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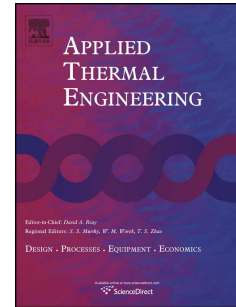
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**Performance and Exhaust Emissions of a Diesel Engine Fuelled with Croton
Megalocarpus (Musine) Methyl Ester.**

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Key Words: Croton Megalocarpus, Musine, Bio-fuel, Methyl Ester, Engine test.

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Abstract

The performance of a 4 stroke 3 cylinder direct injection naturally aspirated, Perkins D3.142 engine was measured in order to determine the suitability of a bio-fuel produced from the seeds of Croton Megalocarpus for engine use. The raw oil from the seeds was subjected to a transesterification process and supplied to the engine as a croton methyl ester (CME) in various blends with diesel fuel. The engine performance (brake thermal efficiency, brake specific fuel consumption and exhaust temperature) were measured and evaluated. A Horiba PG-250 portable analyser was used to measure the CO, HC, CO₂, NO_x, and O₂, concentrations. The tests indicated a lower brake thermal efficiency for CME compared with the pure diesel fuel. The exhaust gas temperature increased with increase in load for all tested fuels. It was found that the performance of the CME was comparable to pure diesel fuel but the bio-diesel produced lower smoke and NO_x emissions. Emissions of CO were reduced at higher loads with the bio-fuel. The performance of the engine indicated that CME has properties and characteristics that make it a viable additive or alternative to conventional fossil diesel fuel.

1.0 Introduction:

As global oil reserves decline and climate change resulting from the burning of fossil fuels becomes more apparent, it has become necessary to develop and exploit sustainable and non-polluting (i.e. carbon neutral) energy sources. At the same time it has been estimated that oil production will show a downward trend to become just 35% of today's production by the year 2075. It is therefore necessary to find alternative sources of renewable energy if present energy consumption (and living standards) is to be

maintained. Of the possible renewable sources bio-fuels are the only viable choice for use in transport systems that do not require huge investment in infrastructure and vehicle design. But some biomass alternatives such as ethanol, methanol and bio-diesel derived from food crops such as palm oil and rape seed oil are not without their critics. The consumption of biodiesel in the USA alone in 2006 was of the order of 250 million US gallons, most of which was produced from food crops or was grown on land previously used for food or animal feed production. In Europe pump diesel now contains 5% biofuel. In Indonesia large tracts of Equatorial forest are being destroyed to make way for palm oil production that is destroying the local ecosystem and it has been reported that the overall carbon signature of palm oil is actually greater than coal. There is now concern about moral and ethical issues associated with the substitution or use of food crops for bio fuel production [1]. The work reported in this paper examined a non food, environmentally friendly source of biodiesel, the Croton Megalocarpus Tree. Croton Megalocarpus is a tree from the family Euphorbiaceae that grows generally in East Africa at an altitudinal range of 4,000 – 6,000 ft. The tree grows up to 15 – 35 m high [2], but can reach a height of 40 m or more [3], figure 1.

Figure 1 A Croton Megalocarpus tree grown as an ornamental plant in Kenya

The wood from the tree is of medium weight, hard, termite resistant and strong; it is used as a source of timber and fencing material. The leaves have high levels of nitrogen and phosphorous and serve as a source of mulch in plantations [4]. Each fruit contains 3 ellipsoid ovoid or oblong-ellipsoid seeds which have an oil content of 30% by mass and a large proportion of protein. The Croton tree can survive on marginal agricultural land, not suitable for food production and can be planted to resist desert encroachment. The high protein content of the seed husks make them a very suitable poultry feed. The oil from the seeds can be extracted by mechanical extraction methods (pressing) or by solvent/chemical extraction methods. Presses such as manual screw, stork hydraulic hand press, motor jack press, mechanical press and a combination of these presses are available. Solvent extraction is done after preparatory steps such as crushing, blending and milling. The solvent is then added into the resulting paste and stirred until well mixed. The resulting solution is then filtered and the solvent driven off and recovered by a process of distillation to leave the raw vegetable oil. The seeds used in this study were obtained from the Kenya Forestry Research Institute Seed Centre in Kenya. The oil was obtained by both mechanical and chemical extraction methods in Kenya and then transported to Newcastle to be subjected to transesterification to be converted to bio-diesel. The composition of the resulting fuel was determined by examination in a mass spectrometer and a sample was sent to the Fuel Oil Bunker Analysis Services (FOBAS) for analysis to determine the ignition and combustion characteristics in a constant volume bomb test according to IP541/06. Other properties determined at FOBAS included the density (EN ISO 3675) the sulphur content (EN ISO 20846r), the viscosity (EN ISO 3104) and the ash content (EN ISO 3451). The Croton methyl ester contains predominantly Oleic acid ester, with lesser quantities of Linoleic, Linolenic and Palmitic esters. The properties of CME compared to commercially available red diesel (RD) fuel

(EN590-Directive 98/70/CE) and a biodiesel derived from recycled vegetable oil (RV) [5] are shown in table 1.

Table 1. Properties of CME compared with red diesel and biodiesel produced from recycled vegetable oil [5].

2.0 Experimental Equipment and Tests:

The Engine used for the tests was a Perkins D3.152 engine, the main features of which are presented in the table 2 and displayed in figure 2. The air consumption of the engine was measured using the air box method and the cylinder pressure was sensed by a Kistler Piezo pressure transducer (type 401). The transducer was calibrated against a dead weight tester prior to the test. The engine was coupled to a hydraulic dynamometer through a BHL torque transducer. Load was applied to the engine by adjusting a control valve that set the delivery pressure of the dynamometer. The torque and speed of the engine were measured and from these the engine output power determined. Thermocouples (type K fast response) were used to take various temperature measurements on the test bed. The overall air fuel ratio was calculated by the Horiba analyser. Following the method adopted by Pramanik [6] and Puhan et al [7] the test fuel was blended at different levels with conventional base diesel fuel. The mixtures contained 5 %, 10 %, 20 %, and 50 % CME (designated as B5, B10, B20 and B50) on a volume basis and tests were also performed with 100 % CME and 100 % red diesel (designated B100 and D100 respectively). Fuel flow measurements were made using an ISO-certified graduated cylinder connected to the fuel inlet piping via a three-way valve. A second three-way valve allowed fuel to be diverted from the fuel return line to the graduated cylinder thus forming a closed loop and ensuring that only the fuel consumed by the engine was measured. At each engine setting the time to consume a measured quantity of fuel was recorded. The exhaust flue gas concentrations of CO, HC, CO₂, O₂ and NO_x were measured with an Horiba PG-250 analyser which was calibrated at the start and the end of

Table 2 Data of the Perkins Engine

Figure 2 Test bed layout

each days testing with span gases and the drift determined. The drift is a result of two factors, zero drift due to a change in ambient conditions and span drift produced by a change in the sensitivity of the instrument. The drift per hour was determined from the initial and final calibration and used to correct the experimental readings. The zero calibration was established using Nitrogen as a zero gas and the composition of the span gases is shown in table 3.

Table 3 Span gas concentrations

The systematic uncertainty of the analyser is $\pm 0.5\%$, $\pm 2\%$ and $\pm 1\%$ in terms of

repeatability, linearity and drift. The expected level of random uncertainties is shown in table 4. The smoke level was measured using a Bosch RTT100 smoke meter.

Table 4 random uncertainties of gas emission measurements

3.0 Engine Test Procedure:

The test performed was in conformity to ISO 8178-4, type E5 for diesel powered marine craft of less than 24 m in length. The test load points for this test are shown in table 5. The weighting factor is used to calculate specific exhaust emissions. The engine was warmed up at a light load setting with 100% diesel fuel until thermal stability was established in conformity with the manufacturer's recommendations. The test fuel was then delivered to the engine which was allowed to run for several minutes to clear the common parts of the fuel system of the pure diesel fuel. The load on the engine was then set at the test condition by adjusting the control valve on the dynamometer and at the same time the fuelling was adjusted to bring the engine to the test speed. The exhaust gas temperature; inlet water temperature; outlet water temperature and water jacket temperature were measured and monitored throughout the test. The fuel consumption was measured once the engine was stabilised at the operating point. Throughout the test the ambient air temperature and humidity readings were recorded to facilitate NO_x correction in accordance to ISO 8178-1 to normalise the test readings to standard ISO conditions with humidity of 10.71 g/kg and ambient temperature of 25°C.

Table 5 Test mode cycle ISO 8178-4 type 5

4.0 Test Results and Discussions:

The brake thermal efficiency of the engine with diesel fuel and the various blends of CME with red diesel (B5, B20, B50 and B100) was determined from the measured results and plotted against brake power output as shown in figure 3. The test results show that with increasing brake power the thermal efficiencies of all the fuels show similar trends with the straight diesel fuel showing the better performance over the whole power/speed range. The 100 % CME showed the worst performance. The drop in thermal efficiency with increase in the blend of CME-bio-diesel can be attributed to the higher fuel supply for a given power which produces slower combustion times and counteracts the possible benefit of the presence of fuel borne oxygen in enhancing the combustion process. The combustion chamber and injection characteristics of the test engine were optimised for operation with red diesel so it is possible that small modifications to the injection timing may improve the situation for the bio-fuel. The calorific value of CME oil is 40.280 MJ/kg as compared to the 42 MJ/kg for the diesel fuel. These results are in general agreement with those of Pramanik [6] and Puhan et al [7, 8] for other bio-fuel diesel blends.

Figure 3 Brake thermal efficiency (%) vs. engine power for the test fuels

The brake specific fuel consumption (bsfc) of the CME varies depending on the engine power and speed. For all the fuels tested the consumption was high at low speed but decreased with increasing speed. This is shown in figure 4.

Figure 4. Brake specific fuel consumption vs. engine speed (rpm) for the test fuels.

At high speeds, friction heat losses and deteriorating combustion increases bsfc. Although the blend gave almost the same power as red diesel, its bsfc is higher. This can be attributed to the oxygen content of the CME which takes no part in the combustion process and reduces the heating value compared with red diesel fuel. With an increase in biodiesel percentage in the blends, the calorific value of the mixture decreases. Hence the specific fuel consumption of the higher percentage of biodiesel in blends also increases. It can be concluded that the amount of fuel required to produce the same amount of power output varies from oil type and the loading conditions. Raheman and Gadge [9] reported that higher densities resulted in higher values for bsfc. As the density of B100 was higher than that of diesel fuel, it means the same fuel consumption on a volume basis resulted in higher bsfc as the proportion of CME is increased. The variation of exhaust temperature with bmep is shown in figure 5. The highest exhaust gas temperature of 448°C was recorded for the B100 at the maximum power of 30kW. The least exhaust temperature of 165°C was with D100 at 7.5 kW power rating. There is a steady rise of temperature as the power and speed are increased on the engine. The B5, B20 and B50 have almost a similar rating of exhaust heat. The poorer combustion characteristic of the CME as a result of its higher viscosity compared to the red diesel was assumed to be the cause. The higher exhaust temperature of the Croton SME is indicative of lower thermal efficiency, less of the energy input in the fuel was converted to useful work, and the remaining heat is given out as exhaust temperature [6]. Puhan [8] considered that the high exhaust temperature results from longer ignition delays that produce a higher exhaust temperature but Al-Widyan et al, [10] stated that the higher exhaust temperatures may result from higher combustion temperatures.

Figure 5 Exhaust Temperature vs bmep for the test fuels.

The emissions of Carbon Monoxide (CO) from the test engine when fuelled with the diesel and the CME and its blends are compared in figure 6. The CO emissions of the blends were higher than those of the Diesel fuel at the higher load and speed settings but were lowest at the lower speed and power settings.

The increase of the CME percentage in the fuel blend reduces the CO at the low load setting as the B100 has the least CO but the reverse is the case with the higher load settings. There are several variables acting on the combustion process that has an impact on CO formation. The additional Oxygen present in the CME will assist in making the

combustion more complete in the combustion zone but at the high load condition the increased viscosity of the CME could affect the fuel injection and atomisation characteristics could adversely impact on the CME as the injector was optimised for Diesel fuel. The increased in-cylinder temperatures at high load would have a greater impact on the CO production of Diesel fuel due to the enhanced atomisation and mixing this produces. Modifications to the fuel injection system may improve the atomisation characteristics of the CME and hence improve the combustion at high load.

Figure 6 Variation of CO emissions with speed and load for CME and its blend with red diesel

Figure 7 shows the differences in HC emission between the blends of the biodiesel and the red diesel. The recorded emission levels for the biofuel are comparatively low and reduce with increased engine speed until at 2200 rpm they increased. This has been observed for other biofuels [10] for reasons related to the oxygen content of the fuel. Studies by Monyem et al [11] show that unburned hydrocarbons generally emanate from the regions in a cylinder where there is a poor fuel/air mixture to such a high extent that the ratio is past the combustion limit. This process would be less likely to occur with fuel borne oxygen that can extend the combustion limit and reduce the extent of fuel quench. The B20 has shown a consistent low level of HC emission in this study compared to both the B100 and D100 at 1380 rpm and 1760 rpm but slightly higher than the diesel at 2002 and 2200 rpm. Without information about the complex in-cylinder combustion chemistry further considerations on this matter are just speculation but the results are encouraging.

Figure 7 Variation of HC emissions with speed for CME and its blends with red diesel

There was a general increase of NO_x emissions as load and speed were increased. This increase in NO_x is consistent with increase in cylinder temperature and exhaust temperature but the emissions for the bio-fuel were lower than the red diesel fuel at higher operating loads as shown in figure 8. These results are in agreement of those found by Roskilly et al [5]. At low loads the overall oxygen concentration is higher but the combustion temperature is lower and (a feature of the chosen test method) the combustion time is longer which could both lead to low NO_x but the fuel borne oxygen is most effective at producing NO_x in the reaction zone which aided by the high local temperatures will then have more time to revert back to an equilibrium concentration [12].

Figure 8 Variation of NO_x emissions with speed and load for CME and its blends with red diesel.

It has been observed from the result that at low load and speed the smoke emission is best with the red diesel fuel as a result of perhaps more favourable viscosity and density of this fuel as shown in figure 9. As the engine load and speed is increased, the smoke produced by the CME is initially higher than the red diesel for all blends but as the load is increased the bio-fuel begins to have a reduced level of emissions compared with the red diesel. The smoke emission of the Perkins engines for B100 is 20% less than that of red diesel, at high speed and load, but at the low speed and load that of the red diesel is the

lowest. As more load was added, the temperature of the engine rises and makes combustion better for the CME. This is in agreement with the results of Mittlebach et al [13] who noticed that smoke density for biodiesel blend was generally lower than that of the diesel oil and they reasoned that higher thermal efficiency indicates better and complete combustion of fuel. Biodiesel has greater oxygen content than red diesel which may assist in reducing the smoke by locally increasing the constituent of oxygen available for combustion. Puhan et al [8] reported a reduction of 70% smoke in case of Mahua oil methyl ester when compared to diesel. The fuel injection equipment and timing of the test engine were at the normal setting for red diesel fuel; it may be that the smoke level for the CME could be lowered at low load if the injection timing was optimised for this fuel.

Figure 9 Variation of Smoke emissions with speed and load for CME and its blends with red diesel.

Carbon dioxide, (CO_2) has a great effect on the green house gases, in that it has the tendency to form a blanket effect on the atmosphere which aids global warming. The CO_2 generated with the CME at the various loads and speed is shown in figure 10. There is a steady increase of CO_2 with engine speed and load due to increased fuelling. The CO_2 from Croton is seen to be higher than that of diesel fuel (D100). This is consistent with the lower hydrogen/carbon ratio and lower calorific value of the bio fuel. The CO_2 emissions of the bio-fuel can however be considered as zero carbon emissions as they are sourced by the plant from air bourn carbon.

Figure 10 Variation of CO_2 emissions with speed and load for CME and its blends with red diesel

The oxygen concentrations in the exhaust are shown in figure 11. The biofuel contains oxygen as part of its chemical make up which is not the case for red diesel fuel. It is expected that the oxygen content in the exhaust decreases as the engine load is increased as the air fuel ratio decreases with load.

Figure 11 Variation of exhaust O_2 content with speed and load for CME and its blends with red diesel

5. Conclusions and Recommendations:

This paper has demonstrated that biodiesel from Croton Megalocarpus has a very strong potential for use as a biofuel for diesel engines in terms of power output, economy and exhaust emissions. The performance of a Perkins engine when fuelled with biofuel and

biofuel/diesel blends is very similar to that when fuelled with red diesel. The main conclusions derived from this research are;

- The Croton biodiesel when blended with diesel fuel produces a level of performance in economy and exhaust emissions that are very similar to other biofuels from other sources.
- The brake thermal efficiency of the engine when fuelled with pure CME and the blended fuels is lower than that of red diesel fuel for the particular engine tested.
- The fuel consumption of B5, B20, B50 and B100 at 1380 rpm and 7.5 kW power was 404.03, 415.5, 420, 424 g/kWhr respectively. This represented an increase of 2.65%, 3.8%, 4.7% and 4.7% respectively over that of basic red diesel fuel.
- CO, CO₂ and HC emissions were higher for the CME and blends but the smoke emission were lower when compared to the red diesel fuel.
- The experimental results tentatively support the assertion that methyl esters of Croton Megalocarpus can be successfully used in existing diesel engines without modifications but this needs to be verified by further long term and comprehensive tests. Use of the bio-diesel as a partial fuel substitute can stimulate the rural farm economy in Africa, bring unproductive land back into profitable production, slow desert encroachment and make farming communities self reliant.

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Table 2

Parameter	Description	Remarks
Type	D3.152	Three Cylinder, four stroke direct injection
Bore	91.44 mm	3.6 in
Stroke	127 mm	5 in
Swept volume	2.5 l	152 cu in
Rated speed	2200 rpm	
Rated power	33.56 kW	45 HP at 2500 rpm
Idling speed	500 rpm	
Firing order	1,2,3	
Compression ratio	18.5 : 1	

Table 3

Span gas	Concentration
CO	1390 ppm
CO ₂	13.9%
NO _x	1390 ppm
O ₂	21.2 %

Table 4

	CO (ppm)	CO ₂ (%)	NO _x (ppm)	O ₂ (%)
Initial span	1385	13.91	1388	21.2
Maximum span drift	63	0.34	87	0
Maximum zero drift	1	0	0	0.16
Full scale of analyser	2000	20	2500	100
Span drift on full scale (%)	3.15	1.7	3.48	0
Zero drift on full scale (%)	0.05	0	0	0.16

Table 5

Mode number (Cycle E5)	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Speed % of Max	100	91	80	63	Idle
Power % of Max	100	75	50	25	0
Engine speed rpm	2200	2002	1760	1380	500
Engine power kW	33.56	25.17	16.78	8.39	-
Engine Torque Nm	145	119	90.9	58.8	-
Weighting Factor	0.08	0.13	0.17	0.32	0.3

Caption to figures

Figure 1 A Croton Megalocarpus tree grown as an ornamental plant in Kenya

Figure 2 Test bed layout

Figure 3 Brake thermal efficiency (%) vs. engine power for the test fuels

Figure 4 Brake specific fuel consumption vs. engine speed (rpm) for the test fuels.

Figure 5 Exhaust Temperature vs bmep for the test fuels

Figure 6 Variation of CO emissions with speed and load for CME and its blend with red diesel

Figure 7 Variation of HC emissions with speed for CME and its blends with red diesel

Figure 8 Variation of NO_x emissions with speed and load for CME and its blends with red diesel

Figure 9 Variation of Smoke emissions with speed and load for CME and its blends with red diesel.

Figure 10 Variation of CO₂ emissions with speed and load for CME and its blends with red diesel

Figure 11 Variation of exhaust O₂ content with speed and load for CME and its blends with red diesel

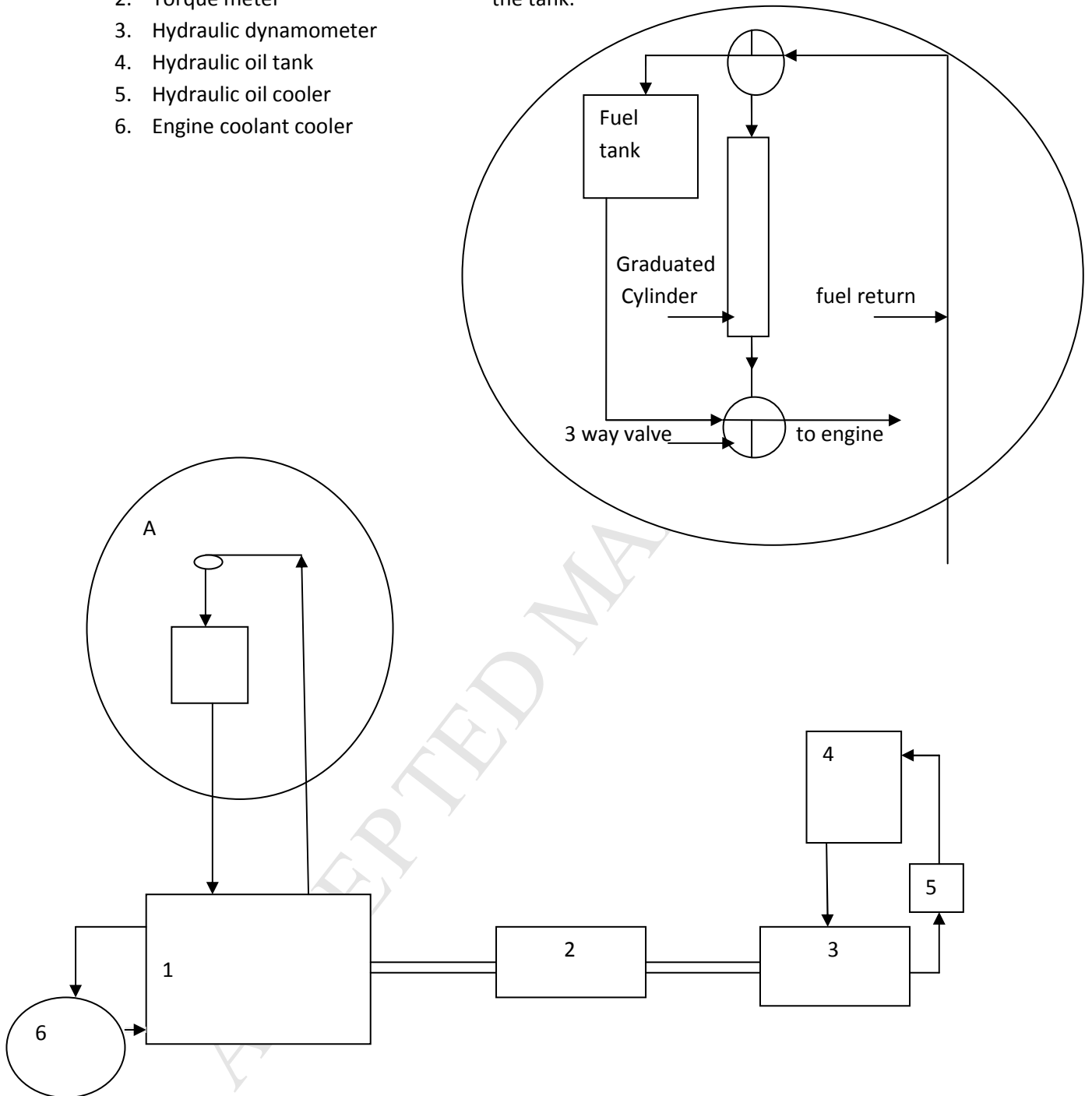


Figure 1

Figure 2 Test bed layout.

1. Engine
2. Torque meter
3. Hydraulic dynamometer
4. Hydraulic oil tank
5. Hydraulic oil cooler
6. Engine coolant cooler

Detail A engine fuel supply arranged to draw fuel from the tank.



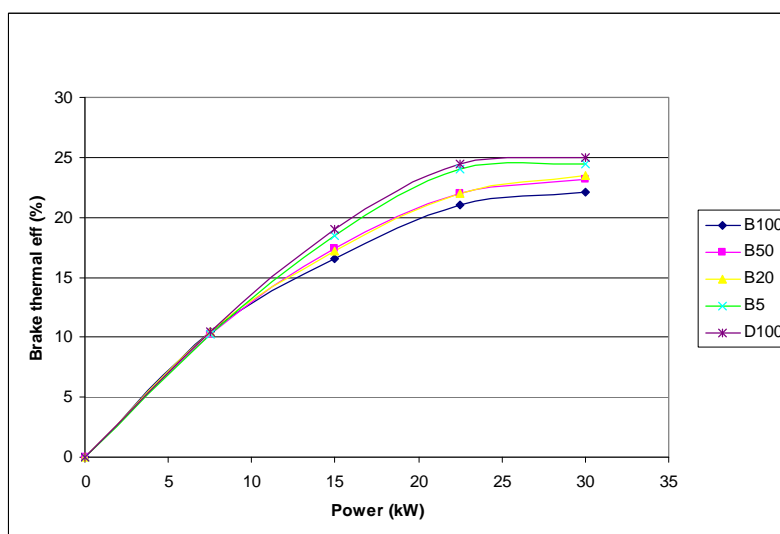


Figure 3

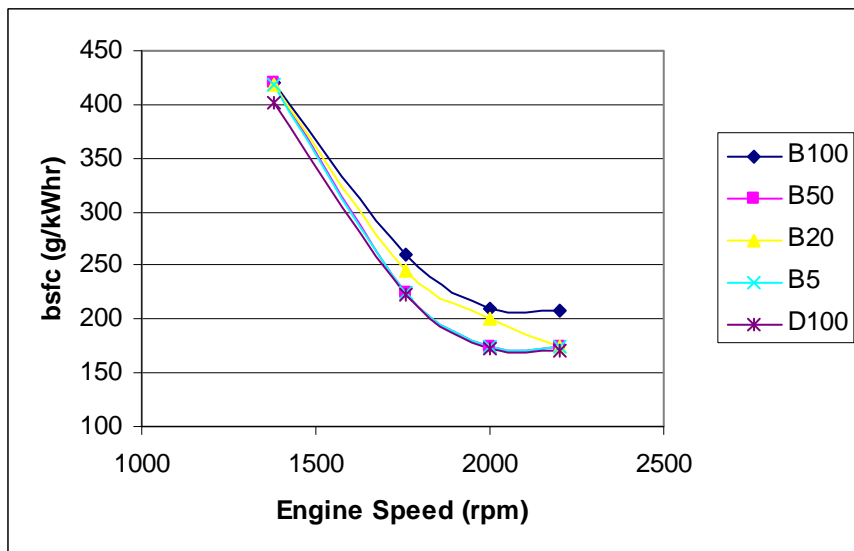


Figure 4

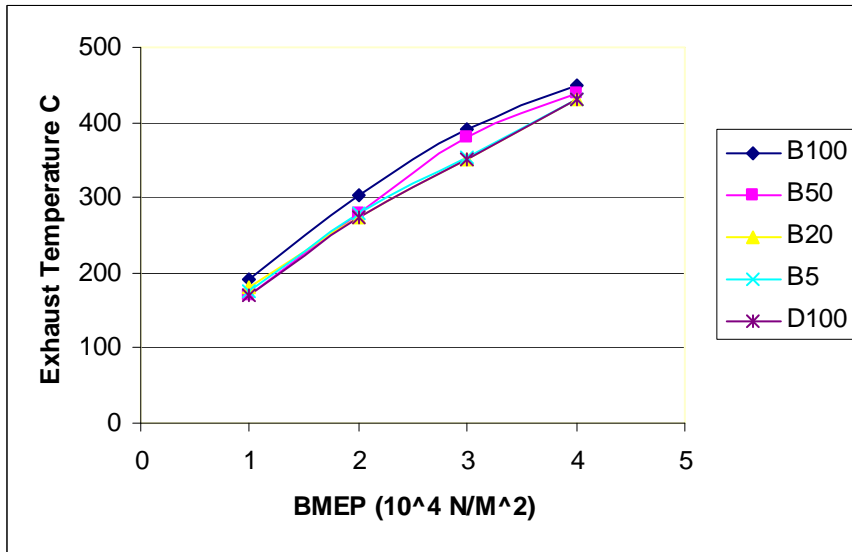


Figure 5

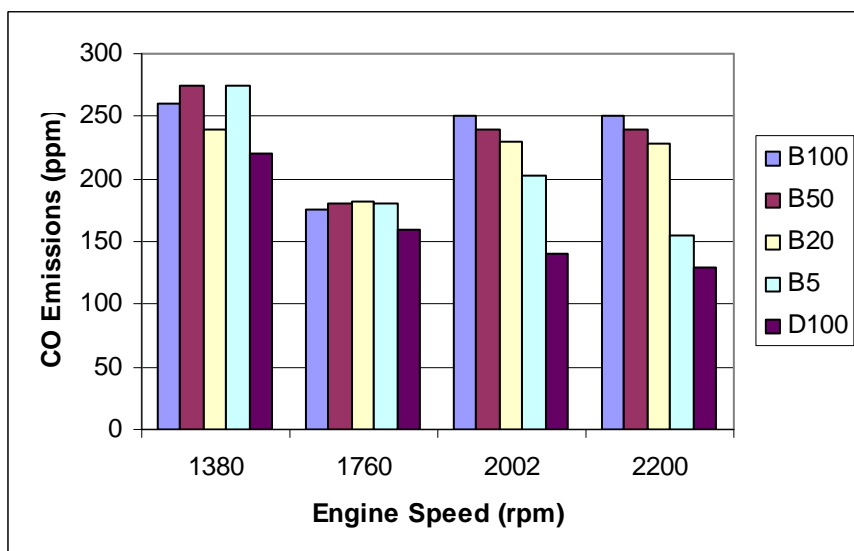


Figure 6

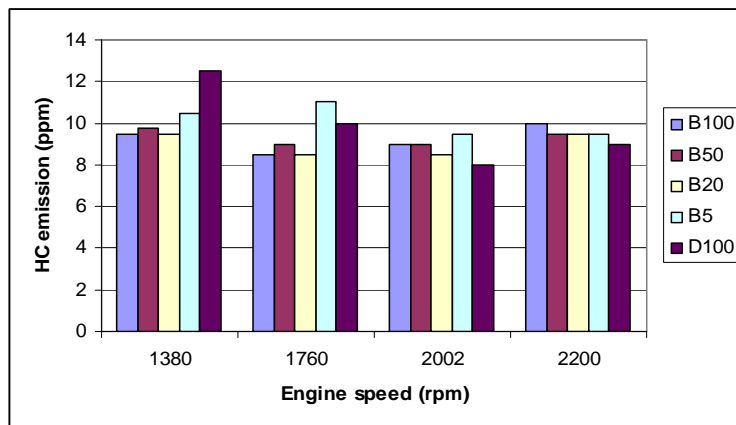


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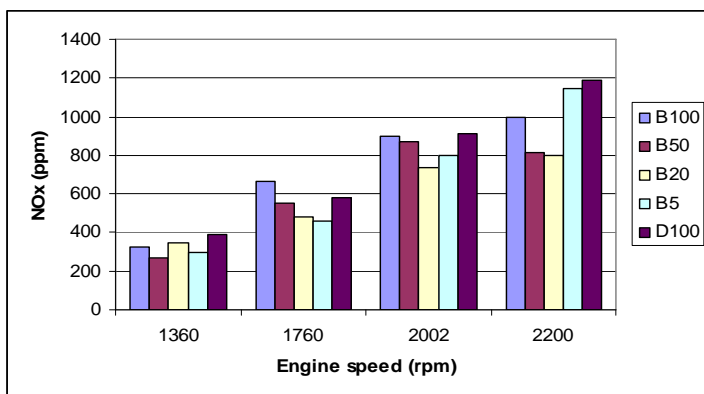


Figure 8

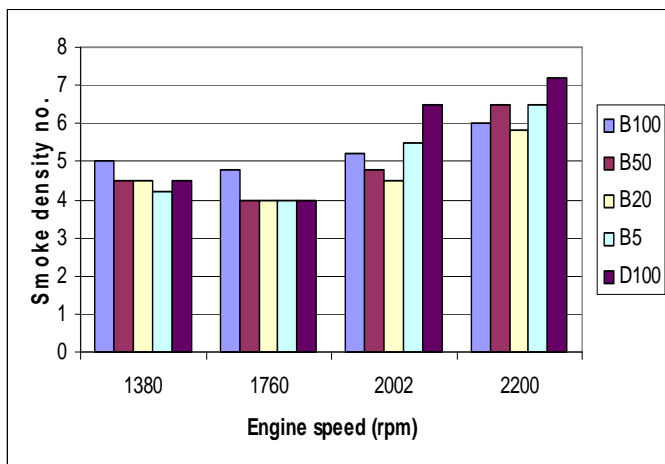


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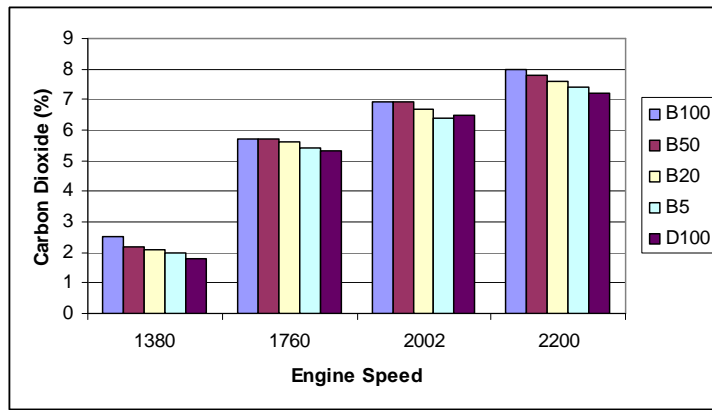


Figure 10

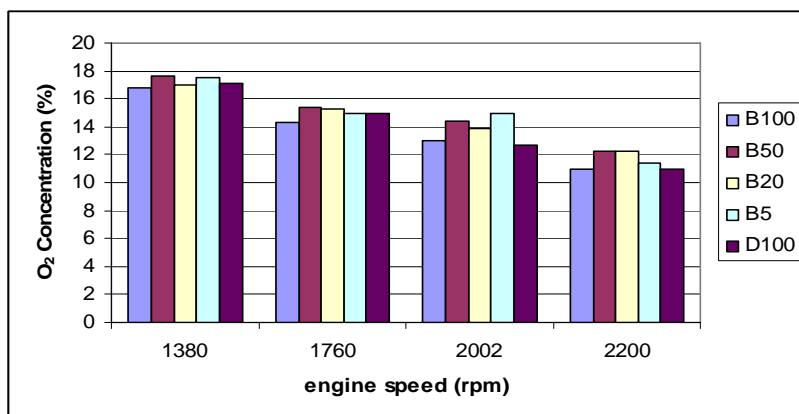


Figure 11