A comparative study on the performance, emission and combustion studies of a DI diesel engine using distilled tyre pyrolysis oil–diesel blends

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A comparative study on the performance, emission and combustion Studies of a DI diesel engine using Distilled Tyre pyrolysis oil-diesel blends

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Abstract

Increase in energy demand, stringent emission norms and depletion of oil resources have led the researchers to find alternative fuels for internal combustion engines. Many alternate fuels like Alcohols, Biodiesel, LPG, CNG etc have been already commercialised in the transport sector. In this context, pyrolysis of solid waste is currently receiving renewed interest. The disposal of waste tyres can be simplified to a certain extent by pyrolysis. In the present work, the crude Tyre pyrolyisis oil (TPO) was desulphurised and then distilled through vacuum distillation. Also, two Distilled Tyre pyrolysis oil (DTPO)-diesel fuel (DF) blends at lower and higher concentrations were used as fuels in a four stroke single cylinder air cooled diesel engine without any engine modification. The results were compared with diesel fuel (DF) operation. This paper presents the studies on the performance, emission and combustion characteristics of a single cylinder four stroke air cooled DI diesel engine running with the Distilled Tyre pyrolysis oil–diesel blends at two concentrations.

Keywords: Diesel engine, Distilled Tyre Pyrolysis Oil (DTPO)-diesel fuel (DF), Performance, Emission, Combustion

1. Introduction

Diesel engines are most preferred power plants due to their excellent drivability and higher thermal efficiency. Despite their advantages they emit higher levels of NO_x and smoke which will have an effect on human health. Hence stringent emission norms have been imposed. In order to meet the norms and also the fast depletion of petroleum fuels have necessitated a search for alternate fuels for diesel engines. On the other hand, due to the rapid growth of automotive vehicles in transportation sector, the consumption of oil keeps increasing. And also, the disposal of used tyres from automotive vehicles becomes inexhaustible. Though many disposal methods are available to dispose the waste automobile tyres, still the problem persists. Pyrolysis of a substance offers value added products such as pyrolysis oil, pyro gas and char. Investigations report that Pyrolysis of waste automobile tyre chips produce Tyre pyrolysis oil, pyrolytic gas and char. It is also reported that TPO has properties similar to that of diesel fuel. In reference [1], Experimental work was carried out on a one ton batch pyrolysis unit to produce oil, char and gas from waste automobile tyres through pyolysis process.

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A single oil droplet combustion study was carried out and also the oil was analysed in detail for its content of polycyclic aromatic hydrocarbons (PAH). The derived oil was combusted in a 18.3 kW ceramic-lined, oil-fired, spray burner furnace, 1.6 m in length and 0.5 m internal diameter. The emissions of NO_x, SO_2, particulate and total unburned hydrocarbons were determined in relation to excess oxygen levels [1, 2]. Throughout the combustion tests, comparison of the emissions was made with the combustion of diesel. The oil was found to contain 1.4 % sulphur and 0.45 % nitrogen on mass basis and have similar fuel properties to those of DF.

I.de Marco Rotriguez et al [3] studied the behaviour and chemical analysis of Tyre pyrolysis oil. In this work it is reported that Tyre Oil is a complex mixture of organic compounds of 5-20 carbons with a higher proportion of aromatics. The percentage of aromatics, aliphatic, nitrogenated compounds, benzothiazol were also determined in the Tyre pyrolysis oil at various operating temperatures of the pyrolysis process. Aromatics were found to be about 34.7 % to 75.6 % when the operating temperature was varied between 300 ^oC and 700 ^oC, while Aliphatics were about 19.8 % to 59.2 %. In the same work, an automatic distillation test was carried out at 500 ^oC to analyse the potential use of Tyre pyrolysis oil as petroleum fuels. It was observed that more than 30 % of the Tyre pyrolysis oil was easily distillable fraction with boiling points between 70 ^oC and 210 ^oC, which is the boiling point range specified for commercial petrol. On the other hand, 75 % of the pyrolytic oil has a boiling point under 370 ^oC, which is the upper limit specified for 95 % of distilled product of diesel oil. It was mentioned that distillation carried out between 150 ^oC and 370 ^oC has a higher proportion of the lighter and heavier products and a lower proportion of the middle range of products than commercial diesel oil.

Studies have been carried out on wood pyrolysis oil as an alternate fuel in internal combustion engines [4, 5]. Reliable operation was recorded with wood pyrolysis oil-diglyme blends without any modification in the engine. In recent years some experimental studies revealed that the use of TPO derived from waste automobile tyres can be used as an alternate fuel in diesel engines. Despite the operative and expensive approach, the best possible utilisation of TPO is still to be determined. TPO characteristics strongly depend on the pyrolysis process characteristics, process temperature and nature of waste automobile tyres used. Experiments were carried out using crude TPO in a single cylinder diesel engine [6]. Initially with crude TPO the engine was run using TPO-diesel blends. The maximum TPO blended with diesel was found to be 70 %. Further the engine was unable to run with more than 70 % TPO blended with diesel. The viscosity and sulphur content of crude TPO are the two parameters those influence the engine performance and emissions. High viscosity of the fuel will lead to problems in the long run which include carbon deposit, oil ring sticking, etc.

The high carbon residue indicated by Conradson value and high viscosity is due to the large molecular mass and chemical structure. The high carbon residue is responsible for heavy smoke emissions. The use of crude TPO as an alternate fuel showed similar performance and emission characteristics, with that of neat vegetable oils in compression ignition engines.

Crude TPO contains char, sand and alkali metals [2]. Wear problems will arise both in the injection equipment and in several other engine parts, such as valves, valve seats, piston rings and liners. In addition, exhaust emissions may be impaired by these solid particles. Though the experimental results have no remarks about the emission of oxides of sulphur, the higher sulphur content will definitely affect the use of crude TPO as an alternate fuel in diesel engines.

Crude TPO also contains tar and polymers in the form of gummy materials. The presence of polymers, tar and solid particles may cause the formation of deposits in the injection system. Direct use of crude TPO may build up carbonaceous deposits in the combustion chamber, exhaust valves and ports and in the piston ring grooves. It is evident that the direct use of crude TPO in diesel engines is quite difficult and the problems mentioned above will be faced. The present study is aimed to modify the fuel to reduce the viscosity and sulphur content of the crude pyrolysis oil. The properties of modified TPO were also determined and compared with that of crude TPO. In the present work, the performance, emission and combustion characteristics of a single cylinder air cooled DI diesel engine running with low and high concentration DTPO-DF blends were studied and compared with DF operation.

2. Distillation of Tyre Pyrolysis Oil

2.1 Crude TPO

In the present study, an automobile tyre was cut into a number of pieces and the bead, steel wires and fabrics were removed. Thick rubber at the periphery of the tyre alone was made into small chips. The tyre chips (feed stock) were washed dried and were fed in a mild steel fixed bed reactor unit. The feedstock was externally heated up in the reactor in the absence of oxygen. The pyrolysis reactor designed for the experiment was a fully insulated cylindrical chamber of inner diameter 110 mm and outer diameter 115 mm and height 300 mm and. The reactor was supplied with 2 kW of power for external heating. The temperature of the reactor was controlled by a temperature controller. The process was carried out between 450 ^{o}C and 650 ^{o}C . The heating rate was maintained at 5 ^{o}C/min. The residence time of the feed stock in the reactor was 120 minutes. The products of pyrolysis in the form of vapour were sent to a water cooled condenser and the condensed liquid was collected as a fuel. The schematic diagram of the pyrolysis process of waste automobile tyres is given in Figure 1. 1.9 kg of feed stock was used to produce one kg of Tyre pyrolysis Oil. The products yielded in the pyrolysis process were: Tyre Pyrolysis Oil (55%), Pyro gas (10%), Char (34%) and moisture (1%) of the input. The heat energy required for the pyrolysis process per kg of TPO produced was around 6 MJ/kg.

Figure 1 Pyrolysis process of waste automobile tyres

2.2 Modification of TPO

The modification of the crude TPO involves three stages, (i) removal of moisture (ii) Desulphurisation (iii) Vacuum distillation. The schematic layout of the distillation of TPO is shown in Figure 2.Initially crude TPO was heated upto 100 °C, in a cylindrical vessel for a particular period to remove the moisture, before subjecting it to any further chemical treatment. The moisture free crude TPO contains impurities, carbon particles and sulphur particles. A known volume of concentric hydrosulphuric acid (8%) was mixed with the crude TPO and stirred well. The mixture was kept for about 40 hours. After 40 hours, the mixture was found to be in two layers. The top layer was a thin mixture and lower one was a thick sludge. The top layer was taken for vacuum distillation and the sludge was removed and disposed off.

Figure 2 Distillation of Tyre Pyrolysis Oil

2.3 Vacuum distillation

Vacuum distillation process was carried out to separate the lighter and heavier fraction of hydrocarbon oil. A known sample of chemically treated crude TPO was taken for vacuum distillation process. The sample was externally heated in a closed chamber. The vapour leaving the chamber was condensed in a water condenser and the DTPO was collected separately. Non condensable volatile vapours were left to the atmosphere. The distillation was carried out between 150°C and 200°C. 80 % of DTPO was distilled in the distillation whereas 5 % of DTPO was left out as pyrogas and 15 % was found as sludge.

The DTPO has irritating odour like acid. The odour can be reduced by adding some masking agents or odour removal agents. Several tests were conducted to characterize the DTPO in order to evaluate physical, chemical and thermal properties. DTPO has about 7 % higher heating value than crude TPO. This is due to the elimination of impurities, moisture, carbon particle, sulphur and sediments. Three test fuels have been taken for the experimental work. The first one is standard diesel fuel (DF) and other two are DTPO 20 and DTPO 90. DTPO 20 is 20 % DTPO blended with 80 % DF on volume basis. DTPO 90 is 90 % DTPO blended with 10 % DF on volume basis. Salient properties of TPO, DTPO 20 and DTPO 90 are compared with Diesel in **Table 1**.

Table 1 Comparison of TPO, DTPO, DTPO 20 and DTPO 90 blends with Diesel

3. Experimentation

The schematic layout of the experimental set up is shown in Figure 3. The specifications of the DI engine are shown in Table 2. An electrical dynamometer was used to load the engine. An air box was fitted to the engine for airflow measurement. The fuel flow rate was measured on volumetric basis using a burette and a stopwatch. Chromel alumel thermocouple in conjunction with a digital temperature indicator was used to measure the exhaust gas temperature. A pressure transducer in conjunction with a KISTLER charge amplifier and a Cathode Ray oscilloscope (CRO) were used to measure the cylinder pressure. A TDC encoder was used to detect the engine crank angle. An Infrared gas analyzer was used to measure NO_x/HC/CO emissions in the exhaust. Smoke was measured using a Bosch type smoke meter. Initially experiments were carried out using DF at the rated engine speed of 1500 rpm. All the tests were conducted by starting the engine with DF only. After the engine was warmed up, it was then switched to DTPO-DF blend. At the end of the test, the engine was run for some time with DF to flush out the DTPO-DF from the fuel line and the injection system. &he engine was run about 150 hours.

Table 2 Engine Details

Figure 3 Experimental setup

4. Results and Discussion

4.1 Performance

Figure 4 shows the comparison of the brake thermal efficiency with brake power for the tested fuels. It can be observed from the figure that the thermal efficiency is 29.5 % at full load for DF whereas for DTPO 20 and DTPO 90, it is 28.5 % and 27.3 % respectively. The thermal efficiencies of DTPO-DF blends are lower compared to DF. This may be due to the inferior combustion of DTPO. Reduction in thermal efficiency by about 2 % is noticed at full load for DTPO 90 blend compared to DF. For DTPO 90, the viscosity is lesser compared to DTPO 20 and the fuel spray does not propagate deeper into the combustion chamber and left unburned. This incomplete combustion, results in the reduction of efficiency.

Figure 4 Variation of brake thermal efficiency with brake power

The brake specific fuel consumption is not a very reliable factor to compare the two fuels as the calorific value and the density of the blend are slightly different from that of DF. Figure 5 shows the comparison of the BSEC with brake power for the tested fuels. It can be observed from the figure that BSEC increases with increase in the concentration of DTPO in DTPO-DF blend. BSEC varies from 23.75 MJ/kWh at low load to 13.31 MJ/kWh at full load for DTPO 90 and varies from 24.96 MJ/kWh at low load to 12.64 MJ/kWh for DTPO 20. In the case of DF, it varies from 24.37 MJ/kWh at low load to 12.21 MJ/kWh at full load. This behaviour is obvious since the engine will consume more fuel with DTPO-DF blends than DF, to gain the same power output owing to the lower heating value of DTPO-DF blends.

Figure 5 Variation of BSEC with brake power

Figure 6 shows the variation of exhaust gas temperature with brake power for the tested fuels. The exhaust gas temperature decreases with increase in the blend concentration and the values are lesser compared to DF. The exhaust gas temperature varies from 198 ^{o}C at no load to 444 ^{o}C full at load for DF, it is from 168 ^{o}C to 432 ^{o}C for DTPO 20 and 192 ^{o}C to 433 ^{o}C for DTPO 90. The reason for lower exhaust gas temperatures for DTPO-DF blends is due to lower viscosity, which results a lesser penetration of the fuel into the combustion chamber, and there by releasing lesser amount of heat [7].

Figure 6 Variation of exhaust gas temperature with brake power

4.2 Emission

Figure 7 shows the comparison of NO_x emission with brake power for the tested fuels. It can be observed from the figure that NO_x emission increases with increase in the blend concentration but lesser than that of DF. NO_x varies from 373 ppm at no load to 2221 ppm at full load for DF whereas for DTPO 20 it varies from 307 ppm at no load to 1740 ppm at full load and for DTPO 90 it varies from 337 ppm at no load to 1820 ppm at full load. Two important parameters result in the formation of $NO_{x.}$ One parameter is stoichiometry and the other one is in cylinder temperature. If the stoichiometry of the combustion is lean, then lower NO_x is formed [8,10]. But due to the diffusive mixing of fuel and air occurring along the spray envelope, the combustion takes place with near stoichiometric, forming higher NO_x. The in-cylinder temperature has a strong effect on the formation of $NO_{x.}$ If the combustion temperature is higher, then higher NO_X is formed [8]. In the case of DTPO-DF blends, the lower in cylinder temperature is the reason for lower NO_X levels than that of DF. However NO_x formed in DTPO 90 operation is higher than DTPO 20. This may be due to higher heat released compared to DTPO 20, and it is realized in higher exhaust gas temperature.

Figure 7 Variation of NO_x with brake power

The comparison of Hydrocarbon emission in the exhaust is shown in Figure 8. Unburnt hydrocarbon emission is the direct result of incomplete combustion. It is apparent that the hydrocarbon emission is increasing with the percentage of TPO mixed in the blend. HC varies from 26 ppm at no load to 25 ppm at full load for DF, and it varies from 28 ppm at no load to 27 ppm at full load for DTPO 20 and for DTPO 90, it varies from 29 ppm at low load to 31 ppm at full load. HC emission is slightly higher for DTPO 20 and DTPO 90 compared to DF. This may be attributed to two reasons. One is that the fuel spray does not propagate deeper into the combustion chamber and gaseous hydrocarbons remain along the cylinder wall, the crevice volume and left unburned [8]. The other one is unsaturated hydrocarbons present in the DTPO, which are unbreakable during the combustion process [6,9].

Figure 8 Variation of hydrocarbon emissions with brake power

Figure 9 shows the comparison of Carbon monoxide emission with brake power. Generally, CI engines operate with lean mixtures and hence the CO emission would be low [8]. CO emission for the DTPO-DF blends is higher compared to DF. The concentration varies from 0.1 % at no load to 0.04 % at full load for DF, from 0.2 % to 0.05 % for DTPO 20, and from 0.08 % to 0.06 % for DTPO 90. The fuel air mixture filled inside the cylinder is very lean and the flame will not propagate through some of the mixtures nearer to the wall and crevice volume. Therefore, they do not find time to undergo combustion which results higher CO emission for DTPO-DF blends than that of DF. However, the CO emissions for DTPO-DF blends lie below 0.1 %, which is the maximum value of CO emission from diesel engines.

Figure 9 Variation of CO emissions with brake power

4.2.4 Smoke emission

Smoke is nothing but solid soot particles suspended in exhaust gas [8]. Figure10 shows the comparison of smoke level with brake power. It can be observed that smoke increases with increase in blend percentage and also higher than that of DF at full load. Smoke varies from 0 at no load to 1.45 BSU at full load for DF, from 0.3 BSU to 1.6 BSU for DTPO 20 and 0.35 BSU to 2 BSU for DTPO 90. It was reported by Yoshiyuki Kidoguchi et al [9] that fuels with longer ignition delay by keeping the aromatic content constant, exhibit lower particulate emissions and higher NO_x at high loads. At the same time, as the aromatic content is increased with constant cetane number, particulate emission increases at high load. Higher smoke values in the case of blends may be due to unburned and partially reacted hydrocarbons as well as sulfur compounds and bound water present in the DTPO-DF blends.

Figure 10 Variation of Smoke with brake power

4.3 Combustion Parameters

Figure 11 indicates the cylinder pressure with crank angle for different fuels at full load. Cylinder pressure obtained at full load is higher by about 2.8 bar for DTPO 90 compared to DF and. In the case of DTPO 20 the peak pressure at full load is lesser by about 3.2 bar than DF. Peak pressure of a CI engine depends on the combustion rate in the initial stages, which is influenced by the amount of fuel burnt in the premixed combustion. The premixed combustion is dependant on the delay period and the mixture preparation [10]. It may be seen that the ignition delays are longer with blends than DF. The ignition delay is longer by about 1.4 ^{o}CA and 2.5 ^{o}CA for DTPO 20 and DTPO 90 respectively than that of DF operation.

Figure 11 Variation of pressure with crank angle

Figure 12 shows the variation of ignition delay for the tested fuels. The ignition delay of DF varies from 7.7 ^{o}CA at low load to 6.5 ^{o}CA at full load whereas the ignition delay for DTPO 20 varies from 8.9 ^{o}CA at low load to 7.9 ^{o}CA at full load and for DTPO 90 it varies from 10.1 ^{o}CA at low load to 9 ^{o}CA at full load.

Figure 12 Variation of ignition delay with brake power

The variation of cylinder peak pressure with brake power for DTPO-DF and DF operation at different loads is depicted in Figure 13. It may be noticed from the figure that the cylinder peak pressure increases with increase in DTPO-DF blend. The cylinder peak pressure for DF increases from 57.5 bar at no load to 71.2 bar at full load, from 57 bar at no load to 68.5 bar at full load for DTPO 20 operation and from 58.4 bar at no load to 74 bar at full load for DTPO 90. Increase in the ignition delay with the increase in DTPO fraction in DTPO-DF blends increases the amount of fuel burned in the premixed burning phase. At the same time, probably the increase in DTPO fraction also increases heat of evaporation, decreases the cylinder gas temperature when the fuel is evaporated. These two factors make the variation in cylinder peak pressure for DTPO 20 and DTPO 90.

Figure 13 Variation of cylinder peak pressure with brake power

Figure 14 shows the heat release pattern of the DTPO-DF operation at full load. The first stage is from the start of ignition to the point where the heat release rate drops and this is due to the ignition of fuel air mixture prepared during the delay period [10, 11]. The second stage starts from the end of the first stage to the end of combustion. The combustion duration increases with DTPO 20 and DTPO 90. This is due to the higher quantity of fuel injected and low mixture preparation rates since DTPO 20 and DTPO 90 have longer ignition delay. The maximum rate of heat release for DTPO 90 is the highest compared to DF and DTPO 20, as expected since fuels with longer ignition delay show higher rate of heat release at initial stage of combustion and increase in cylinder peak pressure [8]. The maximum heat release is 57.4 J / ^{o}CA for DF. It can also be noticed that the maximum heat release is 56.3 J / ^{o}CA for DTPO 20 and 62.8 J / ^{o}CA for DTPO 90. It can also be noticed that during the diffusive combustion, the duration is longer and the heat released is lesser than DTPO 20 and DTPO 90.

Figure 14 Variation of heat release rate with crank angle

The rate of pressure rise defines the load that is imposed by the combustion process on the cylinder head and block and to a large extent, determines the structural design. Longer ignition delay will cause rapid rates of pressure rise. The longer ignition delay, would be the time available for the fuel to evaporate before combustion occurs, and greater the amount of fuel which burns with extreme rapidity during the period of uncontrolled combustion. Figure 15 shows the comparison of the rate of pressure rise for the tested fuels at full load. It can be observed that the rate of pressure rise is comparable for DTPO-DF blend operation compared to that of DF operation. In the case of DTPO 90 the rate of pressure rise is marginally higher compared to DF operation. This is due to the longer ignition delay of DTPO 90 blends.

Figure 15 Variation of rate of pressure rise with crank angle

5. Conclusion

From the experimental work carried out it is observed that engine is able to run upto 90 % DTPO and 10 % DF (DTPO 90). Engine failed to run satisfactorily with 100 % DTPO. Brake thermal efficiency increases with increase in percentage of DTPO blends but lesser than DF. About 1-2 % drop in the thermal efficiency is noticed for DTPO 20 and DTPO 90 operations compared to DF. NO_x is lowered by about 22 % and 18 % in DTPO 20 and DTPO 90 respectively than that of DF operation. HC emission is higher by about 7 % and 11 % for DTPO 20 and DTPO 90 respectively at full load than that of DF operation. Smoke is higher for compared to DF. Ignition delay is 1.4-2.5 ^{o}CA longer for DTPO-DF blends compared to DF at full load. Cylinder peak pressures are higher by about 2.8 bar for DTPO 90 and 3.2 bar lesser for DTPO 20 than that of DF operation. Higher rate of heat release in the initial stages and rate of pressure rise are observed in the DTPO 90 blends compared to DF.

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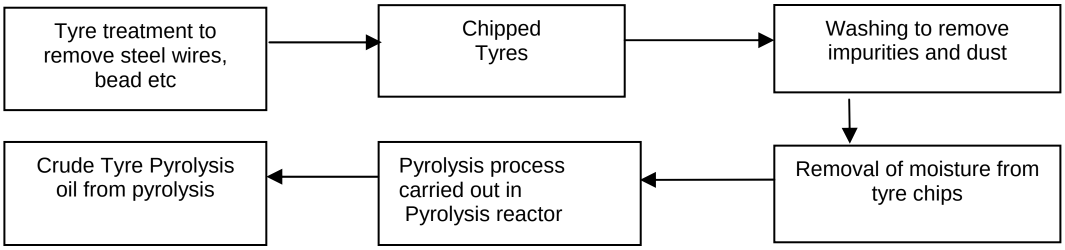


Figure 1 Pyrolysis process of waste automobile tyres

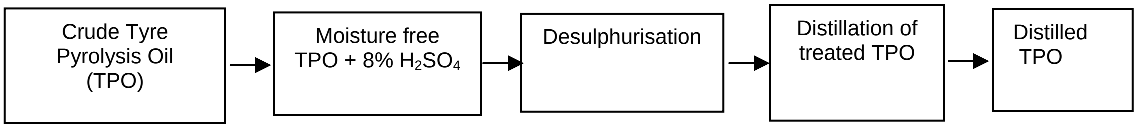
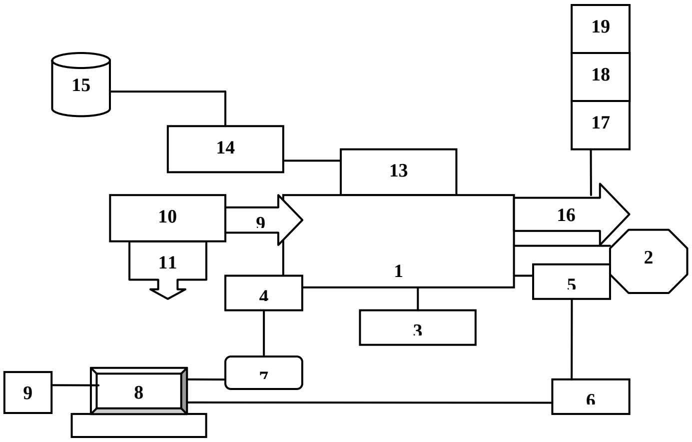


Figure 2 Distillation of Tyre Pyrolysis Oil



1. Engine
2. Dynamometer
3. Control Panel
4. Pressure Pickup
5. TDC Encoder Machine
6. Amplifier
7. Charge Amplifier
8. C.R.O
9. Printer
10. Inlet Manifold
11. Surge Tank
12. Air Flow Meter
13. Fuel Injector
14. Fuel Injection Pump
15. Fuel Tank
16. Exhaust Manifold
17. CO/HC Analyser
18. NO_X Analyser
19. Bosch Smoke Pump

Figure 3 Experimental setup

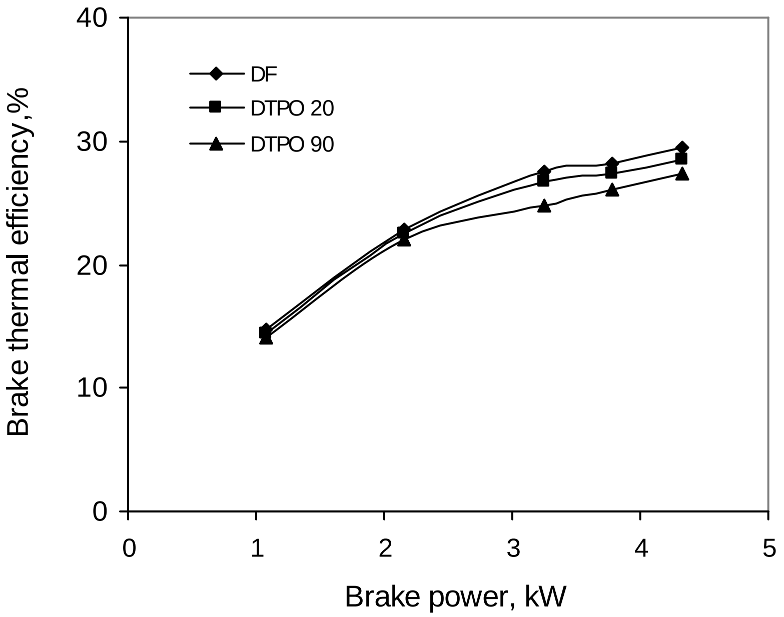


Figure 4   Variation of brake thermal efficiency with brake power

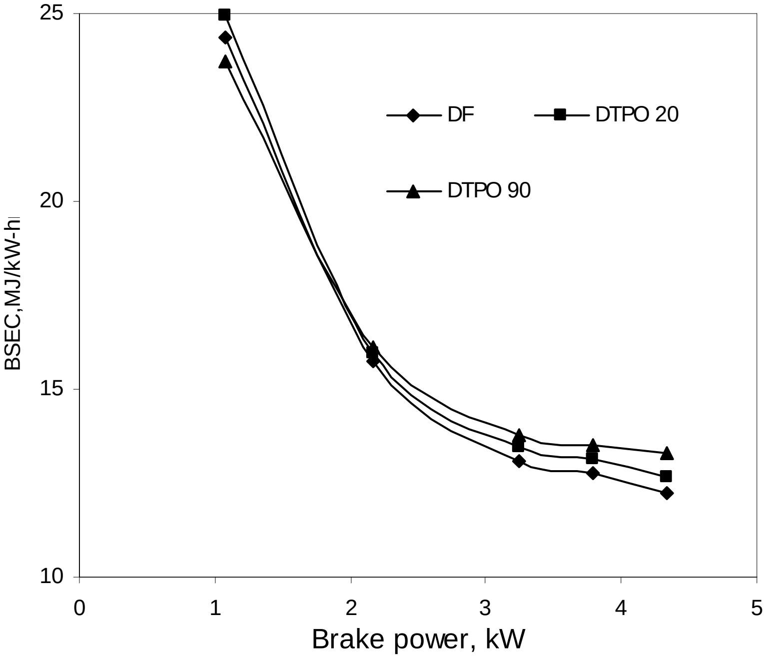


Figure 5 Variation of BSEC with brake power

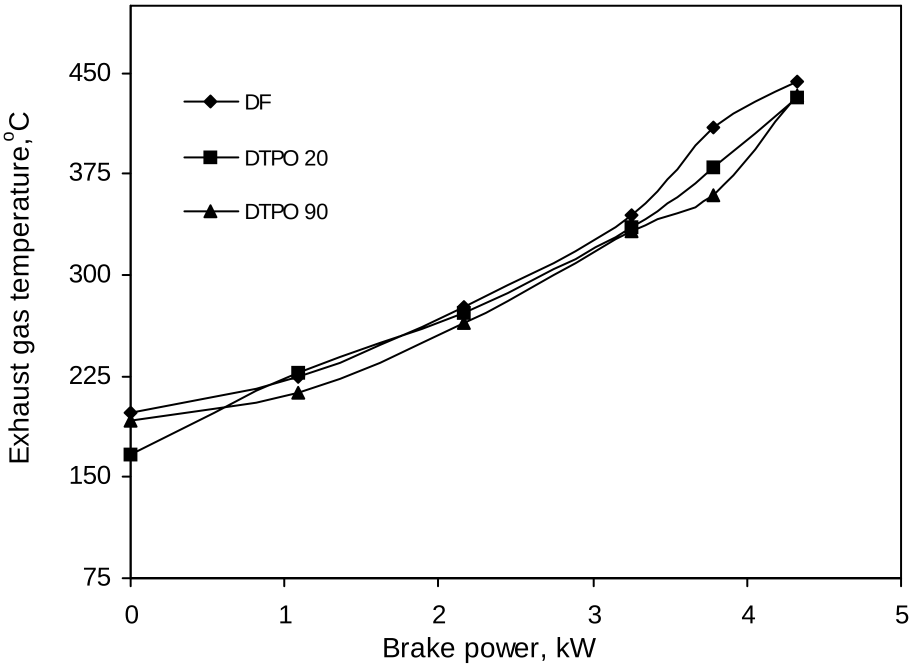


Figure 6 Variation of exhaust gas temperature with brake power

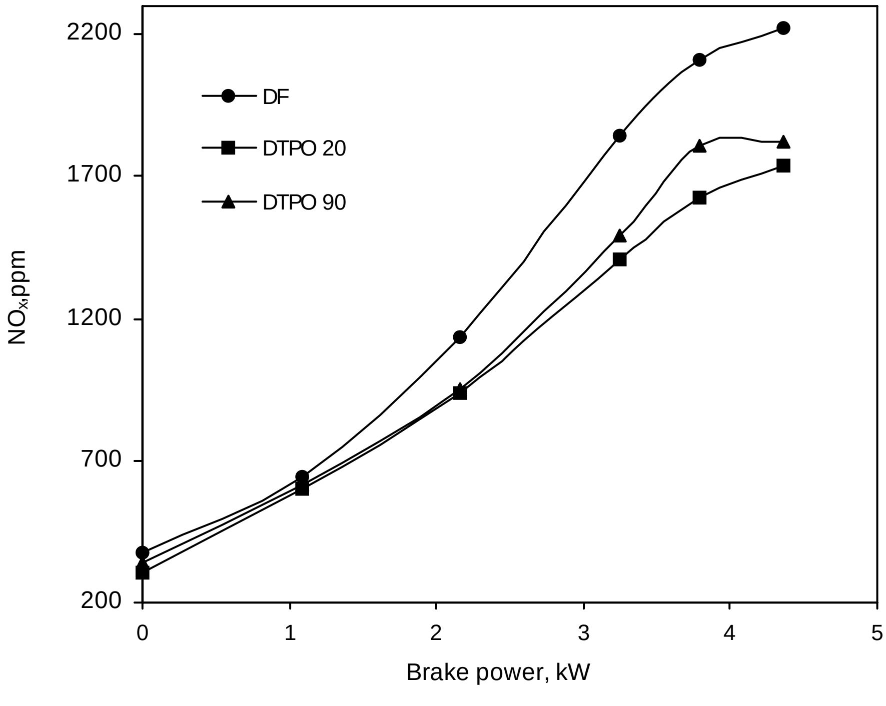


Figure 7 Variation of NO_x with brake power

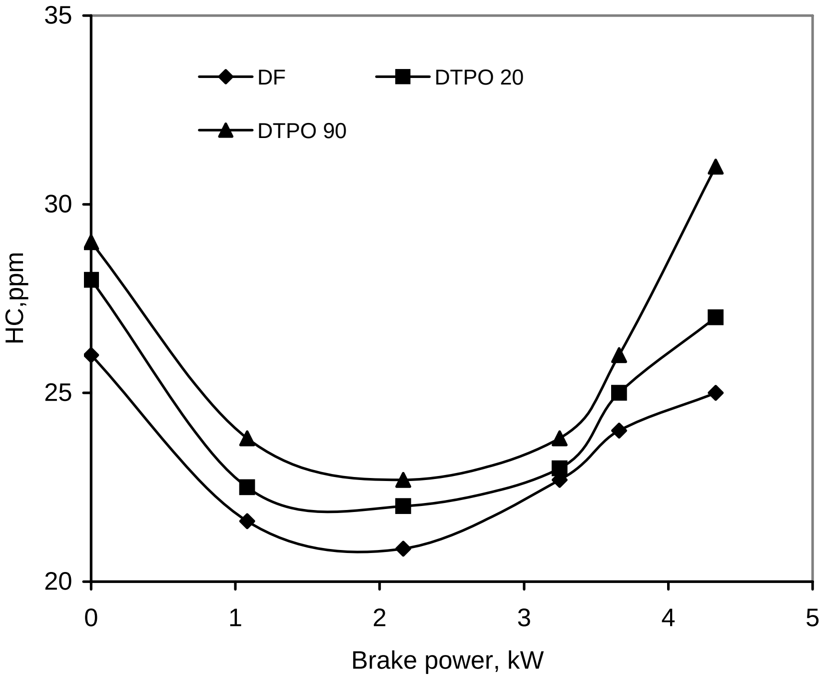


Figure 8 Variation of hydrocarbon emissions with brake power

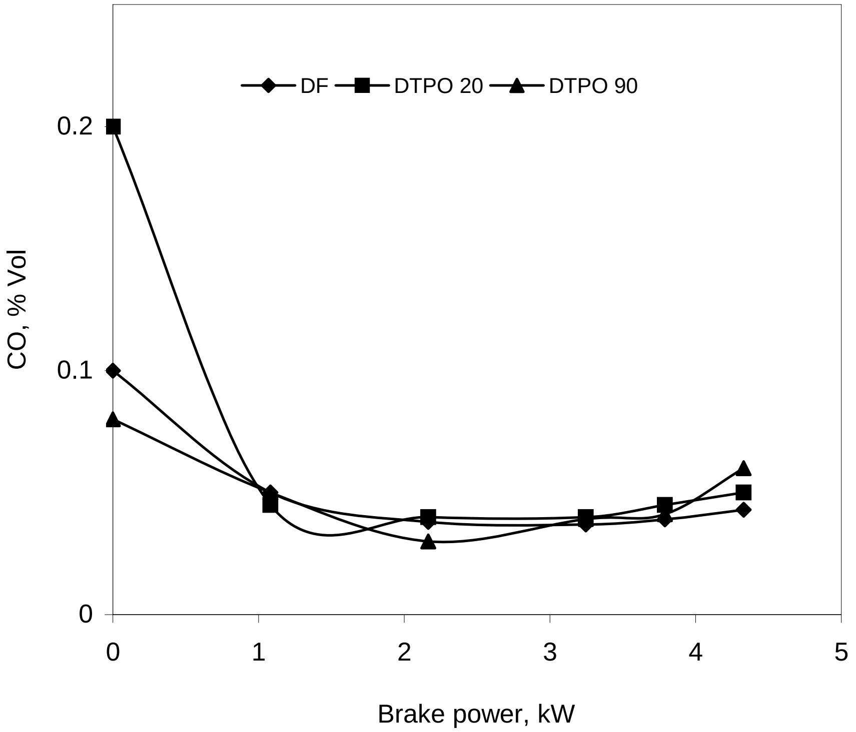


Figure 9 Variation of CO emission with brake power

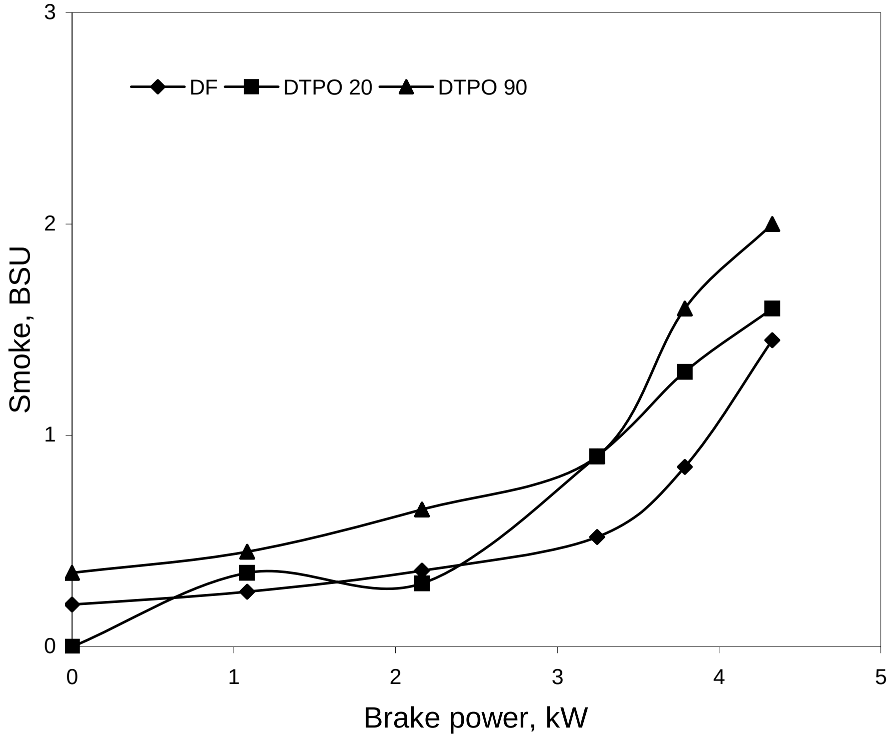


Figure 10 Variation of Smoke with brake power

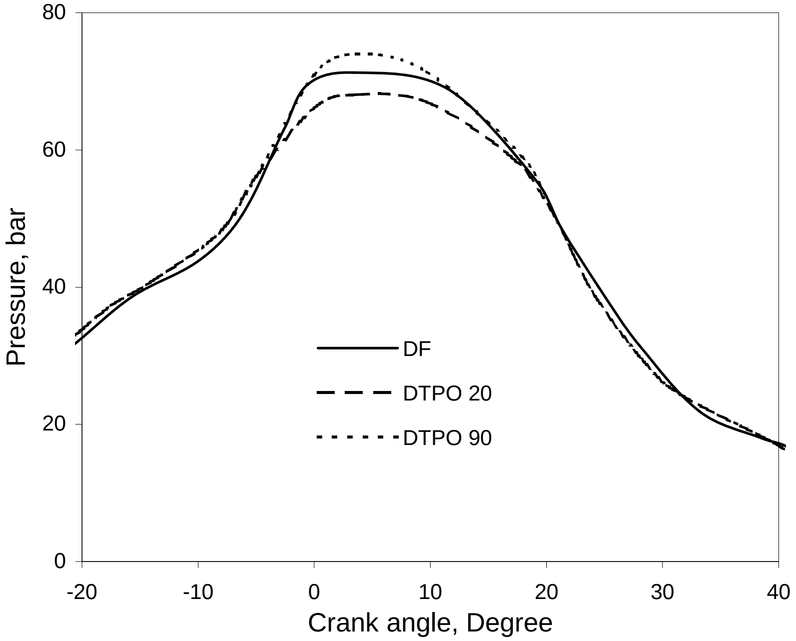


Figure 11 Variation of pressure with crank angle

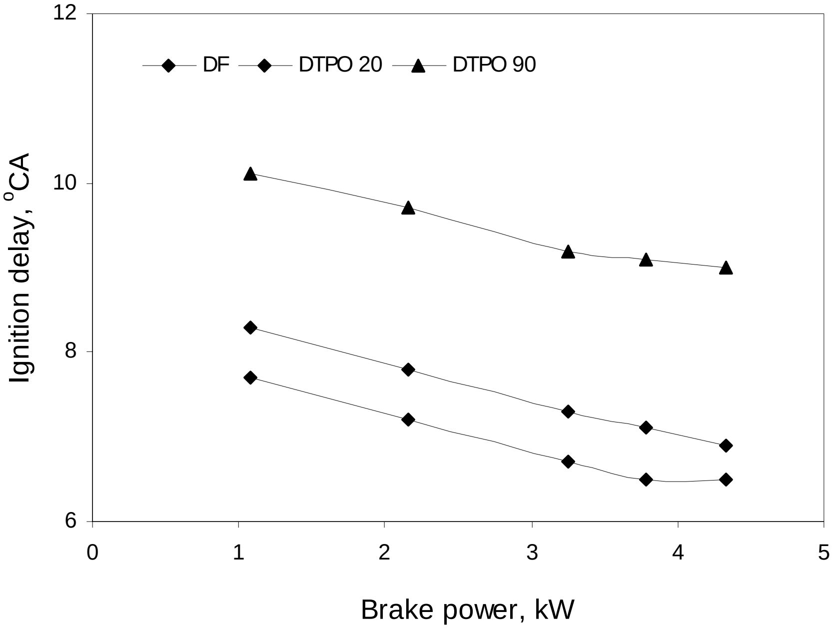


Figure 12 Variation of ignition delay with brake power

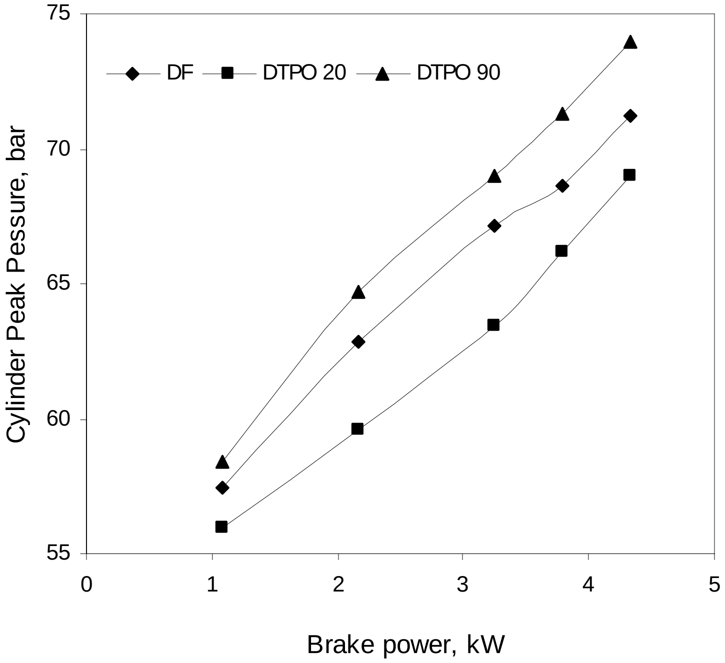


Figure 13 Variation of cylinder peak pressure with brake power

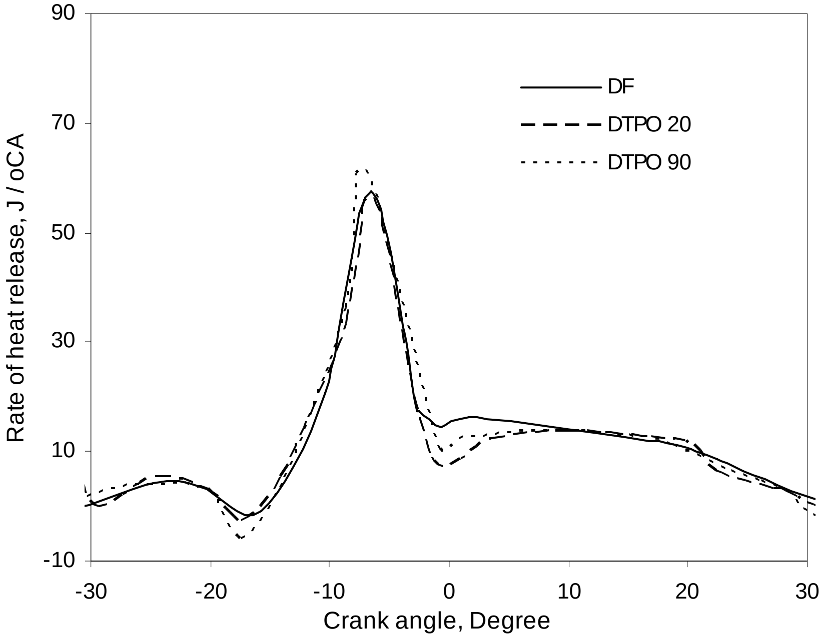


Figure 14 Variation of heat release rate with crank angle

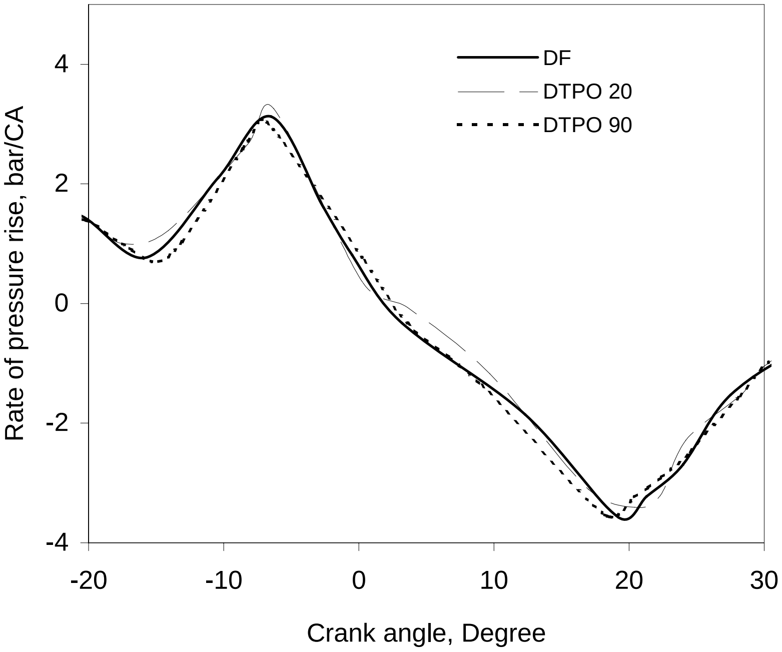


Figure 15 Variation of rate of pressure rise with crank angle

Table 1 Comparison of TPO, DTPO, DTPO 20 and DTPO 90 blends with Diesel

Property		**Diesel**	**Crude TPO**	**DTPO**	**DTPO 20**	**DTPO 90**
Density @ 15^0 C kg/m^3		830	935	871	832	865
Kinematic Viscosity, cSt @ 40^0C		2	3.2	1.7	1.94	1.73
Gross Calorific Value MJ / kg		46.5	42.8	45.6	46.4	45.8
Flash Point, ^{0}C		50	43	36	47	37
Fire Point, ^{0}C		56	50	48	54	48
Sulphur Content, %		0.045	0.95	0.03	0.23	0.23
Ash Content, %		0.01	0.31	--	--	--
Carbon Residue, %		0.35	2.14	--	--	--
Aromatic content, %		26	64	--	--	--
Distillation temperature, ^oC	Boiling Point	198.5	70	--	--	
	10 %	240.5	114.5			
	50 %	278.5	296.1			--
	90 %	330.5	386.4			--
	EP	344	388.7			--

Table 2 Engine Details

Name of the Engine	Kirloskar
General Details	Four stroke, CI,air cooled, Single cylinder
Bore (mm)	87.5
Stroke (mm)	110
Compression ratio	17.5:1
Rated output @ 1500 rpm (kW	4.4
Fuel Injection Pressure (bar)	210
Injection timing (Deg CA)	23 BTDC