Dynamometer Evaluation and Engine Wear Characteristics of Palm Oil Diesel Emulsions

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ABSTRACT: Dynamometer engine tests at steady-state conditions and a wear characteristics study were carried out on an indirect-injection diesel engine with palm oil diesel (POD) and its emulsions. The POD fuel was obtained in commercial form, and its emulsions were created by mixing POD fuel to contain 5 and 10% of water by volume. Variations in the engine's performance characteristics were determined from the results of steady-state tests carried out at fifteen selected torque-speed matrix points of the engine's performance map. The wear characteristics tests were performed by running the engine at half throttle setting for twenty hours for each fuel system. Then a desk-top comparison study was performed between the baseline fuel system of ordinary diesel (OD), POD, and its emulsions. Promising results have been obtained. Neither the lower cetane number of POD fuel nor its emulsification with water presented obstacles to the operation of the diesel engine during a series of steady-state engine tests and the twenty-hour endurance tests. Engine performance and fuel consumption for POD and its emulsions are comparable with those of OD fuel. Accumulations of wear metal debris in crank-case oil samples were lower with POD and its emulsions than with baseline OD fuel.

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KEY WORDS: Diesel engine, engine dynamometer evaluation, engine oil, engine performance, methyl ester, palm oil diesel (POD) emulsions, wear characteristics.

Efforts are under way in many countries to search for suitable alternative fuels and more environmentally friendly systems for automotive internal combustion engines, primarily from the standpoint of preserving the global environment and the concern about long-term supplies of conventional hydrocarbon-based fuels.

Interest in using vegetable oils, such as palm, soybean, sunflower, peanut, and olive oils, as alternative fuels for diesel engines dates back almost seventy years. However, owing to the cheap supply of petroleum-based fuels, their use as viable alternative fuels is yet to become a reality (1,2). The interest in vegetable oils is again springing up in both research and development, and its significance may be greater than that of vegetable-based alcohols because of the relatively simple and more economical methods of production, which lend themselves more readily to small-scale local activities (3).

Vegetable oils are widely available from a variety of sources, and they are renewable. As far as environmental considerations are concerned, unlike hydrocarbon-based fuels, vegetable oils contain no sulfur; hence, the environmental damage caused by sulfuric acid is reduced. Moreover, vegetable oils take away more CO_2 from the atmosphere during their production than is added to it by their later combustion. Therefore, it alleviates the increasing CO_2 content of the atmosphere (4,5). If these oils are good enough to substitute hydrocarbon fuel for power production, "home grown" vegetable oil fuel could be an emergency energy source to maintain or to build the standard of living to something approaching comfort, especially for the less-developed nations, particularly those with few indigenous hydrocarbon resources.

Due to different properties, such as heating values and molecular mass, vegetable oils burn far more complex and variable than the relatively simple hydrocarbon fuels (6).

Because of their high viscosities, the injection, performance, combustion, and atomization characteristics of vegetable oils, in both direct-injection and indirect-injection diesel engines, are significantly different from those of petroleum-derived diesel fuels (7). In long-term operation, highly viscous vegetable oils will normally develop gumming, injector coking, and ring sticking. Another problem is incompatibility with conventional lubricating oils (7–18).

One feasible way of overcoming these problems is to emulsify these fuels with an appropriate amount of water, which leads to improved atomization, improved spray characteristics, possibly through the phenomenon of micro-explosion or explosion vaporization, in direct-injection diesel engines (19). Recent literature indicates that the presence of water does not introduce any significant obstacles to satisfactory engine operation under normal operating conditions with direct-injection diesel engines (20).

The Palm Oil Research Institute of Malaysia (PORIM) successfully converted crude palm oil (CPO) and crude palm stearin (CPS) to their respective methyl esters (ME) through transesterification in 1983. Transesterification gives products with lower molecular weight than the original triglycerides. It also reduces viscosity, but thermal stability of the fatty acid esters is not improved. Volatility is enhanced, and polymer-

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ization of the simple esters does not result in molecular weight increases as rapidly as polymerization of triglycerides. The properties of ME of CPO and CPS, also known as palm oil diesel (POD), have been characterized by PETRONAS (National Petroleum Company of Malaysia, Kuala Lumpur, Malaysia) to be comparable to conventional diesel (21–23).

The objectives of this investigation were threefold: (i) to evaluate the effects of the POD emulsions on engine performance characteristics, (ii) to analyze their effects on the lubricating oil, and (iii) to investigate wear metal debris and injector coking and compare them with the baseline ordinary diesel fuel. Details of the POD characteristics are given elsewhere (5).

EXPERIMENTAL PROCEDURES

Equipment and experimental set-up. The tests were performed at the Combustion Laboratory of the Department of Mechanical Engineering, University of Malaya (Kuala Lumpur, Malaysia). The engine used for testing the fuels was an indirect-injection Isuzu, 4FB1, in-line, horizontal-arranged four-cylinder engine with a rating of 39 kW at 5000 rpm. The engine specifications are given in Masjuki *et al.* (5). The equipment and set-up were the same as used to evaluate performance, emission, and tribological effects of POD and its blends with ordinary diesel (OD) by Masjuki *et al.* (5), except that some additional pieces of equipment were employed, such as a Philips CM-12 (Philips Electron Optics B.V., Eindhoven, The Netherlands) transmission electron microscope for the smoke agglomerate study. The exhaust emissions study and engine endurance tests will be covered in the next part of this project.

Fuels tested. The fuel and its emulsions tested in this project are OD as the baseline fuel system, POD, 5% water + 95% POD (95 POD), and 10% water + 90% POD (90 POD). Table 1 shows the general properties of OD and POD (23).

Emulsions of different proportions were prepared with water in a rotary mixing device driven by a single-phase AC electric motor (1/4 HP). The straight-run Malaysian OD and POD were obtained in the commercial form. The lube oil used was a product of PETRONAS, MOTOLUB SAE 30.

Engine performance test method. The engine mapping procedure was based on the SAE Recommended Practice, SAE J1312 May 87, with the exception that the fuel temperature was maintained between 38 and 42°C. The same test procedure was followed for all fuel systems.

The steady-state tests consisted of running the engine until conditions stabilized. Data were then collected manually and stored on the computer's hard disk. The tests were carried out at fifteen steady-state conditions at half-throttle setting. The outlet cooling water was kept constant at 65 ± 5°C, the lube oil at 90 ± 5°C, and the inlet air temperature at 28 ± 2°C. The engine's performance was mapped in terms of torque, brake power, specific fuel consumption, exhaust temperature, lube oil temperature, air mass flow rate, and inlet manifold pressure for each of the fuel systems.

TABLE 1
Properties of Palm Oil Diesel (POD) and Ordinary Diesel Fuel (OD)

Properties	POD	OD
Specific density (g/cm^3)	0.875	0.832
Kinematic viscosity (@ 40°C)	4.71	3.60
Cetane number	51–52	53
Caloric value (kJ/kg)	41300	46800

The engine baseline performance characteristics were determined by running the engine on 100% OD, at various speeds, initially started at 800 rpm and up to 3600 rpm with an increment of 200 rpm at each interval. Each fuel system was tested three times. The repeatability was 95%. A personal computer is employed to evaluate and analyze the calculated, as well as the measured, parameters. This procedure was then repeated with POD and its emulsions.

Wear analysis method. A half-throttle setting was maintained throughout the wear debris analysis, with the engine running at 2500 rpm for a period of twenty hours for each fuel system. Samples of lube oil were collected through a one-way valve connected to the crankcase sump at 4-h intervals while the engine was still in operation, to ensure that more representative samples were procured with wear debris uniformly dispersed in the lube oil sump. The first sample was collected immediately after the engine had warmed up to establish the initial lube oil specifications and wear debris concentration level. The samples for each test were sent to a private laboratory for oil and wear debris analysis (24).

Smoke agglomerates collection method. A small copper tubing was connected to the main exhaust pipe to supply the gas and blow it onto a filter paper. Then, the filter paper was moisturized and placed on a Formvar-coated copper grid (300 mesh; Syarikat Tai Kwong Hardware (K.L.) Sdn. Bhd., Kuala Lumpur, Malaysia) by pressing it gently. The samples were then photographed with the TEM operated at 80 KV (25).

Injector examination. After completion of the wear analysis for each fuel system, the injectors were removed from the engine block for visual inspection, and their tips were photographed for comparison (26).

RESULTS AND DISCUSSION

Engine performance and fuel consumption. The variation in brake power can be related to (i) cetane index, (ii) relative fuel density, (iii) the caloric value of the fuel, and (iv) fuel quality.

Maximum brake power is achieved at around 2500 rpm (Fig. 1). As the percentage of water increases, there is a tendency of power decline because the specific combustion enthalpy is reduced and there is an increase of back pressure. Similar performance trends were observed with all fuel systems tested.

The OD produced higher power than POD and its emulsions because the caloric value for OD is about 14% higher than for POD, and its lower viscosity, relative fuel density, and differences in volatility and surfaces tension also contribute to better fuel atomization to finer droplets and better

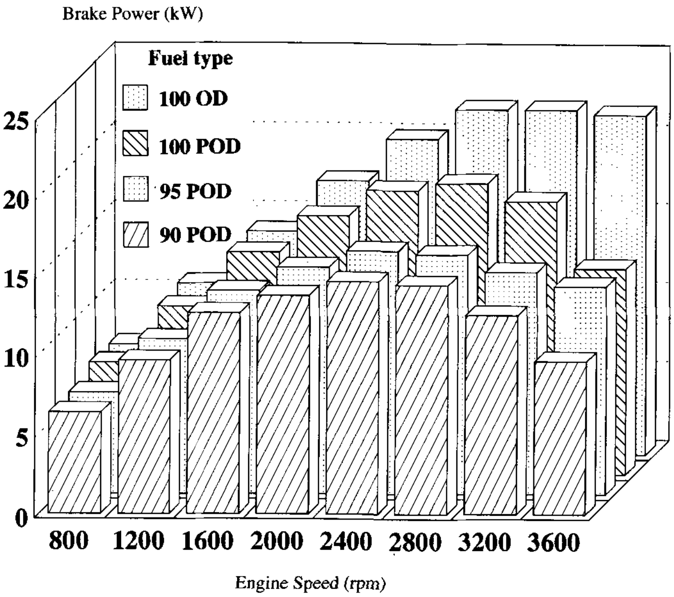

FIG. 1. Brake power produced with ordinary diesel (OD), palm oil diesel (POD) and its emulsions at varying speed; ISUZU diesel engine running at half throttle.

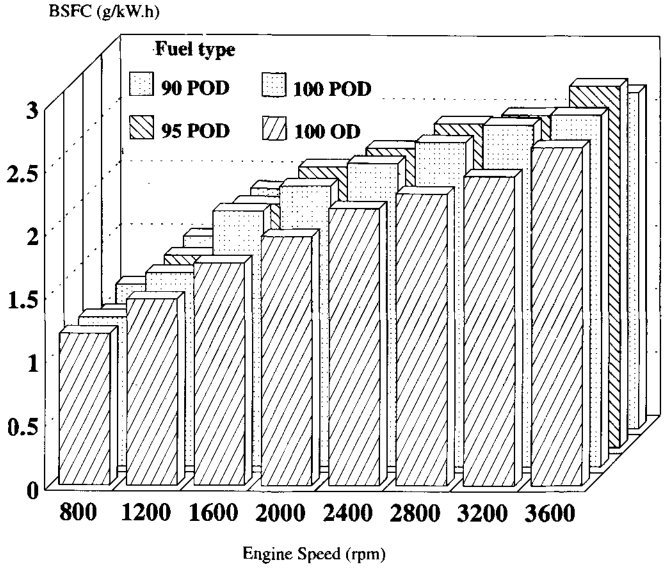

FIG. 2. Brake-specific fuel consumption (BSFC) with OD, POD and its emulsions at varying speed; ISUZU diesel engine running at half throttle. See Figure 1 for abbreviation.

combustion when it is injected into the combustion chamber (7,27). In addition, denser fuel tends to burn slower, and thus, the heat release rate will be reduced and the combustion efficiency also will be discounted.

Overall, POD generated an average of 3% less power than OD. This can be attributed to the higher viscosity of POD, and at higher speed, due to poor atomization, the power is still lower for POD fuel. In addition, the heat content of POD is also less than that of OD. These results are contrary to the findings of Mukti *et al.* (26), where the power output obtained with POD was greater than with OD for the whole range of engine operating speeds.

Taking these factors into account, the brake-specific fuel consumption is one of the best indicators of engine's performance in terms of efficiency. POD and its emulsions exhibit a slightly higher brake-specific fuel consumption than OD (Fig. 2). This is mainly due to the combined effect of the higher specific density (around 5% higher than OD), lower specific combustion enthalpy, and the lower heat release rate of both POD and its emulsions (19). The plot also indicates that the percentage increment in water content has a significant effect on specific fuel consumption for POD, but there is a small penalty in fuel consumption as the water percentage is increased. The general results attained here agree well with the findings of Mukti *et al.* (26). In general, performance of POD and its emulsions is comparable to those of OD fuel.

Smoke agglomerates micrographs. The micrographs for emulsified POD with 5 and 10% of water showed that the mean smoke particle size was reduced as the content of water was increased. This implies that emulsification with water will marginally reduce the particulate size. This finding agrees well with those by Crookes (20).

Wear debris analysis. Engine wear was evaluated on the basis of the concentrations of seven metallic wear particles in the lubricating oil. The metallic wear particles and their sources are: (i) iron—cylinder liner; (ii) aluminum—piston; (iii) chromium—piston ring; (iv) lead—bearing; (v) copper—piston rings, thrust bearing; (vi) silicon—main bearing; and (vii) tin—main bearing and thrust bearing. In a lubrication system, wear particles are in suspension in the oil. By analyzing the variation in the concentration of the metallic particles in the oil after a certain time of running, significant information about wear rate and engine conditions can be obtained.

Table 2 shows the variations of metallic wear particles concentration with running hours. The iron concentrations for OD and for POD and its emulsions are all the same initially at 1 ppm. There is a significant increase in iron concentration for the OD fuel system; its concentration reached 6 ppm after 4 h, 8 ppm after 12 h, and stayed at 7 ppm for the rest of the test. 90 POD and 95 POD have low concentrations of iron. This seems to indicate that POD acts as a lubricant between the cylinder liner and piston ring. Generally, all fuel systems exhibit good wear resistance for aluminum, especially the OD fuel system, which has zero aluminum concentrations. The 95 POD has the highest chromium concentration at 17 ppm after 20 h OD maintains a zero chromium concentration throughout the 20-h running test. The wear debris concentrations of lead for all fuel systems are extremely low, especially for 95 POD. The 95 POD shows the best wear resistance against lead, and the highest wear rate occurs in the OD fuel. Table 2 also shows that all fuel systems show a fluctuating trend in copper concentration. The 90 POD emulsion seems to generate the lowest Cu concentration. The OD fuel system shows a rigorous rise in copper concentration to 119 ppm from 91 ppm after 20 h. A fluctuating trend in silicon concentration for all fuel systems is observed. In general, both POD

TABLE 2
Variation of Metallic Wear Particle Concentration (ppm) with Running Time (h) for OD, POD Emulsion[a]

Metallic	Fuel	Time (h)					
concentration (ppm)	type	0	4	7	12	16	20
Fe	95POD	1	2	2	3	3	4
	90POD	1	2	2	4	4	7
	OD	1	6	5	8	7	7
Al	95POD	0	0	0	0	0	0
	90POD	0	1	0	0	0	0
	OD	0	0	0	1	0	0
Cr	95POD	0	0	0	0	0	0
	90POD	0	2	2	3	6	17
	OD	0	11	0	0	0	0
Pb	95POD	1	0	0	1	0	0
	90POD	1	2	1	1	1	2
	OD	1	3	2	3	2	2
Cu	95POD	91	100	85	95	74	82
	90POD	91	97	84	105	106	95
	OD	91	99	100	119	98	86
Si	95POD	4	2	2	3	2	1
	90POD	4	5	2	3	4	2
	OD	4	6	3	3	1	3

[a] ISUZU diesel engine running at 2500 rpm and half throttle. See Table 1 for abbreviations.

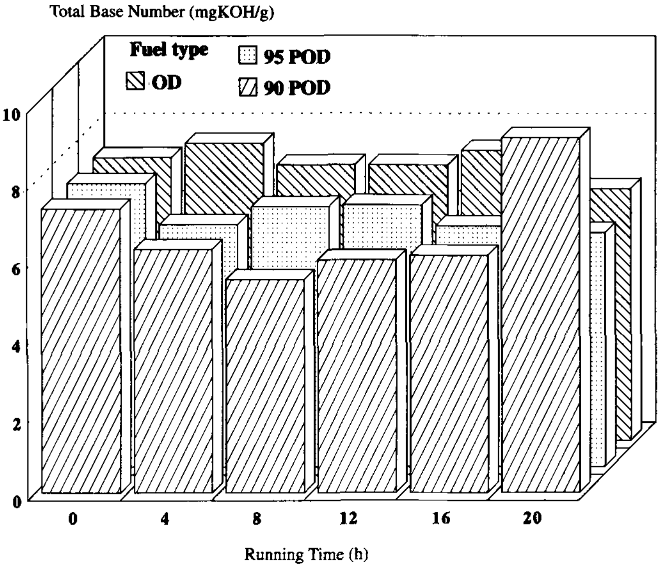

FIG. 3. Variation of total base number (mgKOH/g) against running time (h). OD, POD emulsions ISUZU diesel engine running at 2500 rpm and half throttle. See Figure 1 for abbreviations.

emulsions have a slightly higher silicon concentration compared with OD. There was no tin debris found in the samples for all fuel systems. This may either mean that the tin concentrations level are too low to be detected or only a few particles are available in the engine oil.

Based on the overall evaluation of the wear debris, the OD fuel system shows the worst performance in wear resistance. However, it has a good wear resistance against silicon and chromium. In general, wear metal levels for POD and its emulsions were considered to be normal during the 20-h test.

No major problems with lube oil viscosity were observed throughout the test for all fuels. Chemical analysis showed that POD emulsions have a better viscosity performance than OD because the former demonstrate more uniform viscosity curves than the latter as time progresses. There is no significant deterioration and dilution of the lubricating oil.

Total base number (TBN) is a measurement of the degree of acidity or alkalinity of the lubricant. TBN is expressed as milligrams of potassium hydroxide needed to neutralize a one-gram sample. In Figure 3, the 90 POD emulsion shows the highest TBN after 12 h with a reading of 9.18 mg KOH/g, about 25% higher than the initial value. The other fuel systems show satisfactory TBN levels.

Based on visual inspection of the injector nozzles, there was no significant difference in the degree of coking for any of the fuel systems. The deposits of carbon were comparable in amount but slightly different in color and texture. For the OD fuel system, slightly greater carbon deposits and varnish were observed around the injector tip. The surface of the injector was generally dirtier after OD use than for POD and its emulsions. The percentage of water in the fuel influences the operation of the fuel injector adversely. Based on these findings, an inference can be drawn that an increase in water content in fuel will reduce the alcohol content, thus resulting in heavier carbon deposition. This is due to the fact that alcohol has good solvent action (28).

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