Almutairi A, Guo B, Wu D, Roskilly AP.

Characterization of lubricant degeneration and component deterioration on straight plant oil engine durability.

***In: The 8th International Conference on Applied Energy (ICAE2016)*. 2016, Beijing, China.**

The 8th International Conference on Applied Energy – ICAE2016

Characterization of lubricant degeneration and component deterioration on straight plant oil engine durability

Abdullah Almutairi [a], Baichuan Guo [b], Dawei Wu [a] *, Anthony P. Roskilly [b]

[a] *School of Marine Science and Technology, Armstrong Building, Newcastle University NE1 7RU, UK*
[b] *Sir Joseph Swan Centre for Energy Research, Stephenson Building, Newcastle University NE1 7RU, UK*

Abstract

Straight Plant Oils (SPO) are a promising alternative to diesel for engines, especially in some applications, e.g. remote area electrification, artisan fishing vessels, etc. Due to having comparable properties to mineral diesel, being easy to produce compared to biodiesels from transestification process, and offering smaller emissions footprints, SPOs has been extensively studied by researchers and widely acceptable in the developing countries. However, it is just a stone's throw away from commercialization, because the information on lubricant degeneration and engine component durability is missing, which is crucial to provide effective engine maintenance methods. The experimental study aims to evaluate the long term impacts of crude Jatropha oil (JO) on a small diesel engine generator by measuring gaseous emissions and trace metal elements in lubricant oil, and visual inspection of engine components in overhauls. Engine durability tests of 300 hours on JO were conducted to demonstrate that emission evolution, accumulation of engine part debris in lubricant, loss of functional elements in lubricant, and formation of carbon deposit on components. Fuel spray tests for atomization patterns were conducted to provide evidence on how JO has greater impacts than diesel on engine durability.

Selection and/or peer-review under responsibility of ICAE

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

1. Introduction

The fast growth of developments and regulations emphasise the importance of developing and seeking alternative fuels to reduce emissions as well as maintain operational costs for small 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 such as Straight Plant Oils (SPOs) and biodiesels. SPOs do not require significant modifications to diesel engines, and offer smaller carbon footprints and lower costs in comparison of their counterparts-biodiesels. The

* Corresponding author. Tel.: +44-191-208-8113
E-mail address: dawei.wu@ncl.ac.uk

direct use of SPOs have shown satisfactory engine performance in short term tests. 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 [1-3]. The long term operation study of Pan et al. [4] shows that the exhaust gas emissions of SPO, such as CO, CO_2, are found to be higher than diesel oil and NO_x lower, while Kalam and Masjuki [5] stated that preheating SPO caused decreased CO and HC and increased NO_x. Also, inner engine parts have suffered deterioration after prolonged use of vegetable oil, such as accumulation of carbon deposits, inadequate spray, wear of piston rings, cylinder liner scuffing and valve sticking [6]. Agarwal and Dhar [7] conducted 512 hours endurance test on preheated JO and reported that carbon deposits on the piston top was found to be 8 times greater than diesel and the life of the lubricant depleted at 400 hours. The concentration of metal elements in lubricant was found to exhibit an increasing trend coupling with the cumulative running duration of the test.

2. Methodology and materials

In this research, the experiments are conducted on a stationary, naturally aspirated, water-cooled, four-stroke, direct injection, single cylinder Yanmer TF120M diesel generator engine as a prime mover and it is loaded through a single phase alternator, which generates maximum 6.5 kWe at a constant speed of 2400 rpm to maintain an electrical frequency of 50 Hz. The duration of the test is 300 hours operating at a constant load of 4.9 kW corresponding to 75% of the engine full load. JO is preheated and maintained at 90°C during the cumulative operating time of the test. Horiba MEXA-1600D exhaust gas analyser is used to measure the gaseous emissions. The instrument is equipped with analyser 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. Inductively coupled plasma mass spectrometry (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 trilling.

The spray test bench for atomization tests is coupled with Schlieren optical module for spray pattern capture with high speed camera. The images are used to investigate the spray cone angle and penetration length. Four injection pressures, two fuel temperatures and two nozzles with different diameters are the variables used in the tests.

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 engine failed. Also, the result shows that the efficiency of the engine increases after the intervals 100 and 200 hours for approximately 30 hours before it starts to drop again. The decreasing trend and the temporary increase are mainly related to the carbon deposits around the injector tip affecting the behaviour of the fuel spray causing the fluctuations. The higher viscosity of JO results in large fuel droplets affecting the atomization of the fuel causing inadequate air/fuel mixture. This scenario leads to carbon deposits on the injector tip, piston top and 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 effects of 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.

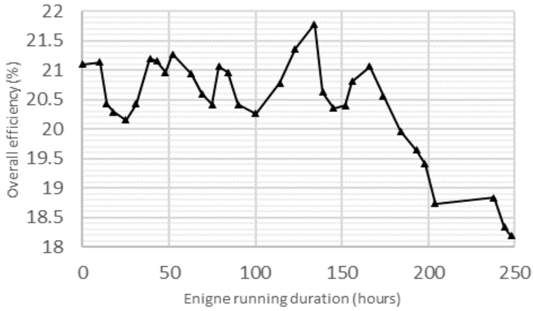

Figure 1. JO fueling overall engine generation efficiency for 250 hours

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 deposits around the injector tip provokes slow combustion rate, prolonging the process and dropping the thermal efficiency. Therefore, the energy converted from the fuel injected is less and part of the fuel might burn late in the process, thus the exhaust temperature increases.

Unburnt hydrocarbon is generated through non-homogenous mixture of air/fuel as well as insufficient temperature in the combustion chamber results in unburned fuels. According to Heywood [8], one of the major sources of unburned HC are the crevices in the combustion chamber. These regions are the piston ring, valve seats and cylinder head gasket crevices, where unburned mixtures in the compression process are forced to these crevices and completely or partially burned during the combustion then flow back into the cylinder. Due to the formation of carbon deposits, the volume of these crevices is reduced decreasing the HC production. Furthermore, HC 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, from Figure 2 the exhaust temperature mostly over 600°C. The oxidation of HC increases the level of CO, hence the tendency of CO increase is coupled with the rising of exhaust temperature besides HC decrease.

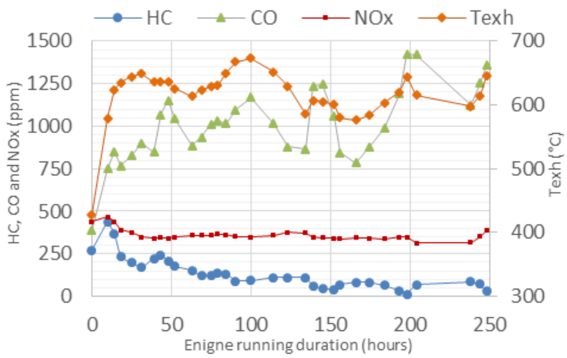

Figure 2. Evolution of exhaust gas emissions during 250 hours

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 unburned 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 unburned fuel, NOx are forced into the lube oil passing through the clearance of the cylinder. Furthermore, 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 such as cylinder liner, piston and bearing. 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 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 in the engine components. The Zn increase in concentration after 200 hours is remarkable, demonstrating the deterioration of lubricant and anti-wear effects. The zinc debris is due to the wear of brass components and bearings. This result is similar to the reported findings of Sinha and Agarwal [10] for rice-bran oil methyl ester.

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. The increasing tendency of these metallic elements is a symptom of the accumulation of wear debris in the lubricating oil. Similar findings and trends were supported by Agarwal and Dhar [7], Sinha and Agarwal [10] as well as Nantha and Thundil Karuppa [11] after conducting endurance tests of 512, 100 and 256 hours respectively.

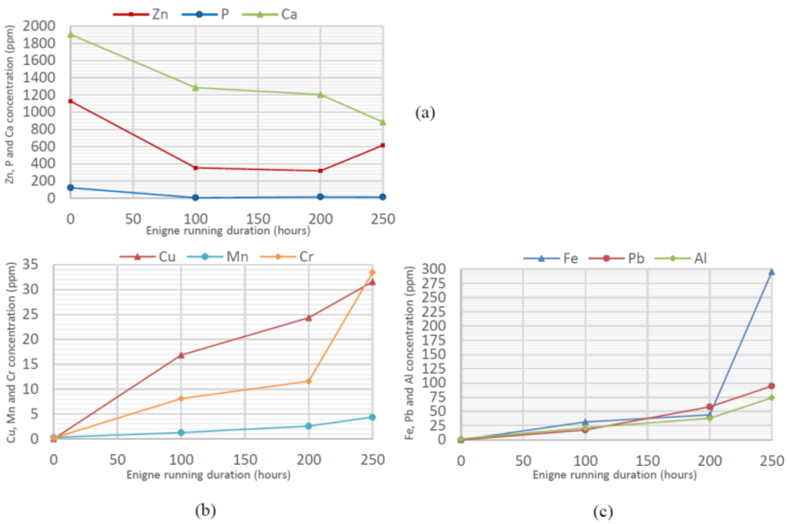

Figure 3. Concentration of various metal elements

3.3 Carbon depositions and component deterioration

The deterioration of the engine is a reflection of the carbon depositions accumulated on the engine in-cylinder parts as well as lubricant contamination and thickening (gelling). 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. [12] reported that the formation of deposits starts on the tip of the injector as it is the coldest part in the combustion chamber, pursued by the rings and the throat, 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 [13] 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 atomised and vaporised, thus spray penetration length is expected to be increased and cone angle decreased, which leads to fuel impingement. Ryan et al. [14] conducted a Jet Fuel Thermal Oxidation test and stated that the degree of unsaturation (iodine value) affected the deposition tendency, moreover, the viscosity caused fuel impingement which results in deposition.

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

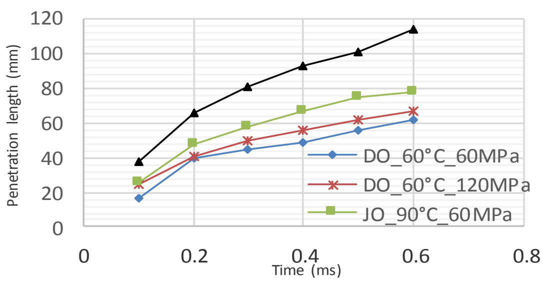

Figure 4. . Diesel and JO penetration lengths under different injection parameters

3.1 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. Penetration length of JO is longer than that of diesel, as the droplets of JO decreases in size slower than diesel and the boiling point is high, thus the evaporation rate is reduced.

4. Conclusions

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 have new maintenance guidance for SPOs.

Reference

[1] Chalatlon, V., Mohon Roy, M., Dutta, A., and Kumar, S. (2011) ‘Jatropha oil production and an experimental investigation of its use as an alternative fuel in a DI diesel engine’, Journal of Petroleum Technology and Alternative Fuels, 2(5), pp. 76-85.

[2] Chauhan, B., Kumar, N., and Cho, H. (2010) ‘Performance and emission studies on an agriculture engine on neat Jatropha oil’, Journal of Mechanical Science and Technology, 24(2), pp. 529-535.

[3] Hebbal, O., Reddy, K., and Rajagopal, K. (2006) ‘Performance characteristics of a diesel engine with deccan hemp oil’, Fuel, 85(14-15), pp. 2187-2194.

[4] Pan, S., Om, R., Phol, N., Chunhieng, T., Shimizu, Y., Yamamura, Y., Oyama, K., Uchiyama, I., Nakamura, A., and Yamasaki, T. (2011) Performance and Durability Test of Diesel Engine Generator Using Hundred Percent of Jatropha Curcas L. Oil. GMSARN International Journal, 5(2), pp. 81-88.

[5] Kalam, M. and Masjuki, H. (2004) Emissions and deposit characteristics of a small diesel engine when operated on preheated crude palm oil. Biomass and Bioenergy, 27(3), pp. 289-297.

[6] Bari, S., Yu, C., and Lim, T. (2002) ‘Performance deterioration and durability issues while running a diesel engine with crude palm oil’, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 216(9), pp. 785-792.

[7] Agarwal, A., and Dhar, A. (2010) Experimental Investigation of Preheated Jatropha Oil Fuelled Direct Injection Compression Ignition Engine—Part 2: Engine Durability and Effect on Lubricating Oil. J. ASTM Int., 7(2), p.102415.

[8] Heywood, J. (1988) Internal combustion engine fundamentals. New York: McGraw-Hill.

[9] Song, B. and Choi, Y. (2008) Investigation of variations of lubricating oil diluted by post-injected fuel for the regeneration of CDPF and its effects on engine wear. Journal of Mechanical Science and Technology, 22(12), pp. 2526-2533.

[10] Sinha, S. and Agarwal, A. (2010) ‘Experimental Investigation of the Effect of Biodiesel Utilization on Lubricating Oil Degradation and Wear of a Transportation CIDI Engine’, J. Eng. Gas Turbines Power, 132(4), pp. 04280-1-042801-9.

[11] Nantha, G. K. and Thundil Karuppa, R. R. (2016) ‘Effect of pongamia oil methyl ester–diesel blend on lubricating oil degradation of di compression ignition engine’, Fuel, 165, pp. 105-114.

[12] Sidibé, S., Blin, J., Vaitilingom, G., and Azoumah, Y. (2010) ‘Use of crude filtered vegetable oil as a fuel in diesel engines state of the art: Literature review’, Renewable and Sustainable Energy Reviews, 14(9), pp. 2748-2759.

[13] Akintayo, E. (2004) ‘Characteristics and composition of Parkia biglobbossa and Jatropha curcas oils and cakes’, Bioresource Technology, 92(3), pp. 307-310.

[14] Ryan, T., Dodge, L., and Callahan, T. (1984) ‘The effects of vegetable oil properties on injection and combustion in two different diesel engines’, J Am Oil Chem Soc, 61(10), pp. 1610-1619.