Investigation on Palm Oil Diesel Emulsion As Fuel Extender For Diesel Engine

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ABSTRACT

Results of performance, exhaust emissions and lube oil analysis of diesel engine fuelled with Malaysian palm oil diesel (POD) and ordinary diesel (OD) emulsions containing 5% and 10% of water by volume are compared with those obtained when 100% POD and OD fuel were used. Very promising results have been obtained. Neither the lower cetane number of palm oil diesel fuel nor its emulsification with water presented obstacle to the operation of diesel engine during steady state engine tests and the twenty-hour endurance tests. Polymerization and carbon deposits on fuel injector nozzles were monitored. 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 emulsified fuels compared with baseline OD fuel, both OD and POD emulsions with 10% water by volume show promising tendency for wear resistance. The exhaust emissions for POD and the emulsified fuels are found to be much cleaner, containing less CO, CO_2 and hydrocarbon (HC); the absence of black smoke from the exhaust is an advantage. Theoretical aspects of diesel combustion are used to aid the interpretation of the observed engine behaviour.

INTRODUCTION

The prediction made by Diesel 70 years ago, stating that his engine is capable of efficient operation using a very wide range of fuels of petroleum, coal and vegetable origins, is borne out by the modern high speed diesel engines (Masjuki and Salit, 1993). Concern about long term supplies of conventional hydrocarbon based fuels and the growing awareness of the environmental consequences of increasing exhaust emissions products from automobile internal combustion engines and other energy converting devices have motivated the search for suitable alternative fuels and more environmentally friendly systems (Crookes *et al.*, 1992).

Vegetable oils such as palm oil, soybean oil, sunflower oil, peanut oil, olive oil, *etc.*, have been identified as alternative fuels, and found to be suitable for use in diesel engines, since 70 years ago. However, their use as viable alternative fuels is yet to become a reality, owing to the cheap supply of petroleum based fuels (Barsic and Humke, 1981). The renaissance of interest in vegetable oil is again springing up anew in both research and development and their significance may be greater than that of vegetable-based alcohols owing to the relatively simple methods of production.

Vegetable oils are widely available in a variety of sources and they are renewable. They do not produce carbon dioxide during combustion. Indeed plants producing vegetable oils recycle the carbon dioxide formed in the combustion of fossil fuel through photosynthesis into new plants materials including the oils themselves. Moreover, vegetable oils contain no sulphur, so this can greatly reduce the existing environmental damages caused by sulphuric acid (Crookes *et al.*, 1993). If these oils are good enough to substitute hydrocarbon fuel as a means of power production, hence, 'home grown' vegetable oil could be an emergency energy source to maintain and build up the standards of living to something approaching comfort, especially for those less developed nations, particularly those with little or shortage of indigenous hydrocarbon resources.

Due to their similarities in molecular structures and the C:H ratio to hydrocarbon based diesel fuel, vegetable oils seem to be suitable for use in diesel engine. However, the properties of vegetable oils are different from OD fuel. Although, both have long methylene group (CH_2) chain, vegetable oils have relatively higher viscosity and molecular mass than ordinary diesel fuel and contain oxygen in the molecules. Moreover, the heating values are also different (about 90% of diesel fuel), and on a chemical basis they are far more complex and variable than the relatively simple hydrocarbon fuels.

Owing to 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

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TABLE 1. FUEL CONFIGURATION

a. OD95 : 5% water + 95% ordinary diesel
b. OD90 : 10% water + 90% ordinary diesel
c. POD95 : 5% water + 95% palm oil diesel
d. POD90 : 10% water + 90% palm oil diesel
e. POD : 100 % palm oil diesel
f. OD : 100 % ordinary diesel

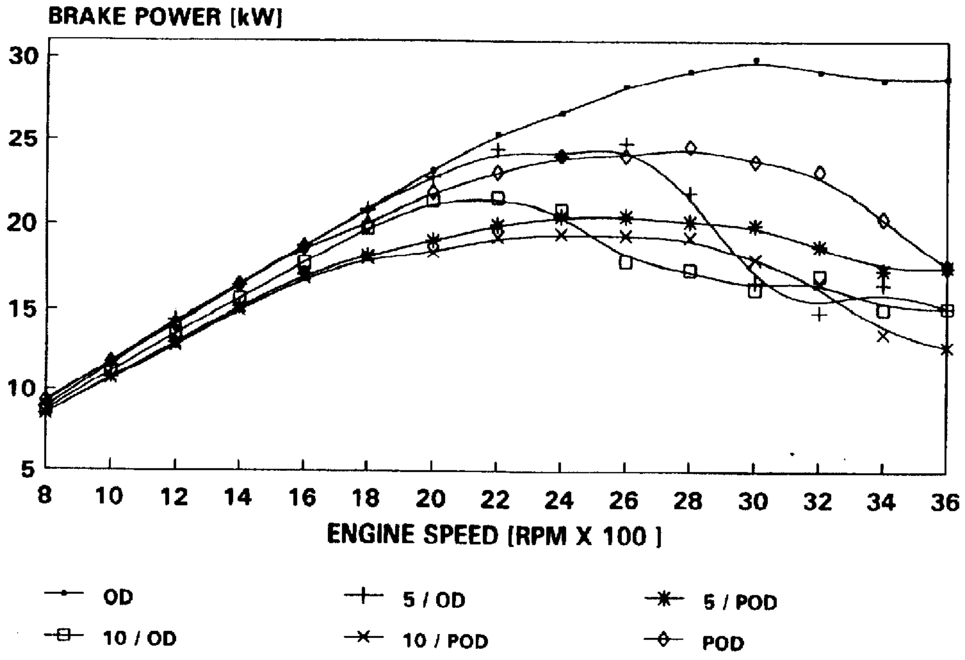

Figure 1. Brake power vs engine speed

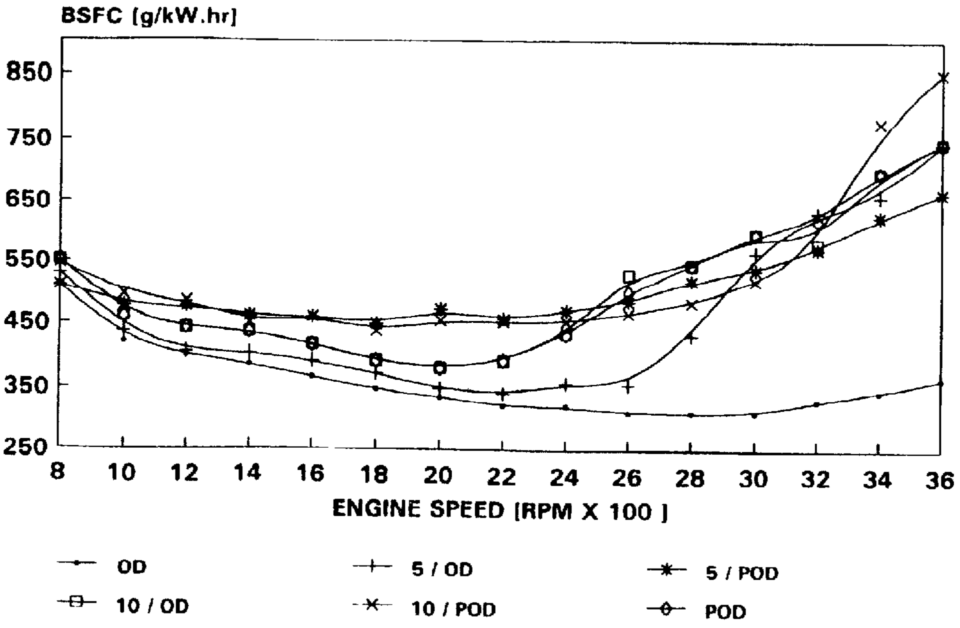

Figure 2. Brake specific fuel consumption vs engine speed

TABLE 2. PROPERTIES OF FUEL

Properties	POD	OD
Specific Density, g/cm^3	0.875	0.832
Kinematic Viscosity, @ 40 °C,cSt	4.71	3.60
Cetane Number	50-52	53
Calorific Value, kJ / kg	41300	46800

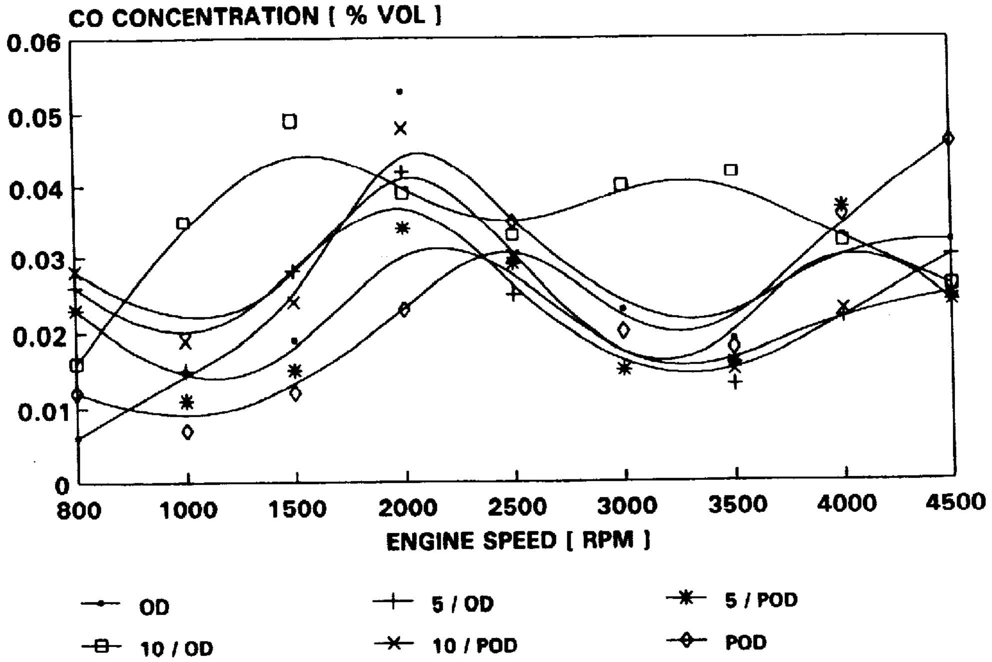

Figure 3. CO concentration vs engine speed

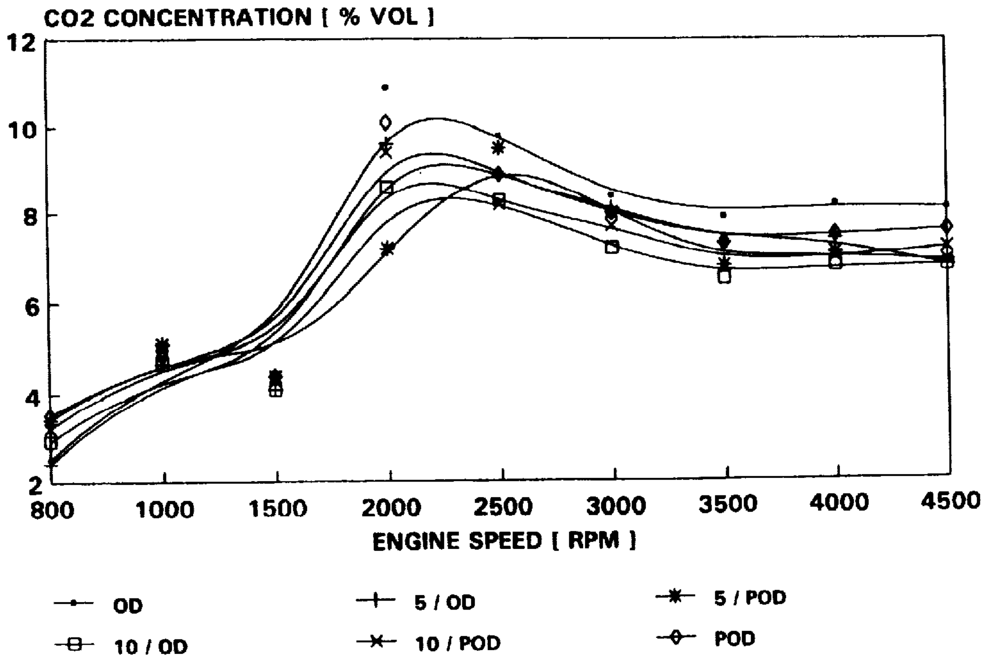

Figure 4. CO_2 concentration vs engine speed

those of petroleum-derived diesel fuels (Ryan, 1985). Having high viscosity, vegetable oils will in long term operation normally lead to the development of gumming, the formation of injector deposits, ring sticking as well as the incompatibility with conventional lubricating oils.

One feasible means of overcoming these problems is to emulsify these fuels with different proportions of water, leading to improved fuel atomisation, improved spray characteristics possibly through the phenomenon of micro-explosion which is suggested by Ziejewski (Ziejewski, 1984). Recent investigations show that the presence of water did not introduce a significant obstacle to satisfactory engine operation under normal operating conditions. Details of the POD characteristics are given in Masjuki, *et al.*, October 1993.

This investigation aims:

(a) to evaluate the influences of emulsions of both POD and OD fuels on engine performance and emission characteristics
(b) to study the effects of emulsions on lube oil deterioration and
(c) to investigate the effects of emulsions on wear rate and injector fouling and compare them with baseline ordinary diesel fuel.

EXPERIMENTAL SETUP AND PROCEDURE

Test Engine and Instrumentations

The tests were conducted at the Tribology Laboratory of Department of Mechanical Engineering, University of Malaya. The test engine used was an Isuzu 4FB1 horizontally arranged four cylinder engine with a rating of 39 kW at 5000 rpm. The engine specification and details of instrumentations are described in Masjuki *et al*, October 1993.

Fuels Properties And Emulsion Configurations

Tests were carried out with ordinary diesel (OD) as the baseline fuel system followed by tests with palm oil diesel (POD) and their emulsions. Brief qualitative description of the fuels is given in *Table 1* and *Table 2*. OD was obtained directly from market in the commercial form whilst POD was provided by PORIM. The lube oil used was PETRONAS MOTOLUB XGD (SAE Grade 30). The physicochemical characteristics of this crank-case oil are given in *Table 3*.

Engine Performance Test Procedure

The engine compression ratio was kept constant at 21:1. The throttle was set at 50% (half throttle setting) and the outlet cooling water was kept constant at 65±2 °C, the lube oil at 95±2°C and the inlet air temperature at 28±2 °C. The engine baseline performance characteristics was determined by running the engine on OD for various speeds from 800 rpm to 3600 rpm with an increment of 200 rpm. Once the engine was stabilised, data such as load, fuel consumption, inlet air, lube oil, cooling water and exhaust gas temperatures for a particular matrix point were measured and repeated three times. The repeatability was 96%. This procedure was repeated for other matrix points, running on the same fuel system. The same method was applied to other tests using POD and their different emulsions.

Exhaust Emissions Analysis Procedure

Exhaust-gas species are sampled at location in the exhaust system just 2 m downstream of the exhaust valve. A sample probe is placed at the junction at which the four separated exhaust ports merged. A Bosch four-component-gas analyser was used.

Wear Analysis Procedure

Half throttle setting was also maintained throughout the wear debris and lube oil analysis, with engine running at 2500 rpm for a period of twenty hours for each fuel system. The sample of lube oil was collected through a one-way valve connected to the crank-case sump at four hours interval. The first sample was collected immediately after the engine had warmed up to establish initial lube oil specification and wear debris concentration level. The samples were sent to a private laboratory for wear debris analysis. Current Inductively Coupled Plasma (ICP) emission spectrometer system is employed to automate the quantitative determination of elements in lube oil samples; these include wear metal debris, additives and contaminants. Physical tests on Total Base Number (TBN) and viscosity at 40°C are also determined.

Smoke Agglomerates Collection Procedure

A filter paper was placed next to the exhaust pipe. A small tubing was located at the main exhaust pipe to obtain exhaust gas and blowing it onto the filter paper. The filter paper was then damped, followed by placing a Formvar-coated copper grid (300 mesh) on top of it and was pressed gently. The samples were then photographed and analysed by means of a Phillips CM-12 Transmission Electron Microscope operated at 80 KV (Chua, 1993 and Seow, 1993/1994).

Injector Examination

At the end of each 20 hours test run, the injectors were removed from the engine block for visual inspection, graded and photograph of its tip was taken for comparison study.

RESULTS & DISCUSSION

Brake power

Referring to *Figure 1*, the maximum brake power is achieved at around 2000 rpm which agrees very well with the manufacturer's specifications. It can be seen that the engine produced almost identical performance on each fuel system and no apparent performance penalty in using POD, OD and their emulsions with water. It is also observed that as the percentage of water content is increased there is a tendency of power reduction as the specific combustion enthalpy is reduced. This feature applies to all the fuel systems tested. As expected, the OD fuel and its emulsions produced higher power than POD fuel and its emulsions. This is mainly caused by volume limitation on fuel pump delivery and results in a lower energy delivery for POD and their emulsions because of the lower energy per unit volume compared with OD fuel. Furthermore, *Table 1* shows that POD has lower calorific value or heat value than OD fuel (about 14% lower than OD fuel). Its relatively higher viscosity and fuel density will also lead to poorer fuel atomization or coarser droplets and produce poorer combustion when it is injected into the combustion chamber (Ryan *et al.*, 1985 and Yutiamco, 1986). The results followed a general trend that, on mass basis, the fuel energy content will fall as density increases. In addition, denser fuel tends to burn slower and thus the heat release rate will be reduced and the combustion efficiency will also be lowered. In general, POD fuel generated an average of 3% less brake power than the OD fuel. These results are contrary to the findings of Mohamad *et al.*, 1984, where their power output obtained using POD as fuel is greater than OD for the whole range of engine operating speed. With OD emulsions, for every 5% increment in water content an average of 5% drop in power is observed and with POD emulsions, there is a roughly 4% drop in power for every 5% increment in water content.

Specific Fuel Consumption

Plot of specific fuel consumption against engine speed as shown in *Figure 2* illustrates that POD fuel and its emulsions exhibit a slightly higher specific fuel consumption than OD fuel and its emulsions. This is mainly due to the combined effects of the relative fuel density, calorific value of fuel, fuel quality and quality of fuel in terms of the cetane index. Referring to *Table 1*, POD has a higher specific density (around 5% higher than OD), lower specific combustion enthalpy and lower heat release rate than OD fuel. The higher specific gravity of POD compared with OD fuel indicates that a 15% lower calorific value by mass becomes only 10% reduction in volume. Since diesel injection equipment meters by volume, the maximum fuel energy delivery without modification is effectively reduced by 10%. In other words, an extra 10% POD fuel is required to produce the same level of energy output as with OD fuel. This is possibly due to hydrodynamic effects within the fuel pump. The emulsified fuels show similar fuel characteristics respectively, but with a proportional reduction in specific combustion enthalpy as the water content is increased in the emulsions. The trends demonstrated in *Figure 2* also indicate that increment of water content has more adverse effect on specific fuel consumption for POD fuel than OD fuel. The general results attained here agree very well with Mohamad *et al* findings (1984).

Engine Exhaust Emissions

Figure 3 shows the variation of CO concentration with engine speed. It is observed that all values are below 0.1%, since the operating conditions are exclusively lean, with an air/fuel ratio of around 1.8. It can be seen that the CO concentration decreased slightly as the water percentage in emulsions increased. POD and its emulsions produced less CO than OD. This probably could be attributed to the presence of oxygen in POD. *Figure 4* illustrates the variation of CO_2 concentration with speed. A decrease in CO_2 expressed in % vol. is observed as the content of water in emulsions gets higher. It is also noted that the CO_2 concentration is reduced as the engine speed gets higher. *Figure 5* shows the variation of HC as a function of engine speed for both fuels and their emulsions. HC values are consistently below 7 ppm. It is observed that the HC concentration decreased as the engine speed increased up to 3000 rpm, at which the lowest HC concentration was found. HC concentration then increased with speed. It can be seen that there is a small reduction in HC concentration when water content is increased in the fuels.

TABLE 3. PHYSICOCHEMICAL DATA OF PETRONAS MOTOLUB XGD (PETRONAS DAGANGAN)

Characteristics		
Density @ 15 ° C	kg/l	0.890
Flash Point C.O.C.° C		246
Pour Point	° C	-9
Viscosity	cSt	
	@ 40 ° C	106
	@ 100 ° C	11.9
Viscosity Index		95
Sulphated Ash		0.82
Neutralization Value		
Acid Number		0.05
Base Number		6
Colour (ASTM)		4.0
Elemental Analysis	% wt	
P		0.08
Ba		-
Ca		-
Zn		0.08

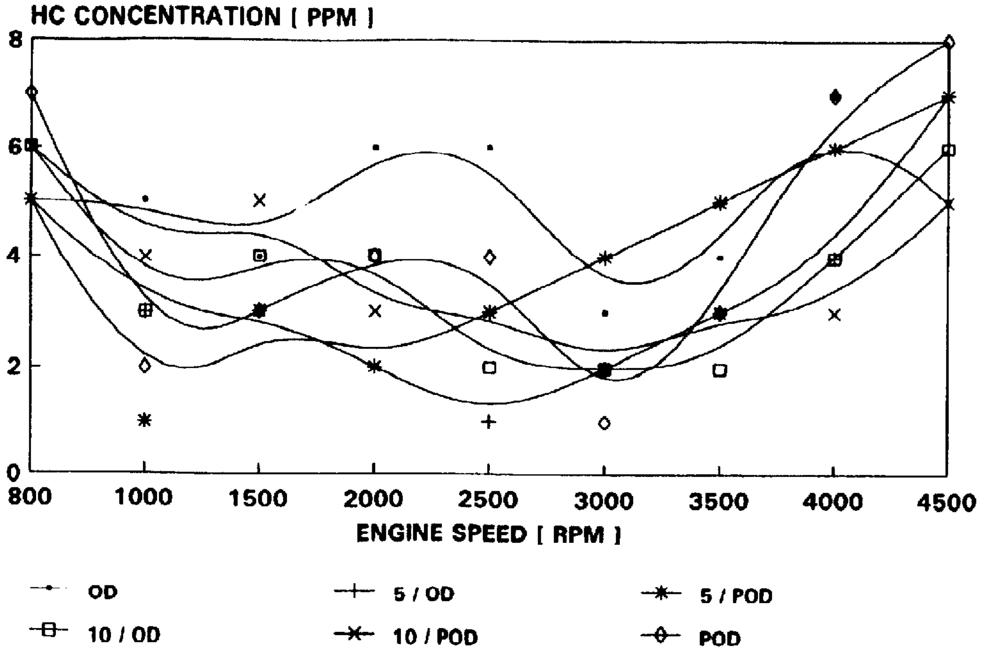

Figure 5. HC concentration vs engine speed

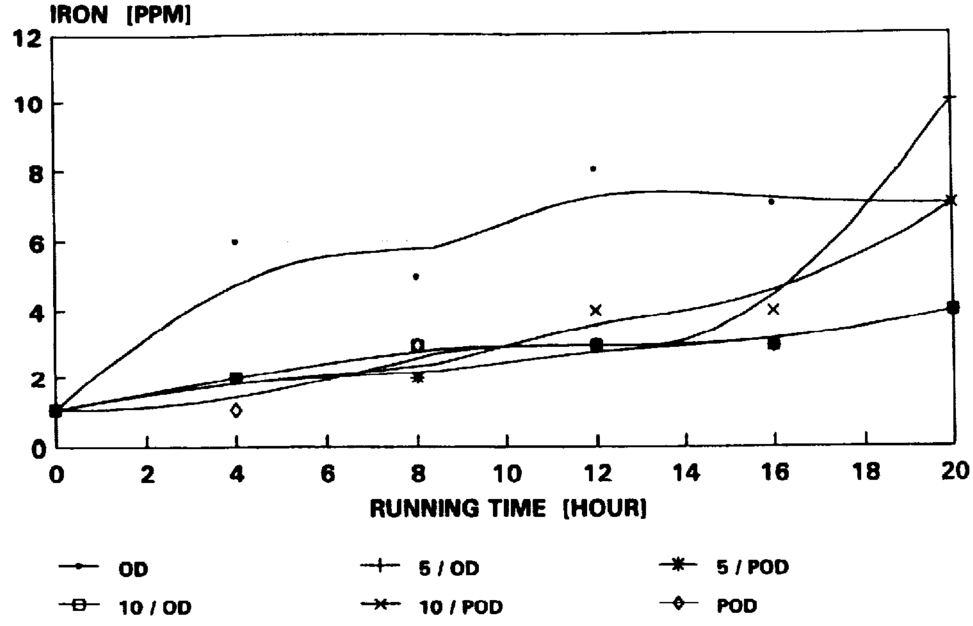

Figure 6. Variation of iron concentration vs running time

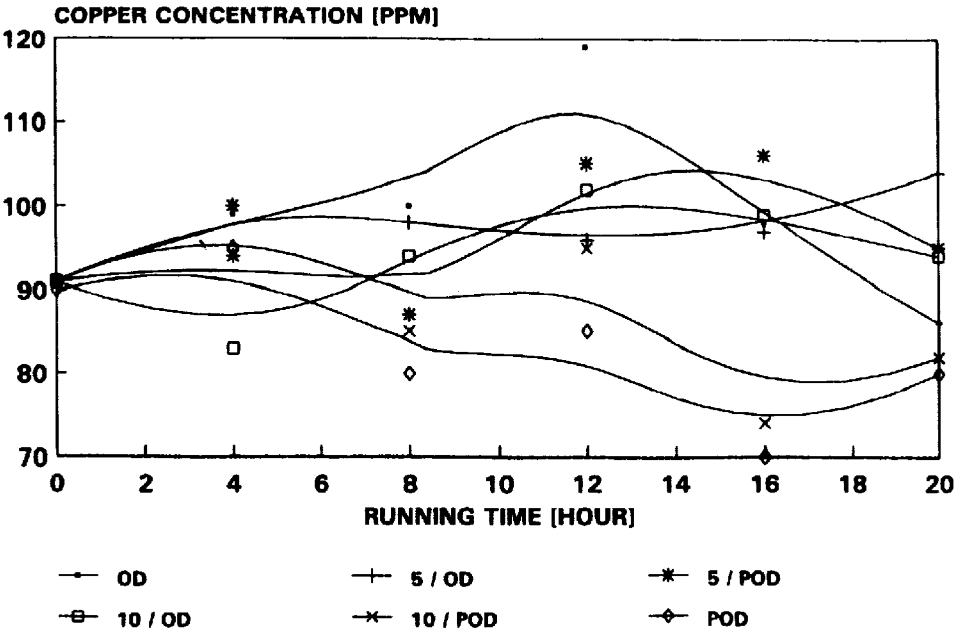

Figure 7. Variation of copper concentration vs running time

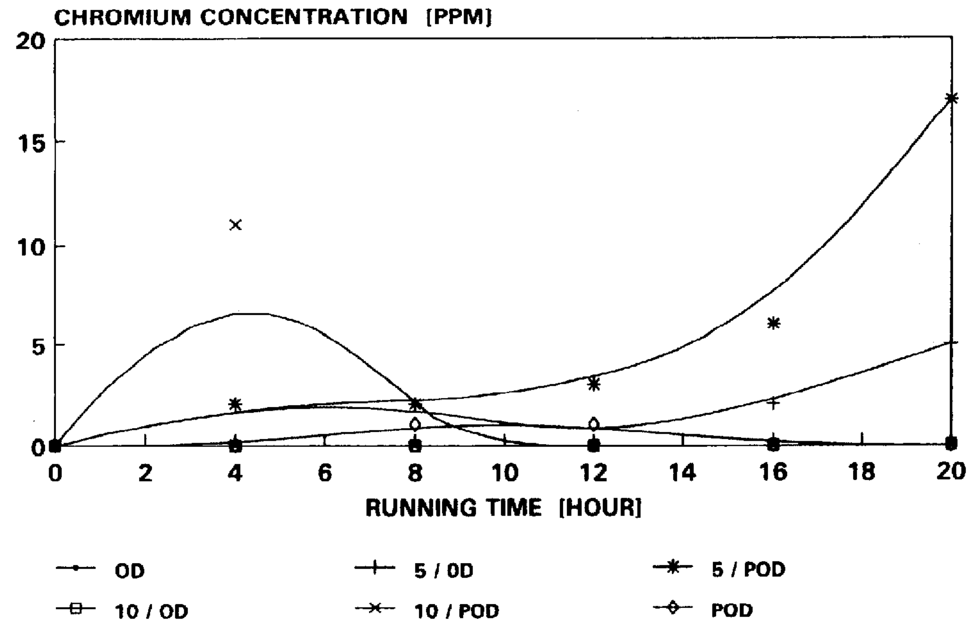

Figure 8. Variation of chromium concentration vs running time

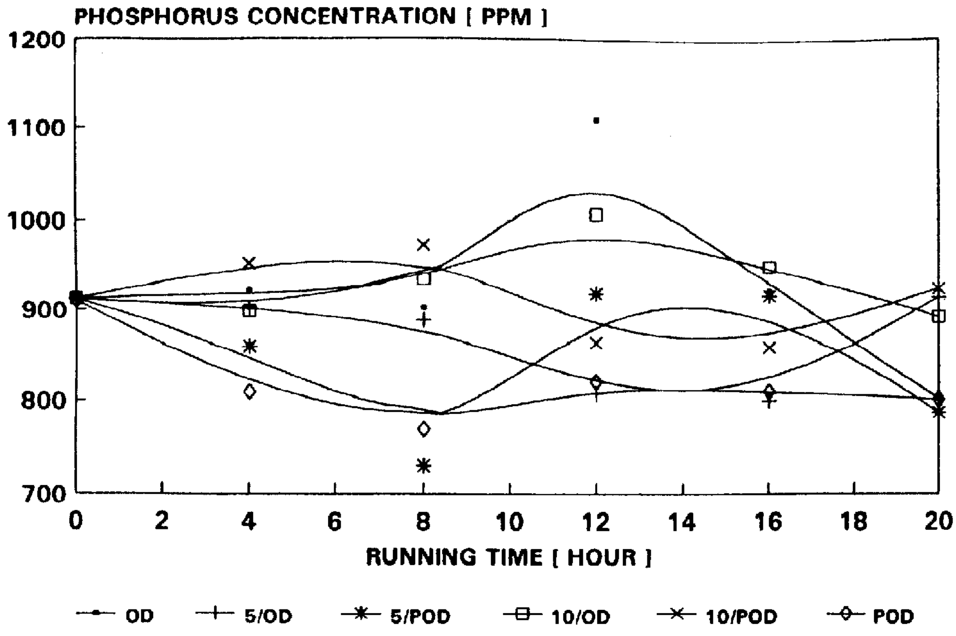

Figure 9. Variation of phosphorus concentration vs running time

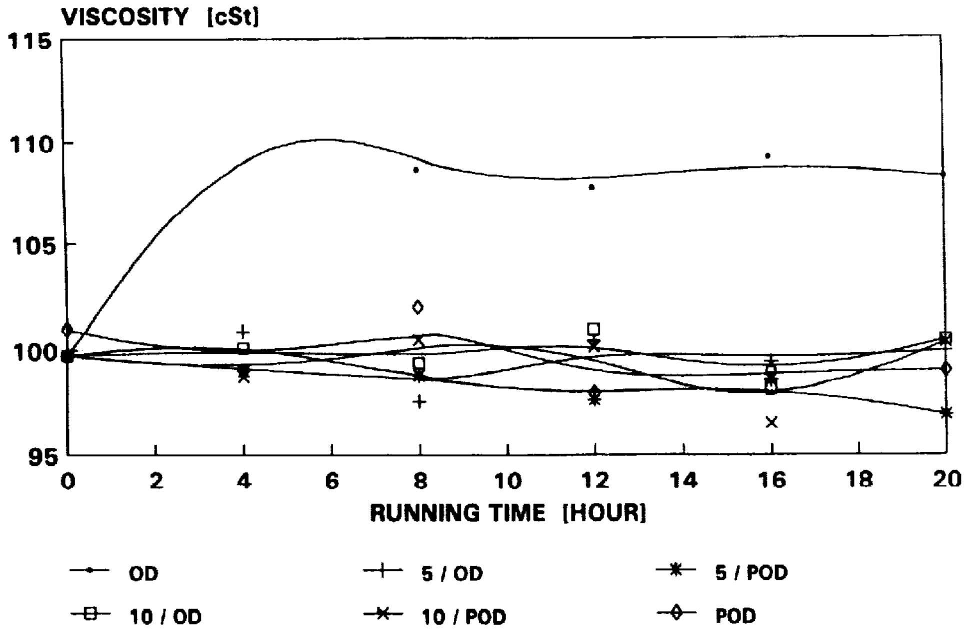

Figure 10. Variation of lube oil viscosity vs running time

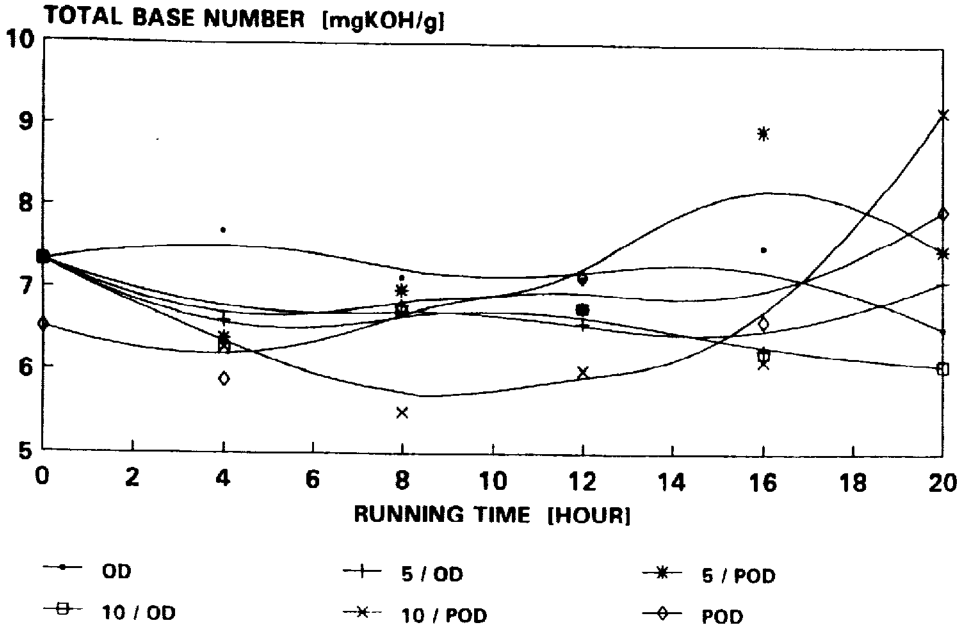

Figure 11. Variation of total base numbers vs running hour

It can be observed that the patterns of CO, CO_2 and HC appear very favourable for the POD and its emulsions. Therefore they have great potential as alternative diesel substitute as they are environmentally-friendly.

Smoke Agglomerate's Micrographs

Comparing the micrographs between emulsified OD and POD with 5% and 10% water show a reduction in the mean particle size of the smoke produced as the content of water is increased. This implies that emulsification with water will marginally reduce the particulate size. This finding agrees very well with Crookes', 1993. However, the particulate size of emulsified POD is marginally greater than emulsified OD, although their particles are denser.

Wear Debris Analysis

A crank-case lube oil may be considered as much an integral part of an engine as any of its components and it must perform various vital tasks over extended periods of operation. Sliding contact between metallic components of any mechanical system is always accompanied by wear which results in the generation of minute particles of metal. In diesel engine, the components normally subjected to wear process are piston, piston ring, cylinder liner, bearing, crankshaft, cam, tappet and valves (Jones, 1993). In a lubrication system, wear particles are in suspension in the oil. By testing a sample of lube oil from the engine after certain running duration it is possible to measure the lubricant's ability to continue to perform its original function and also to gain information on the operation and condition of the engine.

Iron (Fe)

The iron concentration is shown in *Figure 6*. The Fe content for OD, POD and their emulsions were initially at 1 ppm. There is a significant increase of Fe content for OD fuel system to 6 ppm at the fourth hour, 8 ppm at the twelfth hour and a steady value of 7 ppm for the rest of the test. Both OD 95 and POD 90 demonstrate a good indication of anti-wear characteristics. The highest level of iron was detected from pure conventional diesel and the lowest was from pure palm oil diesel fuel. This seems to indicate that POD fuel acts as lubricant between the piston ring and cylinder liner, shaft, valve train and gears. As for emulsified fuel (due to the presence of fatty acid in POD fuel), it was observed that the iron level drops as the percentage of water increases. This indicated that the presence of water in fuel could lower the combustion temperature (this was obviously indicated by the exhaust temperature difference) and hence reduce the wear rate between engine rubbing components.

Copper (Cu)

The copper concentration is depicted in *Figure 7*. Each fuel and their emulsions show a fluctuating trend in copper content within 80 and 100 ppm, except in the OD 95 which showed a close to constant level in copper concentration throughout the twenty hours run. The POD 90 emulsion exhibits the best wear resistance against copper. The OD fuel system shows a drastic rise in copper content to 119 ppm from 91 ppm at the twelfth hour. The concentration of copper is sometimes in conjunction with lead readings and bearings are the most common source of copper debris.

Chromium (Cr)

The chromium concentration for each fuel is shown in *Figure 8*. It is observed that POD 95 emulsion generated the highest chromium content of 17 ppm at the twentieth hour. Chrome plated rings or liners are the most common source (aggravated by silicon contamination or defective plating are the other possible causes). Both OD and OD 90 maintain a zero chromium concentration throughout the 20 hours running test. Based on the overall evaluation of the wear debris analysis, it is observed that OD 90 fuel has the best wear resistance characteristics. It achieves relatively low wear rate in almost every type of element. Conversely, baseline OD fuel system shows the worst performance in wear resistance. However, it has a good wear resistance against silicon and chromium. In general, engine fuelled with POD and its emulsions has relatively lower wear metal concentrations than engine running on OD fuel. This could possibly be attributed to the lower peak pressures, slower rate of pressure rise, the presence of fatty acid and lower combustion temperature.

It has been recognised that boundary lubrication occurs where hydrodynamic lubrication fails between engine parts during starting and stopping (bearings, pistons, rings) during normal running at the piston ring/cylinder interface at top and bottom centre crank positions, between increased loaded parts, between slow moving parts such as valve stems and rocker arms, crankshaft timing gears and chains, under high temperatures and squeezing out of the lubricant (Nautiyal *et al*, 1983). The two saturated fatty acids found in POD are palmitic (40-46.5%) and stearic (3.6-4.6%). The presence of these fatty acids reduce the friction values under boundary lubrication conditions precipitously.

ADDITIVE ELEMENTS ANALYSIS

Phosphorus (P)

Phosphorus acts as anti-wear and antioxidant additive in typical commercial lube oil. The phosphorus concentration level was found to be significantly high in all the cases and this indicated that no additive depletion by precipitation from fuel or additive under-treatment took place. The trends are shown in *Figure 9*.

Injector Observation

Visual inspection of the injector nozzles at the end of each running test for all the various fuel systems shows little polymerization of the fuels took place. Deposits of carbon were comparable in amount but slight difference in colour and texture were observed. Using OD fuel system, greater carbon deposit and varnish were noticed around the injector tip. The surface of injector using OD emulsions is generally dirtier than using POD emulsions. The percentage of water in fuel seems to influence the operation of the fuel injector. The findings here shows that increasing the water content will reduce the alcohol content in the fuel system, thus resulting in heavier carbon deposit. This is due to the loss by dispersion in lube oil since alcohol has a good solvent action (Carrol *et al.*,1984) and it has a strong affinity for dirt particles and surround each with oil soluble molecules which keep sludge and varnish from agglomerating thus keeping the debris in suspension in a very fine state of dispersion in lube oil.

Lubricating Oil Viscosity

Viscosity is the most important single property of a lube oil, since it is the sole property which determines the load carrying capacity at a specific load and speed. Thus, it is an important criterion of diesel engine operation as it affects the wear rate of engine components. Very high viscosity lube oil will increase the friction loss through the shearing forces of the lubricant and too low in viscosity will prevent the formation of protective film and this may even evaporate the oil under high temperature, following the mechanical reaction during combustion. Hence, at high temperatures, e.g. the surface of combustion cylinder, lubricant with high viscosity is needed to prevent the failure in forming the protective film. In addition, lubricant also acts as coolant for the lubricated components.

Referring to *Figure 10*, all the fuel systems demonstrate similar trends in viscosity throughout the 20-hour running test at 40°C (without noticeable oil thickening or thinning being observed), except for the baseline OD fuel system. It shows a sudden rise in viscosities from 100 cSt to 112.24 cSt at the fourth hour, possibly due to oxidation, evaporation of lighter oil components and contamination by insoluble. Tribologically, thickened oil may not provide adequate lubrication to critical engine parts and the anti-wear agent may also be depleted. This phenomenon may explain the presence of relatively higher wear debris concentration of iron and copper elements in lube oil samples when using pure OD fuel.

Figure 10 shows that the viscosities of all the fuels used appear to be constant. However, the baseline OD shows a higher level in viscosity and more fluctuating trend. Results obtained from chemical analysis of lube oil samples also show that emulsified fuels for both POD and OD have a better viscosity performance than the baseline OD fuel since emulsified fuels are capable of maintaining a more uniform viscosity level than OD fuel.

Total Base Number (TBN)

TBN is a measure of the lube oil's alkalinity which is an indication of its ability to counter the corrosive effects of high sulphur diesel fuels. *Figure 11* generally shows that TBN depletion is negligible as all lie within the allowable limits for SAE 30 motor oil. Based on the wear debris and chemical analysis, it is noted that there is no direct correlation of TBN with wear rate. This agrees well with the findings of Shukla *et al*, 1992, though they used methanol fuel.

CONCLUSIONS

The following conclusions may be drawn as a result of the present study :

(a) It is technically feasible to run an unmodified diesel engine using OD, POD and their emulsions without any apparent drawback from the presence of water and relatively lower cetane number. Trends observed generally followed those observed in the engine fuelled with pure OD fuel. The engine did not exhibit starting problems and no audible knock occurred.

(b) Brake power was somewhat slightly lower with POD when compared to engine running on OD at higher engine speeds. However it is higher than emulsified fuels.

(c) Emulsification is effective in reducing the emissions levels for CO, CO_2 and HC. It also reduces the smoke particulate size marginally and also exhibits lower exhaust gas temperature.

(d) Emulsions of POD and OD improve the anti-wear characteristics of the engine components compared with using pure OD fuel.

(e) POD and its emulsions show a slightly higher specific fuel consumption.

(f) Emulsification of POD will prolong the service life span for lube oil since they are capable of maintaining a constant viscosity and TBN levels in lube oil.

(g) Emulsified POD with water seemed to be effective in reducing the carbon deposits on fuel injector nozzles and they performed better as they developed less carbon deposits on the injector tips.

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