(a) that injector has dry and dark hard deposits at and around the injector tip area and its nozzle holes are almost covered or otherwise obviously obstructed by the same deposits. Mostly, the higher carbon content was observed in the dark areas.

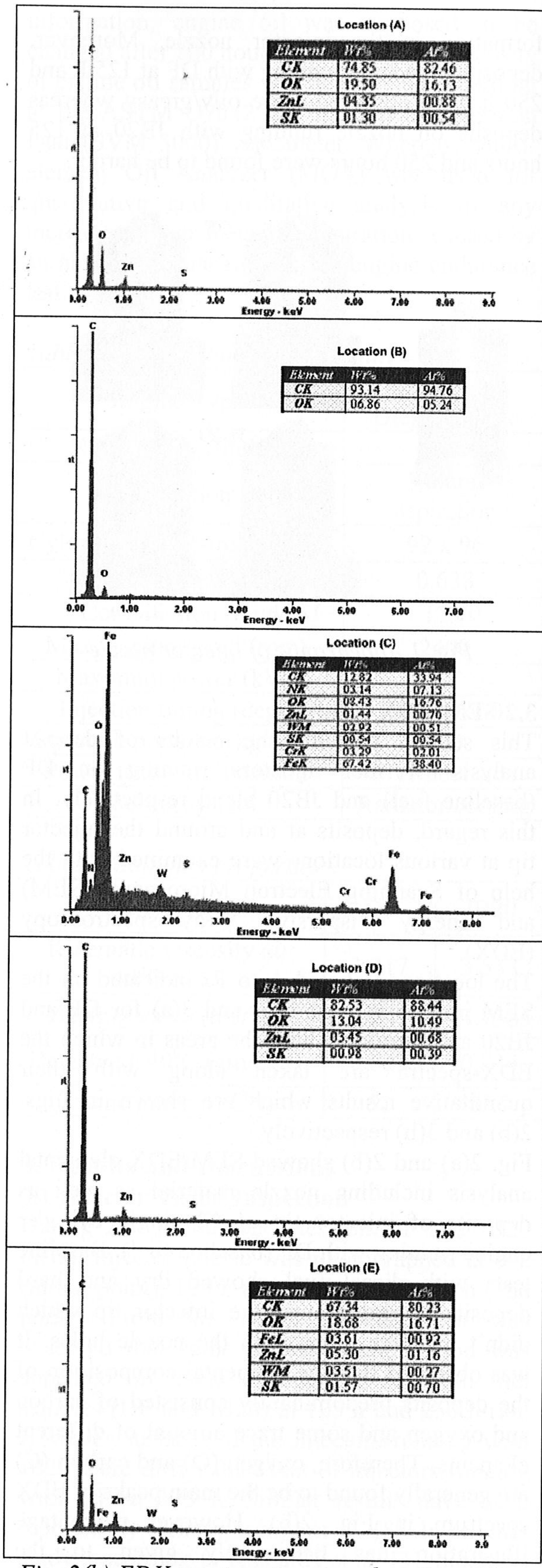

Fig. 2(b) EDX spectra at various locations when nozzle running with DF

This may produce a negative impact on the loss of fuel flow through injector hole, atomization, mixing process leading to lower engine efficiency and increase in exhaust emissions [1,9]. Different types of biodiesel fuels due to their respective feedstock have different properties and combustion behaviors in combustion chamber. It has been reported that some biodiesel properties such as higher viscosity, lower volatility, 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 been operated on for a longer time period [6]. Moreover, higher viscosity and low volatility of biodiesel fuel result in poor fuel atomization and air/fuel mixing due to the formation of the larger size of fuel droplets during fuel atomization in engines. 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 the tendency of deposit formation rate may increase [10].

The chemical elements observed in the deposits and identified by EDX-spectra in Fig. 3(b) are almost similar to the DF. However, as these measurements have been performed on the exterior surface of the injection nozzle which is protruded into the combustion chamber, and thus in the path of swirling combustion gases, it is possible that these deposits will also contain combustion products. This may show the presence of some metals that would be found in lubricating oil, either from the lubricating oil additive package or from the wear metals that would accumulate in the lubricating oil [11]. In general, addition to carbon (C), oxygen (O) and some base materials like iron (Fe) and chromium (Cr), the EDX spectra (ref. Fig. 3(b)) on injector nozzle tip shows the presence of phosphorus (P), sulfur (S) and zinc (Zn). These latter elements are common components of engine oil additive systems used in the crankcase lubricating oil and are not found in fuel additives. Moreover, percentage (% wt.) illustration for the predominant elements (carbon and oxygen) in the deposit at various locations (labeled A to E) in SEM images in Fig. 3(a) and correlated with the EDX-spectra shown in Fig. 3(b) on injector tip is found to be 91.21% and 6.51% at location A, 89.25% and 10.75% at location C, 85.55% and 10.72% at D and, 85.32% and 14.68% at location E respectively. Moreover similar to DF higher percentage of iron (Fe) (62.72%) at location B can clearly be seen in Fig. 3(a) at labeled B due to nozzle base material with little deposit. However, appearance of some other elements could not be clarified such as: nitrogen (N), aluminum (Al) and silicon (Si) at location B in Fig. 3(b)

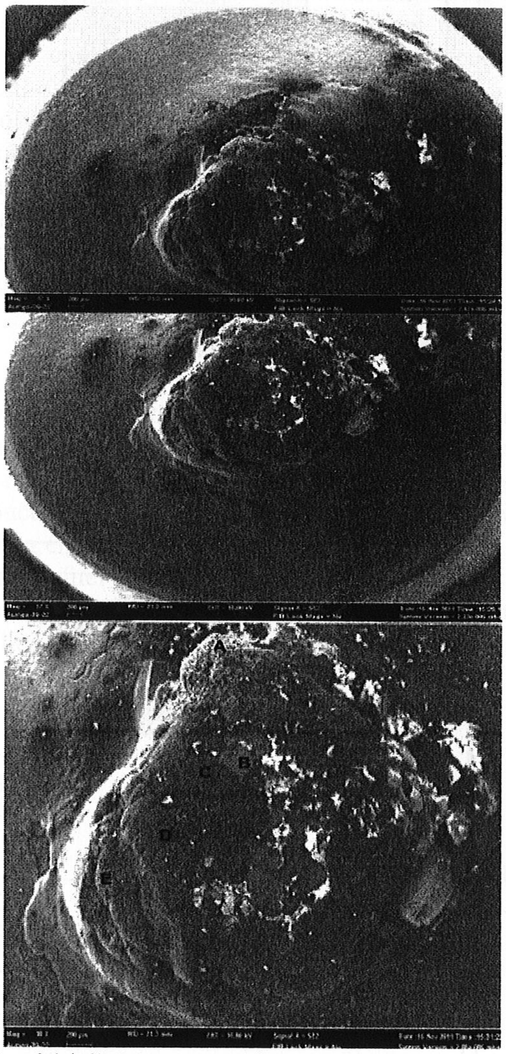

Fig. 3(a) SEM images when nozzle running with JB20

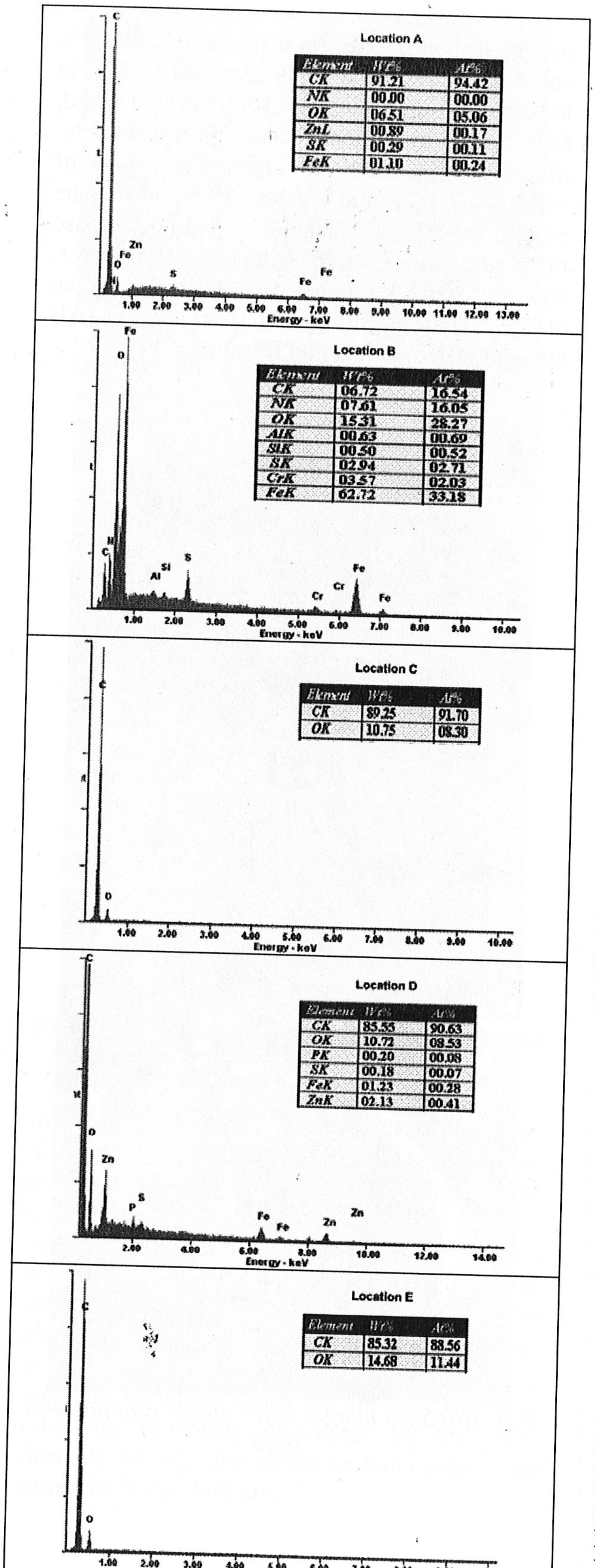

Fig. 3(b) EDX spectra at various locations when nozzle with JB20

3.3 Lubricating Oil Analysis

In IC engines, Lubricating oil plays very important role. It is consisted of complex mixtures of hydrocarbons and is a combination of base oils and additives. Mostly lubricants are used to reduce the friction and lessen wear of various sliding and rotating component in engine and to keep the different elements clean, being able to work as detergents, dispersant agents, anti-oxidants, viscosity modifiers, etc [12,13]. In order to investigate the effect on the engine oil during endurance test carried out on DF and JB20 blend, lubricating oil samples were collected after every 20 h during engine endurance test. The results of the investigations are presented the following sections.

3.3.1 Viscosity

Viscosity is one of the most important properties of engine lubricating oils. Higher viscosity indicates that the lubricant is being deteriorated by either oxidation or contamination, while a decrease usually indicates due to lubrication oil dilution [14]. Viscosity was determined at 40^0C and 100^0C according to the ASTM. Viscosity determined at 100^0C was thought to be close to the average oil temperature during engine operation [8]. As a result of investigation, it can be seen in Fig. 4(a) and 4(b) that there was a decrease in oil viscosity at both 40^0C and 100^0C when engine was fuelled with both DF and JB20 during the endurance test. This decrease in lubricating oil viscosity can most likely be attributed to the fuel dilution of the crankcase oil. The applicable range of engine oil/lubricating oil at 40°C and 100°C are '80 cSt to 150 cSt' and 12 cSt' to 20 cSt' respectively [15]. However engine endurance test carried out on JB20 showed more reduction in engine lubricating oil viscosity as compared to DF. The viscosity reduction of the engine oil samples during endurance test might increase wear between engine moving parts and reduce engine life [16]. In another study, it has been reported that un-burnt biodiesel blend passing to the crankcase may reduce lubricating oil viscosity over time, reducing lubricant film thickness and ultimately increasing component wear in the oil [8]. Similarly, according to Gramstad et al. [17], poor atomization and larger droplets size from the injectors due to higher viscosity, surface tension, and specific gravity for biodiesel fuel combined with a lower volatility resulted in incomplete combustion of the fuel and the left over un-burnt fuel on the cylinder walls is scraped into the crankcase by the piston rings. Further this un-burnt fuel is dissolved with the engine oil, causing engine oil degradability. Thus biodiesel fuel accumulates in the crankcase resulting in higher engine oil dilution. Moreover, excessive engine oil dilution has the potential to create several problems, such as reduced oil performance and durability and catalyst poisoning [18]. While keeping in view the above facts, it can be seen in Fig. 4(a) and 4(b) that more decrease in lubricating oil viscosity was observed when engine was fuelled with JB20 compared to DF.

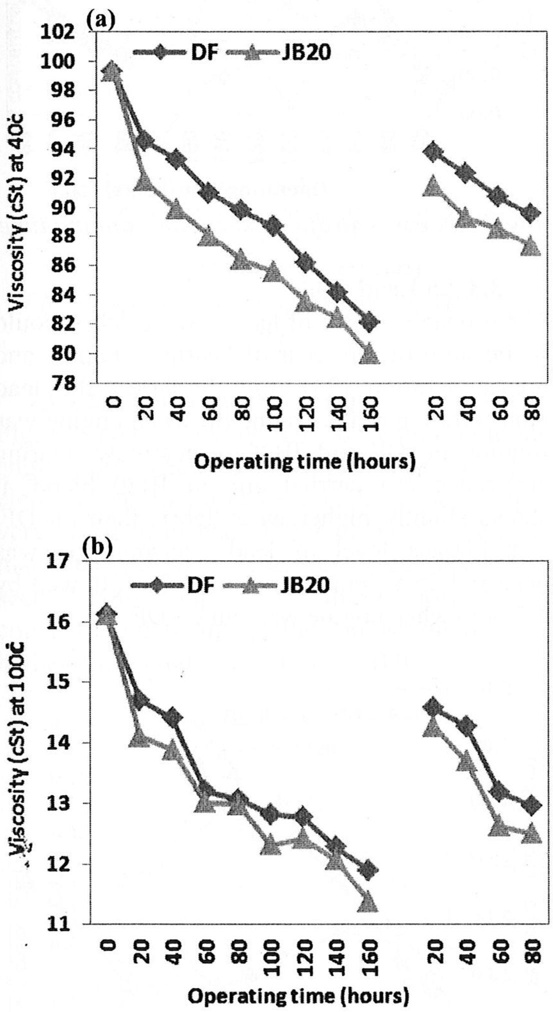

Fig. 4 Kinematic viscosity of the engine oil at 40^0C and 100^0C during endurance test

3.3.2 Engine Wear

During engine endurance test, concentration of the metallic particles available in the engine oil provides sufficient information about wear rate, source of element. Hence metal analysis of lubricating oil gives a fair idea of wear of vital components of the engine. Therefore, the engine condition at that stage can be predicted [19,20]. It has been reported that oxygen available in biodiesel fuels may decrease exhaust emissions but may also lead to more wear than fuels with high sulfur content. Biodiesel consisted of oxygen and unsaturated fatty acids enter into a chemical reaction with the metal surfaces that they come into contact. Thus as a result of investigations, oxidation and wear may occur on metal surfaces [21]. Figs. 5-11 show the iron (Fe), chromium (Cr), aluminum (Al), copper (Cu) lead (Pb), magnesium (Mg) and molybdenum (Mo) concentrations respectively from the engine lubricating oil during the endurance test, when engine was fuelled with DF and JB20. However, it was found that no engine oil sample exceeded the warning level suggested in [5].

3.3.2.1 Iron (Fe)

In wear, iron debris originates from various components such as piston ring, cylinder head, piston, rings, valves, gears, shafts, rust and crankshaft [22]. In Fig. 5, in fact iron concentration in engine oil samples was higher when engine was fuelled with JB20 compared to diesel fuel (DF). The highest level of iron concentration was obtained by JB20 (43 ppm followed by DF (38 ppm) respectively.

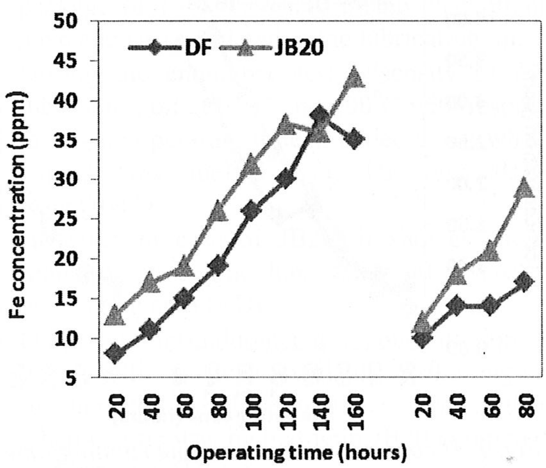

Fig. 5 Fe concentration vs. engine running time

3.3.2.2 Chromium (Cr)

In IC engine, the chromium in wear debris could be because of wear of the cylinder liner, compression rings, gears, crankshaft and bearing [23]. Inside the cylinder, chromium is found in a very small amount but its strength is high, therefore as it can be seen in Fig. 6, a very small amount was present in engine oil. The maximum chromium concentration in engine oil was 1.6 ppm for JB20 followed by 1.2 for DF.

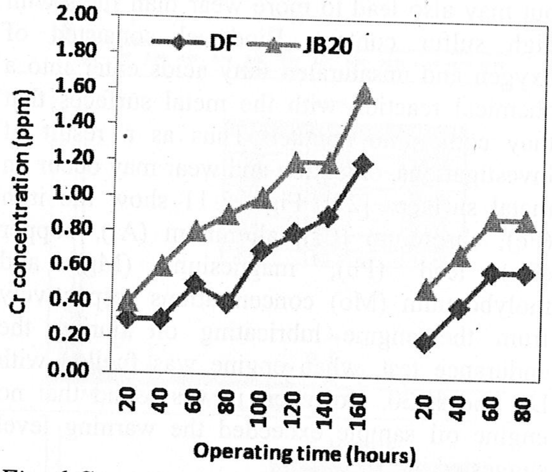

Fig. 6 Cr concentration vs. engine running time

3.3.2.3 Aluminum (Al)

The aluminum concentration in the engine oil indicates piston wear or ingested dust [16]. In Fig. 7, diesel fuelled engine showed lower aluminum wear in comparison with JB20. The highest level of aluminum concentration was occurred 3.9 ppm in case of JB20 followed by 3.7 ppm when engine was run on DF.

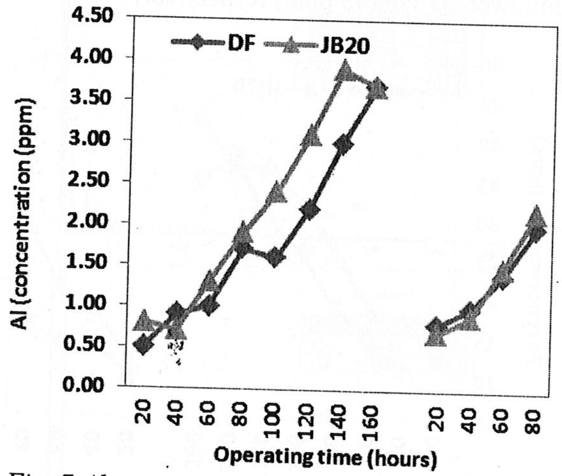

Fig. 7 Al concentration vs. engine running time

3.3.2.4 Copper (Cu)

Copper wear in engine oil samples is one of the most significant issues for biodiesel run engine. Copper concentration could be obtained because of wear of the bearings, bronze, and bushing [22]. Fig. 8 shows the copper concentration in engine oil samples. The engine running on JB20 blend shows higher concentrations of copper in the engine oil when compared to DF. The maximum copper concentration in engine oil was 3.7 ppm when engine was fuelled with JB20 followed by 2.9 in case of DF.

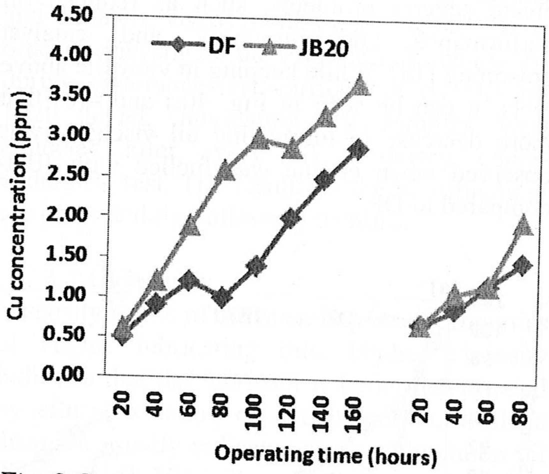

Fig. 8 Cu concentration vs. engine running time

3.3.2.5 Lead (Pb)

The probable source of lead in wear debris could be because of the wear of bearings, paints, and grease addition [23]. Fig. 9 shows the lead concentration in the engine oil when engine was running on DF and JB20 respectively. During endurance test carried out on JB20 blend, it shows slightly higher wear debris than on DF. The highest level of lead concentration was occurred 35.5 ppm in case of JB20 followed by 4.7 ppm when engine was run on DF.

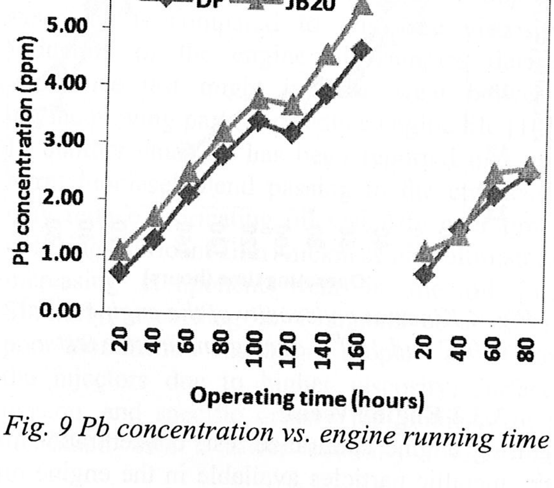

Fig. 9 Pb concentration vs. engine running time

3.3.2.6 Magnesium (Mg)

The magnesium in wear debris may be occurred due to wear of the bearing, gearbox housing and additive depletion [23]. Fig. 10 shows that engine running on JB20 blend presents higher concentrations of magnesium in the engine oil when compared to DF. The highest level of magnesium concentration was observed 9.69 ppm when engine was fuelled with JB20 followed by 6.71 ppm in case of DF.

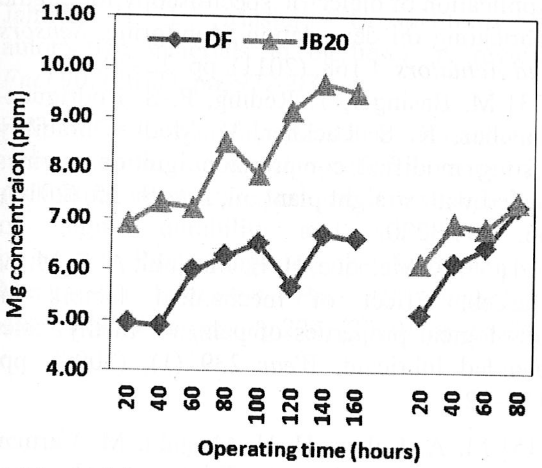

Fig. 10 Mg concentration vs. engine running time

3.3.2.7 Molybdenum (Mo)

Fig. 11 shows molybdenum concentration in the engine oil. The concentration value for this element was 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. 11 that molybdenum concentration in the engine oil is found to be higher when engine was run on JB20.

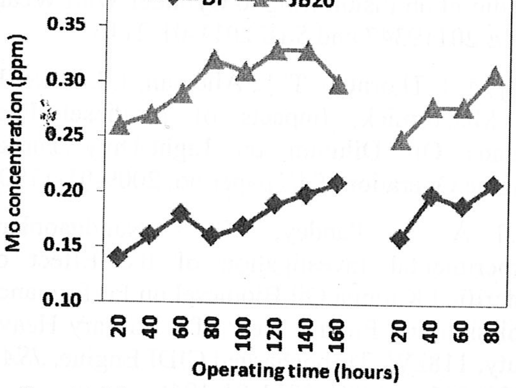

Fig. 11 Mo concentration vs. engine running time

4. Conclusion

In this study, the effect of DF as a baseline fuel and JB20 blend on injector deposit and lubricating oil were investigated during the 250 h endurance test on each fuel sample. In this regard, based on the experimental results, the following conclusions can be drawn:

- From the visual inspection, some deposit accumulation was found on liners of injectors when engine was run on both fuel samples (DF and JB20).
- Deposits on nozzle running with DF at 125 h and 250 h were observed to be oily/greasy.
- However surfaces of the injectors running with JB20 were dirtier than that of injectors running with DF at 125 h.
- At the end of endurance test, SEM images on injector tip when engine was run on DF showed dry and hard deposits at and around the injector tip which didn't interfere much with the nozzle holes.
- Whereas in case of JB20, injector showed dry and dark hard deposits along with increased amount and thickness of the deposits at and around the injector tip area and its nozzle holes are found to be almost covered or otherwise obstructed by the same deposits.
- At the end of endurance test on DF and JB20, EDX analysis showed almost similar elemental composition of the deposits which predominantly consisted of carbon and oxygen and some trace amount of different elements originated either from the engine oil additive package or from the wear metals that might have been accumulated in the lubricating oil.
- During the endurance test, viscosity of the lubricating oil at 40^{0}C and 100^{0}C with respect to engine operating time was decreased when engine was fuelled with DF and JB20 respectively.
- However in case of JB20, it showed more reduction in engine lubricating oil viscosity when compared to DF.
- During engine endurance test, concentration of the metallic particles available in the engine oil showed that these particles were higher when engine was fuelled with JB20 compared to diesel fuel (DF).
- However, the values presented in Figs were found to be lower than the suggested warning level for both fuel samples.

5. Acknowledgement

The authors would like to acknowledge University of Malaya for the financial support through project NoUM.C/HIR/MOHE/ENG/O7, and PPP, No. PS114/2010A.

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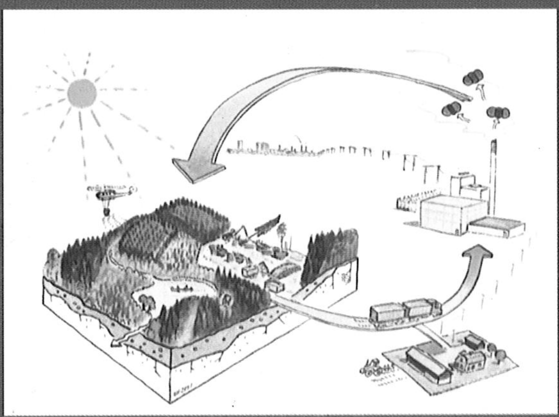

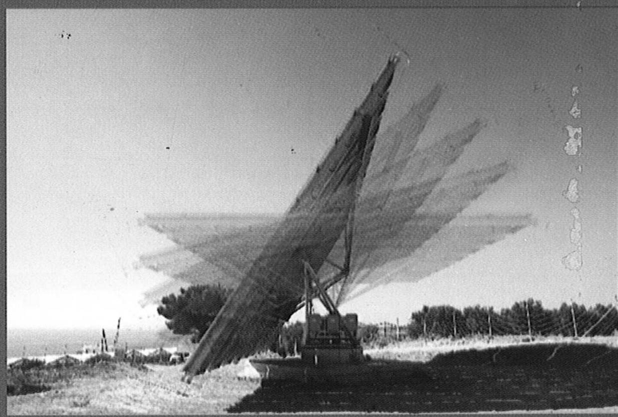

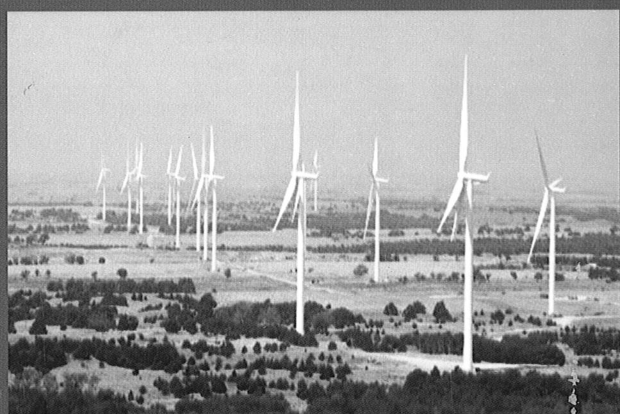

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