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Characterization of lubricant degeneration and component deterioration on diesel engine fueling with straight plant oil

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Abstract

Straight Plant Oils (SPOs) are promising alternatives to diesel fuel in some particular applications, e.g. electrification in remote areas and sustainable modernization of artisan fishing vessels. Moderate commercialization of SPOs is yet to be realized due to lack of critical information on engine durability, lubricant degeneration, and effective methods to offset the adverse effect of directly using SPOs on diesel engines. In this paper, the experimental study evaluates the long term impacts of crude Jatropha oil (JO) on a small diesel engine generator through 300 hour durability tests. The testing results demonstrate the evolution of gaseous emissions, the trace metal element variations in lubricant, and the carbon deposit formation on engine components. The associated fuel spray experiments in the controlled environment further reveal JO atomization patterns and provide important evidence to interpret why JO has greater influence on engine durability than diesel.

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Keywords: Straight plant oils, Engine durability, Lubricant degeration, Fuel atomization

1. Introduction

The fast growth of developments and regulations emphasize the importance of developing and seeking alternative fuels to reduce emissions as well as maintain operational costs for small artisan fishing vessels at acceptable levels in developing countries. The foreseeable future highlights various alternative sources of energy with potential to reduce emissions, e.g. liquefied natural gas (LNG), biogas, and biofuels, i.e. Straight Plant Oils (SPOs) and biodiesels. SPOs have been extensively studied by researchers and widely acceptable in developing countries, due to requiring no significant modification to small marine diesel engines, having comparable properties to diesel, being easy and inexpensive to produce, and offering smaller carbon footprints compared to biodiesels from transestification. The direct use of SPOs have

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shown satisfactory engine performance in short term tests [1-3], although the brake thermal efficiency of engine running on SPOs is found to be lower, whereas the brake specific fuel consumption is higher compared to diesel. The long term engine operation studies on SPOs are very limited and often only present experimental results of engine outer performance and emissions. Pan et al. [4] reported that the gaseous emissions of the engine on JO, such as CO, CO_2, were found to be higher than diesel oil and NO_x lower in the 300 hour durability test. Kalam and Masjuki [5] stated that preheating crude palm oil caused decreased CO and HC and increased NO_x during the 100 hour operation. Another study on engine durability with crude palm oil for 500 hours [6] indicated that inner engine parts suffered deterioration after the prolonged use of SPO, such as carbon deposit accumulation, inadequate spray, wear of piston rings, cylinder liner scuffing and valve sticking. Also using JO as alternative fuel on engine endurance tests for 512 hours, Agarwal and Dhar [7] reported the lubricant life depleted at 400 hours. The concentration of metal elements in lubricant was firstly detected for SPO fueled engines, however, the flame Atomic Absorption Spectroscopy (AAS) is used to identify the increasing trends of the trace metal elements, which fails to detect the trace of Calcium, a functional element in any lubricant, and some other metal elements, due to specific element interference and high detection limits of AAS. In this study, instead of AAS, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is applied to detect all crucial trace metal elements, including both functional and debris metal elements, within the lubricant after the engine durability tests on JO. Together with the engine performance, emission, and fuel spray test results, a thorough picture of engine durability on SPO is presented.

2. Methodology and materials

A naturally aspirated, water-cooled, four-stroke, direct injection, single cylinder Yanmer TF120M diesel generator engine with 6.5 kWe output at a constant speed of 2400 rpm is used in the durability tests for 300 hours. JO is applied as the engine fuel, which is preheated and maintained at 90°C during the cumulative operating time of the test. The chemical composition of JO was given in the literature [8]. During the tests, the engine is operating at a constant load of 4.9 kW corresponding to 75% of the full load. Horiba MEXA-1600D exhaust gas analyzer is used to measure the gaseous emissions. The instrument is equipped with analyzer modules compliant with ISO-8178. At intervals of every 100 hours, the engine is overhauled for inspection. The considerable amount of carbon deposits accumulated around the tip of injector are cleaned to ensure prolonged operation of the engine. The lubricant samples are collected directly from the lubricant base. ICP-MS is used for determining the concentrations of metals and some non-metals in the lubricating oil samples in a very high sensitivity and precision of parts per trillion. The detailed testing bench configuration was presented by Wu et al. [8]. The fuel spray testing bench for atomization is coupled with Schlieren optical module for spray pattern capture with high speed camera. Four injection pressures, two fuel temperatures, and two nozzle sizes are adjusted as the input variables in the tests. The captured images are used to identify spray cone angles and penetration lengths.

3. Results and discussions

3.1 Engine performance and emissions

Figure 1 illustrates the moving average of engine overall efficiency running on JO for the complete duration of 250 hours test. It can be seen that the fluctuation of engine efficiency is from 21.8% to 18.2% before the engine failed. The result shows that the efficiency of the engine increases after the intervals of 100 and 200 hours for approximately 30 hours before it starts to drop again. The decreasing trend and the temporary increase are mainly attributed to the carbon deposit formation and removal around the injector tip, which affecting the behaviour of fuel sprays. The higher viscosity of JO results in large fuel droplets affecting the atomization of fuel causing the inadequate air/fuel mixture. This scenario leads to carbon deposits on the injector tip, the piston crown and the combustion chamber. The deposits around the injector tip would alter the symmetry of spray nozzle, deteriorating the quality of the spray and reducing the fuel flow rate. These produce incomplete combustion, decreased engine efficiency and increased emissions. In addition, besides the carbon deposition the lubricant oil gelling participated critically after 166 hours of running duration. The viscosity of the lubricant increased dramatically leading to an increase in the friction between the engine parts, thus efficiency keeps dropping until engine failure at 250 hours.

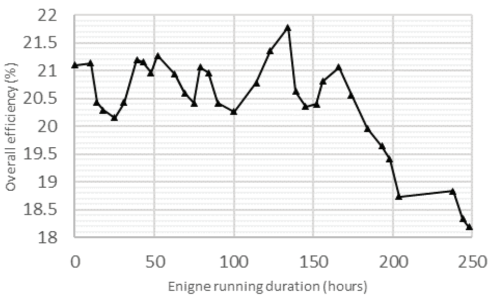

Figure 1. JO fueling overall engine generation efficiency for 250 hours

The exhaust gas emissions emitted by JO fuelled diesel engine during the 250 hours durability test were recorded. Figure 2 presents the moving averages of the exhaust gas emissions, namely CO, NO_x and HC associated with the exhaust temperature. The combustion characteristics are reflected by the exhaust temperature. The temperature fluctuation is between 570 to 670°C. Carbon deposition around the injector tip provokes slow combustion rate, prolongs the process and lowers the thermal efficiency. Therefore, the energy converted from the fuel injection is less, and besides the unburnt fuel forming carbon deposition, a part of the fuel might burn late in the process, thus the exhaust temperature increases.

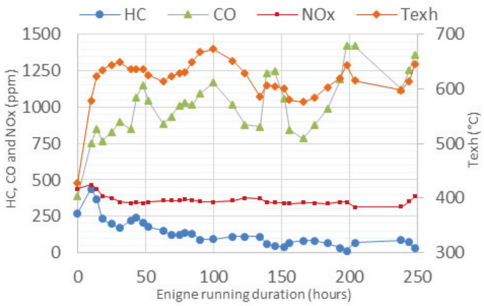

Figure 2. Evolution of exhaust gas emissions during 250 hours

Unburnt hydrocarbon (HC) is generated through non-homogenous mixture of air/fuel as well as insufficient temperature in the combustion chamber due to the unburnt fuel. One of the major sources of unburnt HC are the crevices in the combustion chamber. These regions are the piston ring, the valve seats and the cylinder head gasket crevices, where unburnt mixtures in the compression process are forced to these crevices and completely or partially burnt during the combustion then flow back into the cylinder. Due to the formation of carbon deposits, the volume of these crevices is reduced, in turn, the decreasing HC production. HC also oxidizes in the exhaust process, where the rate of oxidation is dependent on the exhaust temperature. The activation of HC oxidation starts at 600°C. In Figure 2, it shows that the exhaust temperature mostly over 600°C. The intensified oxidation of HC increases the level of CO, hence the tendency of CO increase is coupled with the rising of exhaust temperature as well as the decrease of HC.

The engine failure after 250 hours of running time is a result of gelling of the lubricant. The significant increase in lubricating oil viscosity is an indication of degradation due to JO contamination.

One of the main routes for contaminates to enter the lube oil sump is through piston rings and cylinder clearances. Wear debris and unburnt fuel film are picked up by the lubricant and washed off by piston rings carrying it into the crankcase and mixed with the lube oil. In addition, in blowby mechanism gases such as unburnt fuel mixture, NO_x are forced into the lube oil passing through the clearance of the cylinder. According to Song and Choi [9], the blowby effect increases correspondingly with wear of piston rings. A further study of metal elements chemical analysis is necessary to evaluate the presence and quantity of wear particles in the lubricant to understand the wear of various parts.

3.2 Lubricant degeneration

Metallic elements in the lubricating oil are divided into two groups: additive elements and wear elements. Additives are chemical elements that exist in the lubricant to impart properties and consumed with the running duration of the engine. Wear elements are accumulated in the lubricating oil from wear debris of different engine parts, e.g. piston rings. Figure 3(a) shows the concentration of the additive elements Zinc (Zn), Platinum (P) and Calcium (Ca) in the lubricant. Zn and P exist in Zinc Dialkyl Dithiophosphates (ZDDP), which are used for anti-wear and as an antioxidant. Ca is used as a detergent to control the rust and the accumulation of resinous in the engine. These elements are originally high in content. It is observable that these elements are decreasing in content with the extended running time of the engine. The significant drop in Zn and P reduces the effect of ZDDP, which results in increase in wear of the engine components. The concentration increase of Zn after 200 hours is remarkable, which, however, indicates the deterioration of lubricant and anti-wear effects. The zinc debris is due to the wear of brass components and bearings.

Figure 3(b) and 3(c) demonstrates the concentration of wear elements Copper (Cu), Manganese (Mn), Chromium (Cr), Iron (Fe), Lead (Pb) and Aluminium (Al) in the lubricating oil. The chemical analysis of these metallic elements is for the indication of wear of engine parts during the durability test of JO fuelling. Similar findings are supported by Agarwal and Dhar [7], and also can be found on the studies using biodiesels as engine fuel, e.g. Nantha and Thundil Karuppa [10], which indicates the similar issue of component wearing for engines fuelling with SPOs or biodiesels.

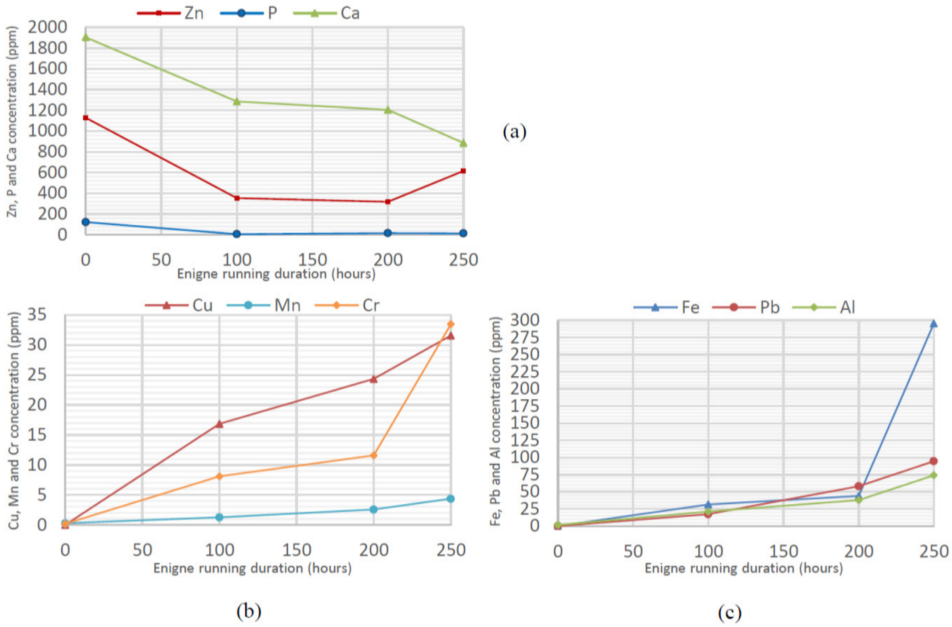

Figure 3. Concentration of various metallic elements

3.3 Carbon deposition and component deterioration

The deterioration of the engine is a reflection of the carbon deposition accumulated on the engine in-cylinder parts as well as lubricant contamination and thickening. It is observed that the direct use of JO as fuel results in excessive deposits formation on various internal parts. It is clear that carbon residues filled up the concave of piston head and covered the nozzle of the injector. Therefore, the volumetric efficiency of the piston concave and the functionality of the injector are decreased. Sidibé et al. [11] reported that the formation of deposits starts on the tip of injector as it is the coldest part in the combustion chamber, pursued by the rings and the throat, the wall of the chamber, then the piston head, etc.

The formation of carbon deposits are mainly attributed to the physicochemical properties of JO, which influences the characteristics of fuel spray and combustion processes. Akintayo [12] showed that the iodine value of JO is 105, which mean it is classified as Di-unsaturated oil. The higher the value the more unsaturated is the oil, hence producing deteriorated combustion, which results in longer evaporation time and ignition delay, associating with carbon deposition. The higher viscosity of JO has a great influence on the combustion as well, as it leads to pressure drop in the flow of the fuel injected and causes unstable atomization. The flash point of JO is about 2.5-3 times greater than diesel, where for JO it is 229±4°C and 71±3°C for diesel. These characteristics produce larger droplets difficult to be atomized and vaporized, thus spray penetration length is expected to be increased and cone angle decreased, which leads to fuel impingement. Ryan et al. [13] conducted a Jet Fuel Thermal Oxidation test and stated that the degree of unsaturation (iodine value) affects the deposition tendency, and the fuel viscosity caused impingement which aggravates the carbon deposition. An independent experimental study on fuel sprays in controlled environment is followed to verify the hypothesis and provide possible remedy for SPOs.

Table 1. Spray cone angles of JO and diesel

Fuel type	Nozzle diameter (mm)	Injection pressure (MPa)	Preheating temperature 60 °C	90 °C
			Spray angle (degree)	
JO	0.12	60	7.33	7.55
		80	7.66	7.76
		100	7.76	7.83
		120	8.20	8.41
	0.18	60	6.67	7.72
		80	7.38	9.74
		100	7.53	9.30
		120	8.14	9.72
Diesel	0.12	60	13.00	11.53
		80	13.30	12.55
		100	13.62	13.55
		120	13.63	13.58
	0.18	60	11.69	11.06
		80	12.23	12.06
		100	12.64	11.72
		120	12.65	11.73

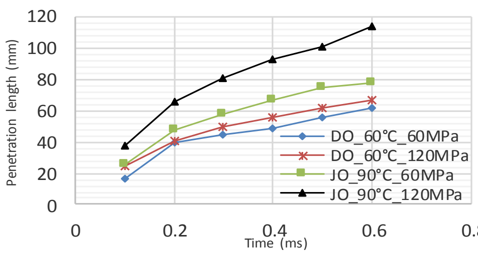

Figure 4. . Diesel and JO penetration lengths under different injection parameters

3.4 Atomization of JO and diesel

Table 1 shows the effect of different fuel injection conditions on the spray cone angle of JO and diesel. For both fuels under the same condition of preheating temperature and nozzle size, the spray angles become wider with the increase of injection pressure. The higher pressure increases the mass of air within the spray producing smaller droplets size and improved atomization. The large size of the nozzle hole with a diameter of 0.18 mm has a minor effect on the cone angles with JO, while it causes narrower angles with diesel compared to 0.12 mm.

The preheating temperature of 90°C has a greater influence on the angle compare to increased nozzle diameter and injection pressure. The JO droplets get smaller and the jet divergence angle increases. This is related to JO properties, as preheating decreases the viscosity and the surface tension of the fuel, where such properties are the cause of poor JO fuel injection. It is noticeable that preheated diesel cone angles are smaller, which is due to the evaporation of the spray in the outer region.

Figure 4 illustrates the comparison of spray penetration length of both fuels at injection pressure of 60 MPa and 120 MPa as well as temperature of injection at 60°C for diesel and JO at 90°C. It is noticeable that the primary breakup point occurs at 0.2ms for diesel, whereas it is difficult to be identified with JO. However, JO with injection parameters of 90°C and 60 MPa presents shorter penetration and shows similar performance to diesel at 60°C and 120 MPa, which suggests that preheating and lowering injection pressure may assist SPO maintaining similar spray pattern as diesel, in turn, reducing carbon deposition, and the following lubricant degeneration, eventually, prolong the endurance of the engine.

4. Conclusion

The durability tests on JO fuelling indicate severe carbon deposition on internal components, which is caused by poor combustion of JO associated with its impaired atomization observed in the spray tests. Lubricant degeneration is a consequence of the engine deterioration, but it also accelerates the engine failure. It is recommended to modify injector and draft new maintenance guidance for SPOs on engines.

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