Deposit Characteristics of Diesel Engine Power Plant Fueled by Crude Palm Oil

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Abstract. This study emphasizes the impact of using Crude Palm Oil (CPO) as fuel (Bio-oil) on the deposit characteristics formed in the diesel engine power plant. Before entering the engine, CPO was treated by heating, separation, and filtering to decrease its viscosity. Deposit composition and morphology were investigated using Scanning Electron Microscope (SEM) equipped with a spectrometer. The result showed that unburned fuel on the surface of the cylinder head and liner wall was found after the performance test. Furthermore, inspection after durability test shows that there are carbon deposits on the combustion chamber, hard deposits on the cylinder head edge, and scratches on the surfaces of the liner. Hard black deposits were also found in the fuel nozzle tip. These deposits can disrupt the fuel atomizing process and create an unbalance pressure between the chambers. The deposits formed were continuous and contained Calcium (Ca), Aluminium (Al), and Iron (Fe). The SEM and spectroscopy analysis showed that the deposit formed by using CPO as fuel for diesel engines contain complex substances and erode materials from the cylinder liner.

Keywords: Bio-oil, deposits, diesel engine power plant, renewable energy

1 Introduction

The declining domestic oil production and increasing fossil oil consumption have made Indonesia a fossil oil importer since 2003 [1]. To reduce its fossil oil imports, Indonesia has done several policies, such as a policy to use biofuel as a substitute for fossil fuel in 2006. These policies are also expected to increase renewable energy to the total energy used [2–4]. One of the largest CPO producers globally is Indonesia. The production of CPO in Indonesia has grown significantly, which can be seen from the increasing variety of products produced from palm oil [5–7]. CPO and its waste are an alternative energy source for fuel in a household, transportation, industry, and power generation and one of the most potential agricultural commodities due to its role in increasing Indonesian society's economic level. However, from the assessment of sustainability index status result, its sustainability index is

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still low or less sustainable [8, 9]. A financial analysis done by Prochazka et al. showed that replacing diesel with CPO (as bio-oil) for the Indonesian diesel engine power plant is highly prospective because the CPO prices are low, and the diesel subsidies from the government are decreasing. The use of CPO to replace diesel could make Indonesia as a leader in the green electricity production in the world's [10]. Simaremare *et al*. highlighted the attractiveness of using CPO economically to replace diesel as fuel at PLN existing diesel power plants if it is used more than five years and the diesel price is higher than IDR 10 000 L^{-1} limitation thus needed government incentives to maintain its sustainability [11]. Other CPO producer countries like Thailand are starting to use CPO as fuel for their power plant replacing fuel oil to achieve their 30 % renewable energy consumption target by 2036 [12].

While CPO is a good substitute fuel for diesel engines at room temperature, its viscosity is ten times higher than diesel, and it can clog fuel lines, filters, and injectors due to its high viscosity. Several studies had reported the use of vegetable oil directly as fuel for diesel engines. Bari et al. propose to heat the CPO at temperatures above at least 92 ºC at the fuel tank to account for heat loss and heating temperature above 60 ºC to provide a good flow of CPO at the fuel line and avoid clogging of filters and injectors [13]. Another study by Bari [13] reported that continuous use of CPO for 500 h of operation in a single-cylinder, direct injection, and 4 kW at 3 600 rad s^{-1} (1 rad s^{-1} = 1/60 Hz) is causing engine performance deterioration. After a visual inspection of the dismantled engine, some heavy carbon deposits were discovered in the combustion chamber, scuff on the cylinder liner, wear on the piston, piston ring, injection pump, and misty spray reduction from the nozzle. The decreasing engine performance was caused by valve sticking because the valves can't return properly to their seat, resulting in leaks during compression and power strokes. Another experimental study done by Kalam *et al*. [14] using preheated CPO on a small diesel engine with the specification of direct injection, loaded at 5.50 Nm at 2 700 rad s^{-1} for 100 h, showed a higher ash deposit compared if the engine uses diesel fuel oil. In another study done by Hoang *et al.* [15], observation of dry deposit formation on the piston crown and injector orifices are studied. The study used preheated jatropha oil at 90 ºC as fuel for a four-stroke, four-cylinder, water-cooled, direct injection, 7.8 kW at 2 400 rad s^{-1} diesel engine, and the engine was tested for 300 h of operation. It is also discovered that there is higher metal content on the lube oil compared to if the engine was operating using diesel fuel.

The studies mentioned above are done on high-speed diesel engine performance with a capacity lower than 1 000 kW. However, in this work, an experimental investigation is done to study the influence of using CPO as fuel on the deposit characteristics for a low-speed diesel engine (600 rad s^{-1}) power plant. The study is done in a diesel engine power plant owned by a national utility company located in Indonesia.

2 Experimental method

The engine used for this study is a MAK diesel power plant engine, type 8M-453-B, which has a rated capacity of 2 554 kW, 600 rad s^{-1} rated speed, using compression-ignition and eight-cylinder arrangement. This power plant is selected because, in 2012, this power plant built an additional facility such as a fuel heater (thermal boiler) to use Marine Fuel Oil (MFO) as its fuel. The thermal boiler is needed to heat the CPO. The layout of the CPO fuel treatment system and the diesel engine experimental setup are shown in Figure 1. CPO is first stored in a storage tank, then filtered and transferred to a settling tank to separate the solid contaminant. After that, CPO was then transferred to the service tank through a separator to decrease the water content. The CPO temperature inlet to the engine is set in the range 77 ºC to 83 ºC to ensure its viscosity is in the range of engine allowable fuel viscosity.

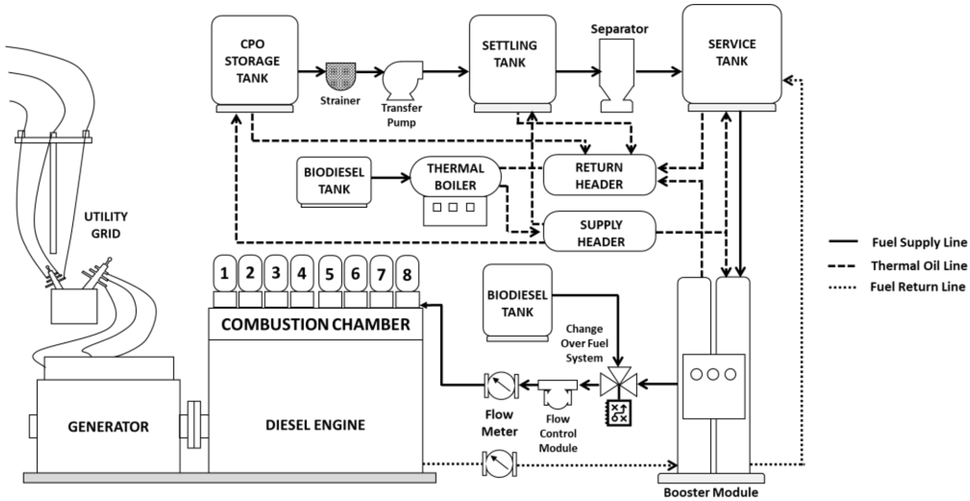


Fig. 1. Experimental setup layout.

Two-stage testing was conducted. In the first stage, performance testing using CPO was done for 7 h with load variation at 750 kW, 1 050 kW, and 1 400 kW load. After performance testing, the engine was disassembled, and a visual examination of cylinder liner, cylinder head, piston, and injector number 5 and 8 was conducted. In the second stage, after reassembly of the engine, a running test using CPO was conducted for 375 h and 8 min loaded following the electric grid demand.

Table 1. CPO Fuel properties used in this study.

Parameter	Reference standard SNI 8483	Unit	Sample number					
			1	2	3	4	5	6
Acid number	< 15	mg KOH g^{-1}	12.93	12.43	13.27	14.03	11.83	12.34
Iodin value	50 to 60	g-I_2 $100g^{-1}$	22.62	23.69	22.56	27.59	25.46	26.98
Kinematic viscosity @50 ºC	< 40	mm^2 s^{-1} (cst)	39.89	37.69	39.61	40.11	40.98	40.63
Saponification value	190 to 205	mg KOH g^{-1}	197.31	198.13	199.78	198.14	197.33	196.42
Flash point	> 200	ºC	236	234	232	234	232	236
Carbon residue	< 0.4	wt %	0.15	0.17	0.21	0.25	0.26	0.23
Water content	< 0.45	wt %	0.5	0.61	1.13	0.32	0.5	0.33
Sediment	< 0.05	wt %	0.012	0.05	0.012	0.015	0.016	0.019
Phosphor content	< 10	mg kg^{-1}	0.2	0.4	0.2	1	0.5	0.2
Sodium content		%	0.00006	0.00007	0.0009	0.0007	0.00032	0.00013
Sulphur content		mass %	0.006	0.008	0.003	0.001	0.007	0.003

After running test, the engine was disassembled, and visual examination on the combustion chamber number 5 and 8 was conducted again. Borescope examination was done after running test on combustion chamber number 1, 2, 3, 4, 6, and 7. Deposit collected from the cylinder head surface, valve, and injection nozzle are analyzed using SEM and spectroscopy to see its morphology and composition using Hitachi Swift ED 3000.

CPO used in this study is supplied from a palm oil processing plant near the power plant in East Kalimantan, Indonesia. CPO sample was taken several times in the period of running test from the booster module line tap and tested in the laboratory. The CPO properties can be seen in Table 1 compared to the Indonesia national standard for CPO fuel requirement SNI 8483 [16].

3 Results and discussion

Visual examination after performance test is carried out on disassembled liner, cylinder head, the piston head, and fuel injector on cylinder number 5 and number 8. Indications of incomplete combustion can be seen in the combustion chamber. Trace of unburned CPO, which is orange, was found on the cylinder liner surface (Figure 2a-b), piston crown (Figure 2c-d), cylinder head (Figure 2e-f), and fuel injector (Figure 2g-h). One of the factors that cause incomplete combustion is the high viscosity of CPO due to a thermal boiler problem that had suddenly shut off during the performance test.

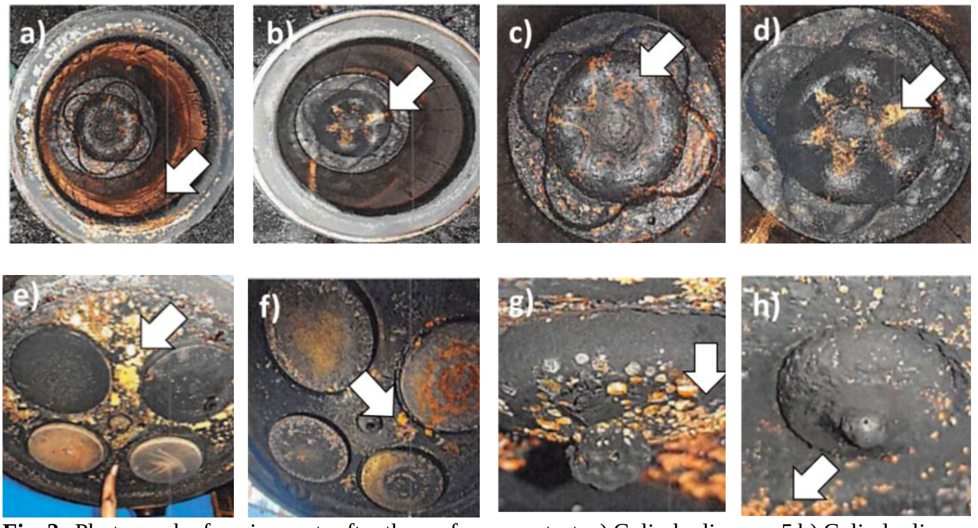


Fig. 2. Photograph of engine parts after the performance test. a) Cylinder liner no.5 b) Cylinder liner no.8 c) Piston crown no.5 d) Piston crown no.8 e) Cylinder head no.5 f) Cylinder head no.8 g) Fuel injector no.5 h) Fuel injector no.8.

After running test using CPO fuel for 375 h 58 min, visual inspection of the combustion chamber condition is carried out again by disassembling the cylinder head no.5 and no.8.

Visual examination showed that there was residual carbon in the combustion chamber and in the middle of the piston (Figure 3a-b), scratch on the liner surface (Figure 3c), irregular deposit formed on the tip of the cylinder head (Figure 3d-h), and black deposits covered the fuel injector nozzle (Figure 3i-j). Scratches on the surface of the liner above the cylinder head could happen due to rubbing between the deposits and cylinder head, piston, and liner. Comparison of fuel nozzle condition before and after the engine operates using CPO for 375 h and 58 min is shown in Figure 4.

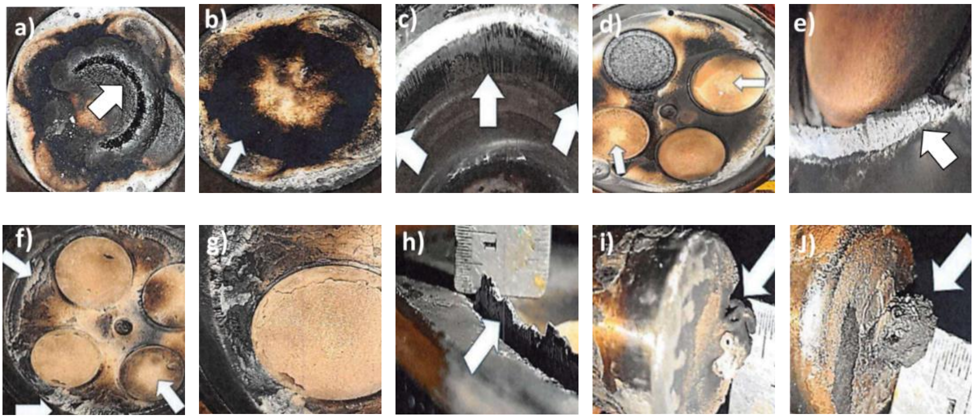


Fig. 3. Photograph of engine parts after running test. a) Piston no.5 b) Piston no.8 c) Cylinder liner wall no.5 d) Cylinder head no.5 e) Cylinder head deposits no.5 f) Cylinder head no.8 g) Cylinder head deposits no.8 h) Enlarge view of (g) i) Fuel injector no.5 j) Fuel injector no.8.

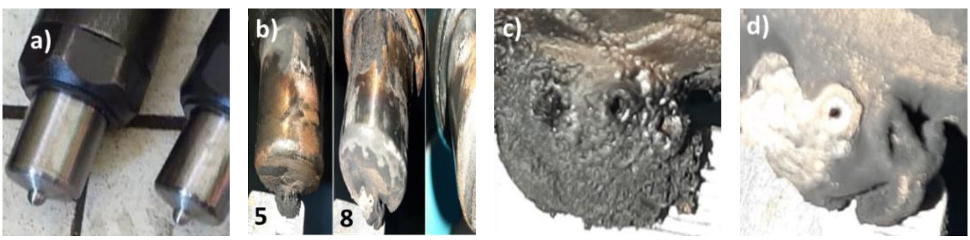


Fig. 4. Photograph of engine parts after running test. a) Piston no.5 b) Piston no.8 c) Cylinder liner wall no.5 d) Cylinder head no.5 e) Cylinder head deposits no.5 f) Cylinder head no.8 g) Cylinder head deposits no.8 h) Enlarge view of (g) i) Fuel injector no.5 j) Fuel injector no.8.

After the running test, borescope inspection was conducted on the combustion chamber cylinders no.1, no.2, no.3, no.4, no.6, and no.7. Inspection results show the same phenomenon: a deposit on the cylinder head and rubbing on the liner's surface in the cylinder head area, as shown in Figure 5.

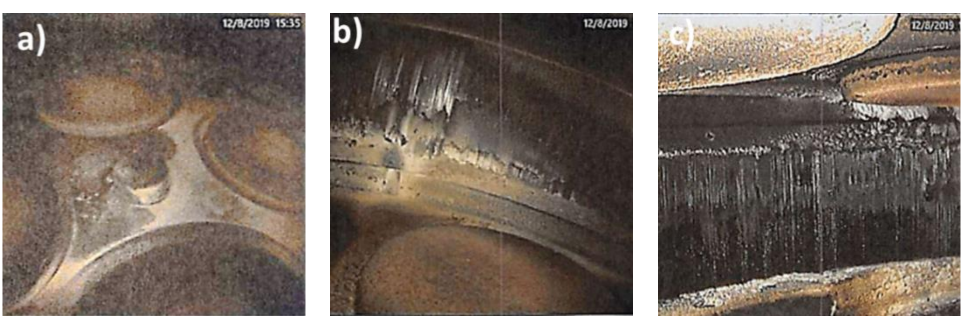
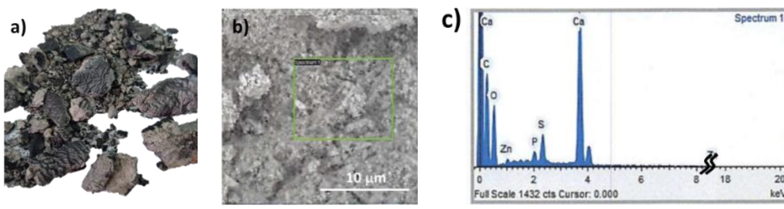


Fig. 5. Borescope image of engine parts after running test. a) Cylinder no.1 b) Cylinder no.2 c) Cylinder no.3 d) Cylinder no.4 e) Cylinder no.6 f) Cylinder no.7.

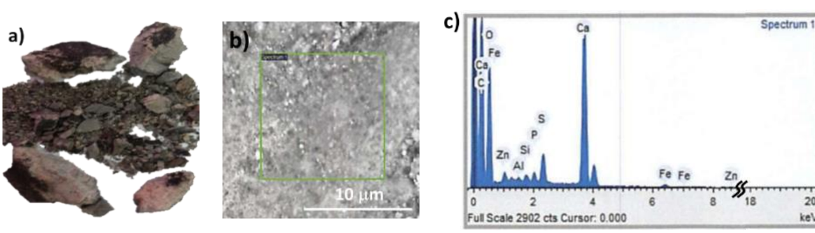
The deposit from the cylinder head, valves, and nozzle are scraped and examined using SEM and spectroscopy. The results of the examination are shown in Figure 6 to Figure 9.



Element	Weight %
Carbon	33.526
Oxygen	38.594
Phosphorus	0.979
Sulfur	2.459
Calcium	23.266
Zinc	1.176

Fig. 6. Deposits from cylinder no.5 a) Macrograph b) SEM photograph c) Deposit composition.

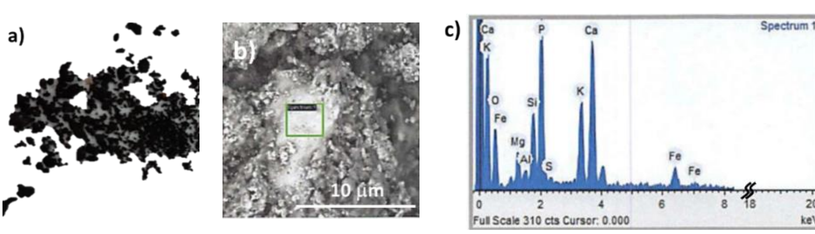
Deposits particles from the cylinder head are coarse, and the color is black (Figure 6a) and grey (Figure 7a). Deposits particle from the nozzle tip are fine, and the color is black (Figure 8a), and the deposits particle from valves are fine, and the color is brown (Figure 9a).



Element	Weight %
Carbon	36.061
Oxygen	43.145
Aluminum	0.150
Silicon	0.294
Phosphorus	0.979
Sulfur	2.459
Calcium	23.266
Iron	0.654
Zinc	1.176

Fig. 7. Deposits from cylinder no.6a) Macrograph b) SEM photograph c) Deposit composition.

Composition analysis on the cylinder head deposits from the cylinder head contains 36 wt % and 32 wt % carbon elements from cylinder head no.5 and no.8, as shown in Figure 8c and Figure 9c. These carbon deposits are formed because of the combination between unburned fuel and the low average temperature surface of the chamber.



Element	Weight %
Oxygen	32.869
Magnesium	2.925
Aluminum	0.973
Silicon	5.344
Phosphorus	15.929
Sulfur	0.724
Potassium	10.327
Calcium	22.500
Iron	8.409

Fig. 8. Deposits from nozzle tip no.7a) Macrograph b) SEM photograph c) Deposit composition.

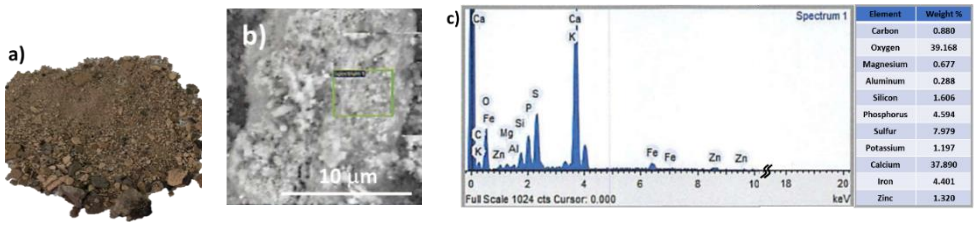


Fig. 9. Deposits from valve surface no.8 a) Macrograph b) SEM photograph c) Deposit composition.

The mechanism of deposits initially started because of the condensation of unburned fuel at the surface. It grew by absorbing condensed fuel at the deposited layer formed a compact deposit structure [15]. The carbon deposit on the engine using vegetable oil is usually more significant than the engine that uses diesel fuel and could create power loss due to valve sticking after continuous operation; thus, engine overhaul interval needed to be shortened [17]. The composition analysis of the deposits from the four locations contains calcium higher than 20 wt %. This deposit has high hardness and difficult to clean. The origin of this calcium deposit may come from the additive package and lubricating oil [18]. In addition, it is necessary to carry out further studies related to the calcium content in CPO to clarify the origin of this element. Aluminum and iron were also detected at the nozzle tip and valve surface that might come from the eroded surface of the combustion chamber and piston wear or dust contamination [19, 20].

4 Conclusion

Using CPO as fuel (bio-oil) for diesel engine power plant have created deposits in several engine parts. The hard deposit found in the nozzle tip can cause plugged nozzle, disrupt the fuel atomizing process, and create an unbalanced pressure between the combustion chambers. The SEM and spectroscopy analysis showed that the deposit formed by using CPO as fuel for diesel engines contain complex substances and erode materials from the cylinder liner.

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