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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 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 some extent by pyrolysis. The properties of the Tyre pyrolysis oil (TPO) derived from waste automobile tyres were analysed and compared with the petroleum products. The crude TPO has a higher viscosity and sulphur content compared to diesel fuel. Early investigations reveal that TPO blended with diesel could be used as an alternate fuel for diesel engines. The maximum TPO concentration in the TPO-diesel blend was 70 % and the engine failed to operate satisfactorily beyond this concentration. In the present work, the crude TPO was desulphurised and then distilled through vacuum distillation. Also, DTPO-Diesel blends were used as an alternate fuel in a four stroke single cylinder air cooled diesel engine without any engine modification. 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 higher concentrations.

Keywords: Diesel engine, Tyre Pyrolysis Oil, Distilled Tyre Pyrolysis Oil

1. Introduction

Diesel engines are most preferred power plants due to their excellent drivability and higher thermal efficiency. Despite their advantages they emit high levels of NO_x and smoke which will have an effect on human health. Hence stringent emission norms and also the depletion of petroleum fuels necessitated a search of 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 in a one ton batch pyrolysis unit to produce oil, char and gas from waste automobile tyres through pyrolysis 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 an 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, SO₂, 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 behavior 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 and 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 °C and 700 °C, while Aliphatics were about 19.8 % to 59.2 %. In the same work, an automatic distillation test was carried out at 500 °C 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 °C and 210 °C, 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 °C, which is the upper limit specified for 95 % of distilled product of diesel oil. It was mentioned that distillation carried out between 150 °C and 370 °C 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-diesel blend was found to be 70 %. Further the engine was unable to run fuelled with TPO-diesel blends. The viscosity and sulphur content of crude TPO are the two parameters that influence the engine performance and emissions. The 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. The performance, emission and combustion parameters of a single cylinder air cooled DI diesel engine was analysed running with the modified DTPO-DF blends and compared with the DF operation.

2. Tyre Pyrolysis Oil

2.1 Crude TPO

In this 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 was alone made into small chips. The tyre chips (feed stock) were washed dried and were fed in a mild steel fixed bed reactor unit. The feed stock was externally heated up in the reactor in the absence of oxygen. The pyrolysis reactor designed for the experiment was a cylindrical chamber of inner diameter 110 mm and outer diameter 115 mm and height 300 mm and fully insulated. 2 kW of power was supplied to the reactor for external heating. The temperature of the reactor was controlled by a temperature controller. The process was carried out between 450 °C and 650 °C . The heating rate was maintained at 5°/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. Three products were obtained in the pyrolysis namely, Tyre Pyrolysis Oil, Pyro gas and Char. 1.9 kg of feed stock was used to produce one kg of Tyre pyrolysis Oil. The yield of the products in the pyrolysis process was: 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.

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.

2.3 Removal of moisture

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.

2.4 De Sulphurisation

The moisture free crude TPO contains impurities, carbon particles and sulphur particle. 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 thick was sludge. The top layer was taken for vacuum distillation and the sludge was removed and disposed off.

2.5 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 TPO was distilled in the distillation whereas 5 % of TPO was left out as pyro gas and 15 % was found as sludge. The time taken for obtaining 200 ml TPO and hundred minutes for 750 ml were 30 minutes and 100 minutes respectively.

The DTPO has irritating odour like acid smell. The odour can be reduced with the help of 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 the 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 DTPO80 and DTPO90. DTPO80 is 80 % DTPO

blended with 20 % DF on volume basis. DTPO90 is 90 % DTPO blended with 10 % DF on volume basis. Different properties of TPO, DTPO80 and DTPO90 are compared with Diesel in the Table 1.

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 provide the engine load. 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 cylinder pressure. The pressure pickup was mounted on the cylinder head and before mounting it was calibrated with a dead weight tester. 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. NO_x was measured in ppm. HC was measured in ppm. CO emission was measured in percentage volume. Smoke was measured in Bosch Smoke Units (BSU) by a Bosch smoke meter. Initially experiments were carried out using DF. All the experiments were conducted at a 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.

4. Results and Discussion

A series of performance and exhaust emission tests were carried out on the single cylinder CI engine using blends of DF and DTPO and the results are presented.

4.1 Performance

4.1.1 Brake thermal efficiency

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 thermal efficiency is 29.45 % at full load for DF. It can also be observed that the efficiencies for DTPO80 and DTPO90 26.2 % and 27.3 % respectively. The thermal efficiencies of DTPO-DF blends are lower compared to DF. This may be due to the lower heating value and inferior combustion of DTPO. The increase in the thermal efficiency for DTPO90 compared to DTPO80 may be attributed to better fuel atomization due to lower viscosity. Reduction in thermal efficiency by about 3 % is noticed at full load for DTPO-DF blends compared to DF.

4.1.2 Brake Specific Energy Consumption

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 is clear from the graph that as the load increases the BSEC decreases for all fuels as expected. At the same time, it can be seen that BSEC increases with increase in the concentration of DTPO in TPO-DF blend. This behavior 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 calorific value of DTPO-DF blends.

4.1.3 Exhaust gas temperature

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 °C at no load to 444 °C at full load for DF whereas it varies from 188 °C at no load to 396 °C at full load for DTPO80. For DTPO90 it varies from 198 °C at no load to 433 °C at full load for DTPO90. The reasons for lower exhaust gas temperatures for DTPO-DF blends are due to lower viscosity which results a lesser penetration of the fuel into the combustion chamber and the lesser amount of heat is developed [7].

4.2 Emission

4.2.1 Oxides of Nitrogen

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 as expected. NO_x varies from 373 ppm at no load to 2221 ppm at full load. It can also be observed that NO_x varies from 269 ppm at no load to 1733 ppm at full load whereas for DTPO80 it varies from 337 ppm at no load to 1820 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 the lower NO_x levels than that of DF.

4.2.2 Hydrocarbon emission

Figure 8 shows the comparison of Hydrocarbon emission in the exhaust for the tested fuels. 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 23.7 ppm at no load to 28 ppm at full load for DF, and it varies from 19.86 ppm at no load to 27 ppm at full load for DTPO80. Similarly for DTPO90, it varies from 19 ppm at low load to 26 ppm at full load. HC is slightly higher at peak load for DTPO80 and DTPO90. 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 and 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].

4.2.3 Carbon monoxide emission

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 vary from 0.01 % at no load to 0.06 % at full load for DTPO80 and 0.01 % at no load to 0.05 % at full load for DTPO90, whereas it varies from 0.013 % at no load to 0.04 % at full load for DF. The fuel air mixture fills inside the cylinder is very lean and some of the mixtures nearer to the wall and crevice volume, the flame will not propagate. 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 0.9 % which is a maximum value of CO emission from diesel engines.

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 is observed that smoke increases with increase in blend percentage but higher smoke emission than that of DF at full load. Smoke varies from 0 to 1.45 BSU for DF whereas it varies from 0.3 BSU at no load to 1.8 BSU at full load for DTPO80 and 0.35 BSU at no load to 2 BSU at full load for DTPO90. 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 increased with constant cetane number, particulate emission increases at high load. From the figure it can be

noticed that the smoke emission is higher for DTPO80 and DTPO90 compared to DF. Higher smoke values may be due to unburned and partially reacted hydrocarbons as well as sulfur compounds and bound water present in the DTPO-DF blends.

4.3 Combustion Parameters

4.3.1 Pressure crank angle diagram

Figure 11 indicates the cylinder pressure with crank angle for different fuels at full load. Cylinder pressure obtained at full load indicates higher values for DTPO80, DTPO90 compared to DF. It can be noticed that the combustion of DTPO-DF blends takes place earlier 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]. The early combustion of DTPO-DF blends results in a rise in cylinder peak pressure. It may be seen that the ignition delays are longer by about 2° CA and 2.5° CA for DTPO80 and DTPO90 respectively than that of DF operation and the peak pressures increased by about 1.6 bar and 2.8 bar for DTPO80 and DTPO90 respectively compared to DF operation as a result of ignition delay. Figure 12 shows the variation of ignition delay for the tested fuels at full load.

4.3.2 Cylinder peak pressure

The variation of cylinder peak pressure with brake power for DTPO-DF operation at different loads is given in Figure 13. It may be noticed from the figure that the cylinder peak pressure is increased with increase in DTPO-DF blend. The cylinder peak pressure for DF increased from 57.47 bar at no load to 71.2 bar at full load. The cylinder peak pressure increased from 58.2 bar at no load to 72.8 bar at full load for DTPO80 operation. It can also be noticed that cylinder peak pressure increased from 58.4 bar at no load to 74 bar at full load for DTPO90. In a CI engine, the peak pressure depends on the combustion rate in the initial stages, which is influenced by the amount of fuel taking part in the uncontrolled combustion phase, which is governed by the delay period. It is also affected by the fuel mixture preparation during the delay period [10]. Longer ignition delay is the reason for higher peak pressures for DTPO90 blends.

4.3.3 Rate of heat release

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. DF shows lowest heat release rate at initial stage and longer combustion duration at full load. The rate of maximum rate of heat release for DTPO90 is the highest compared to DF and DTPO80, 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 $57.4 \text{ J}^\circ\text{CA}$ for DF. It can also be noticed that the maximum heat release is $61.4 \text{ J}^\circ\text{CA}$ for DTPO80 and $62.8 \text{ J}^\circ\text{CA}$ for DTPO90 respectively.

4.3.4 Rate of pressure rise

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 is higher for DTPO-DF operation compared to that of DF operation. This may be due to the longer ignition delay of DTPO which results in rapid pressure raise in the premixed combustion phase.

Conclusion

- Engine is able to run upto 90% DTPO and 10% DF (DTPO90). Engine failed to run satisfactorily with 100 % DTPO.
- Brake thermal efficiency increases with increase in percentage of DTPO blends but lesser than DF. About 3 % drop in the thermal efficiency is noticed.
- NO_x is lower by about 21 % for DTPO80 and 18 % lower in DTPO90 operation than that of DF operation.
- HC and CO are higher than DF. This may be due to the presence of unsaturated hydrocarbon in the DTPO.
- Smoke is higher for DTPO-DF blends compared to DF.
- Longer ignition delay is noticed for DTPO-DF blends compared to DF. It is $2\text{-}2.5^\circ \text{CA}$ longer for DTPO-DF blends compared to DF at full load.
- Cylinder peak pressures are higher by about 1.6 bar and 2 bar for DTPO80 and DTPO90 respectively than that of DF operation.
- Higher rate of heat release in the initial stages and rate of pressure rise are observed in the DTPO-DF blends compared to DF. This is attributed to longer ignition delay of DTPO-DF blends.

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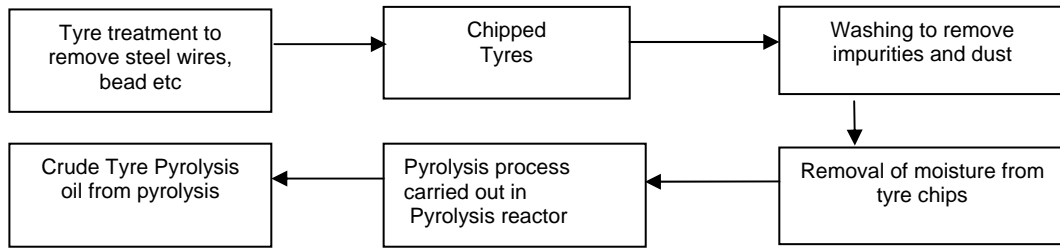


Figure 1 Pyrolysis process of waste automobile tyres

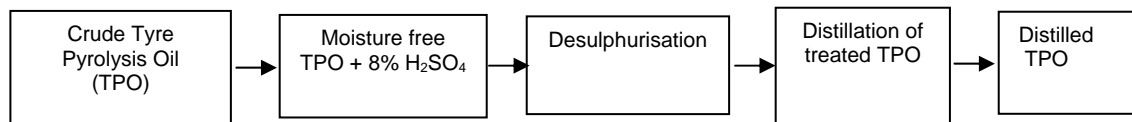
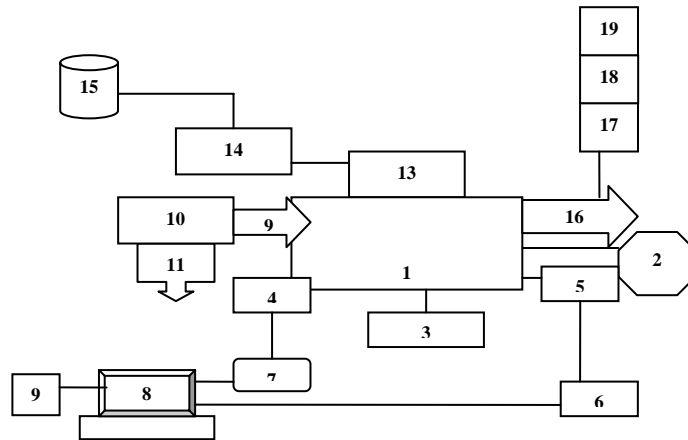


Figure 2 Distillation of Tyre Pyrolysis Oil



- | | |
|------------------------|------------------------------|
| 1. Engine | 11. Surge Tank |
| 2. Dynamometer | 12. Air Flow Meter |
| 3. Control Panel | 13. Fuel Injector |
| 4. Pressure Pickup | 14. Fuel Injection Pump |
| 5. TDC Encoder Machine | 15. Fuel Tank |
| 6. Amplifier | 16. Exhaust Manifold |
| 7. Charge Amplifier | 17. CO/HC Analyser |
| 8. C.R.O | 18. NO _x Analyser |
| 9. Printer | 19. Bosch Smoke Pump |
| 10. Inlet Manifold | |

Figure 3 Experimental Setup

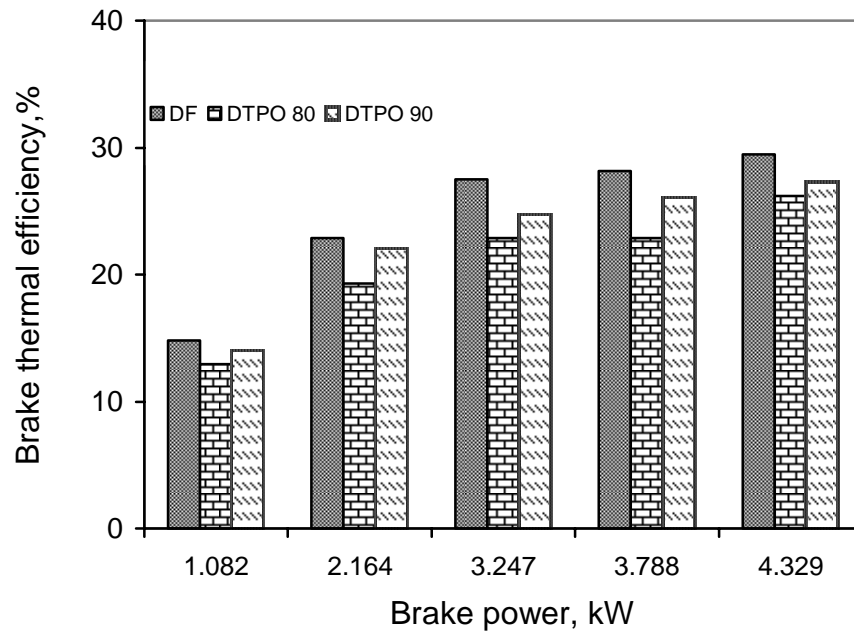


Figure 4 Variation of brake thermal efficiency with brake power

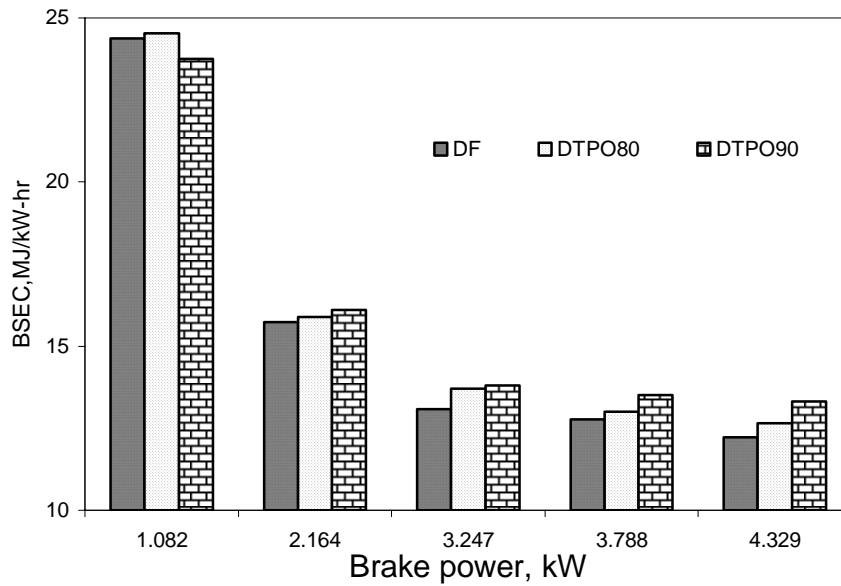


Figure 5 Variation of BSEC with brake power

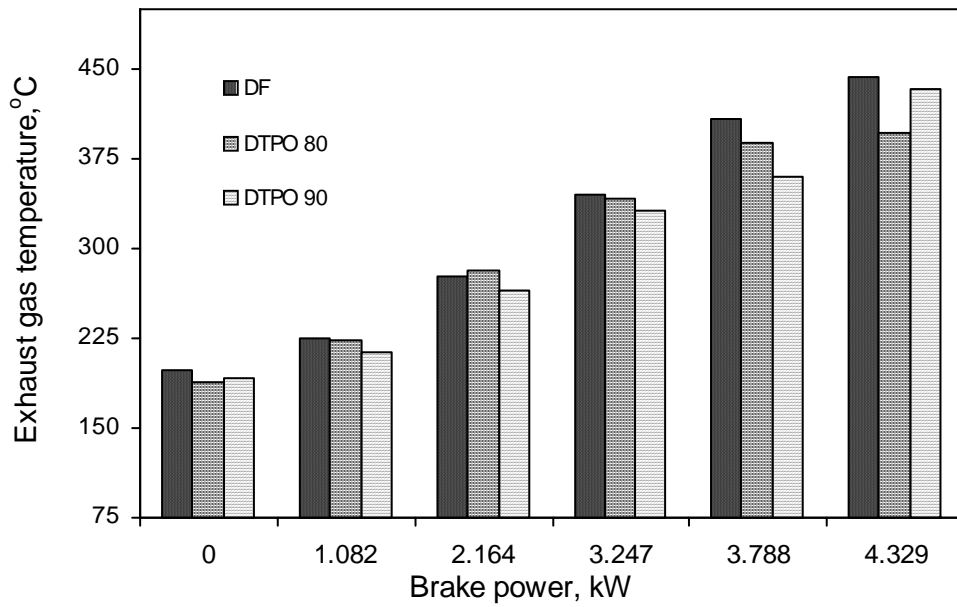


Figure 6 Variation of exhaust gas temperature with brake power

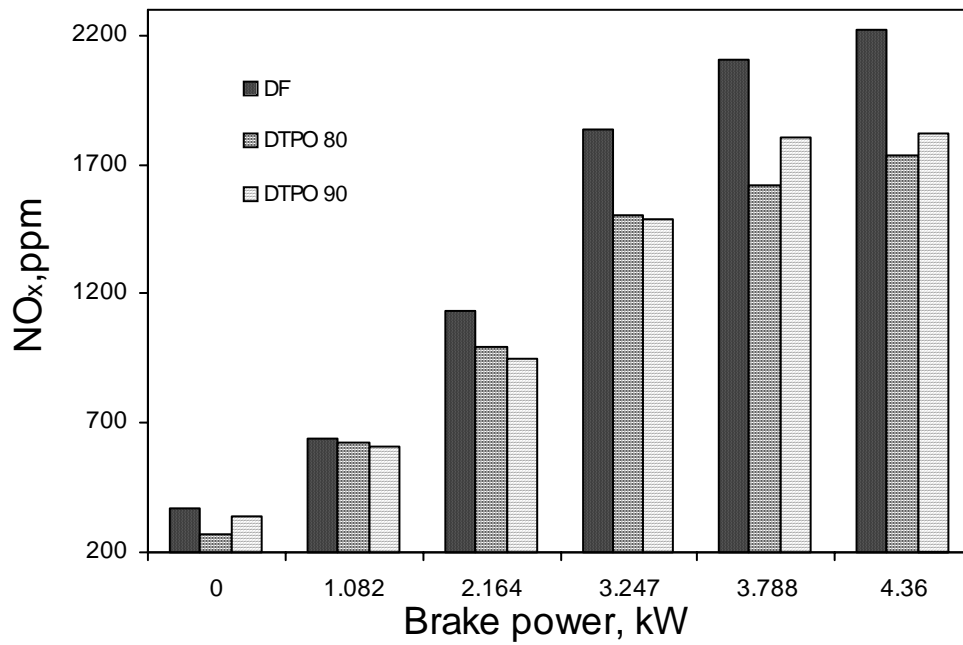


Figure 7 Variation of NO_x with brake power

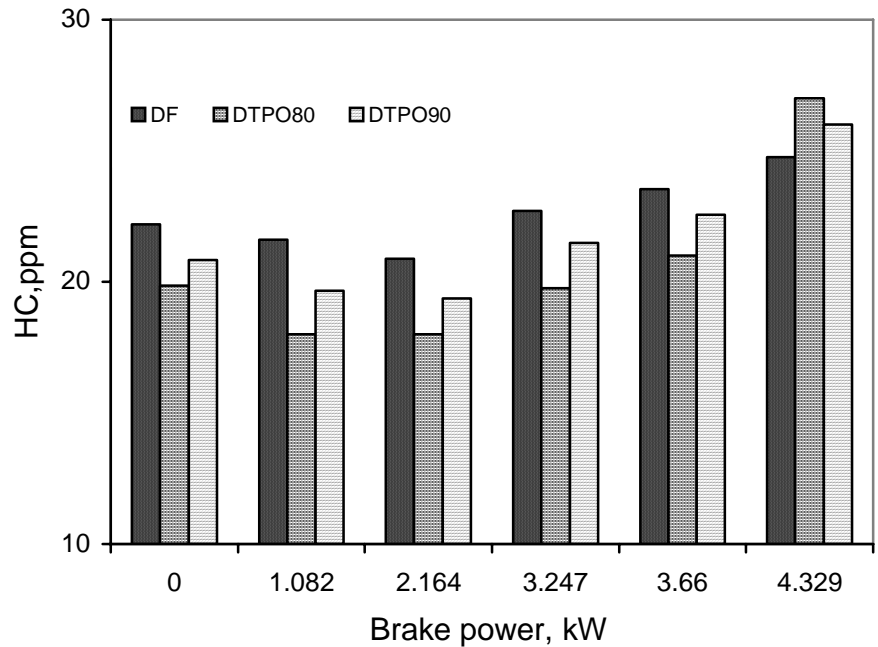


Figure 8 Variation of Hydrocarbon emission with brake power

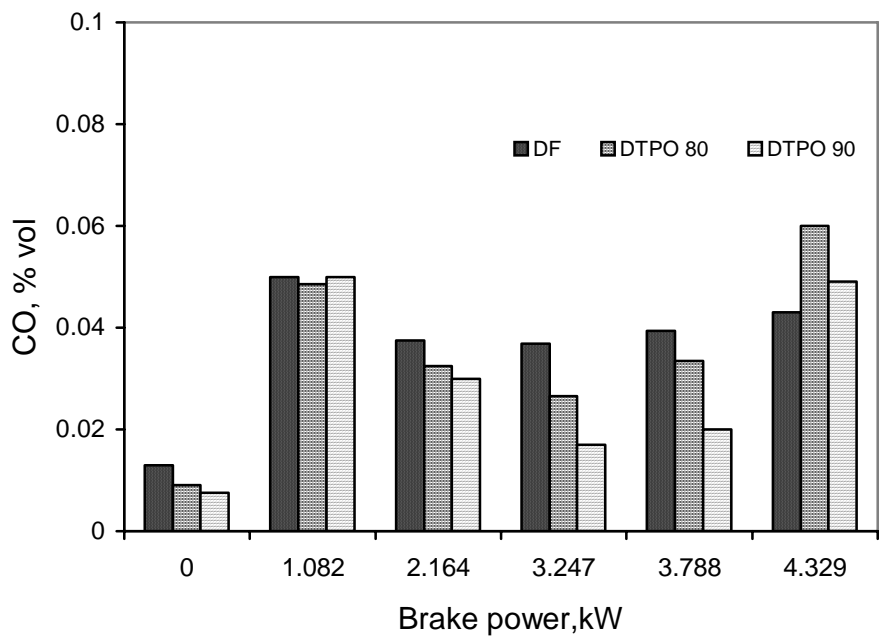


Figure 9 Variation of CO emission with brake power

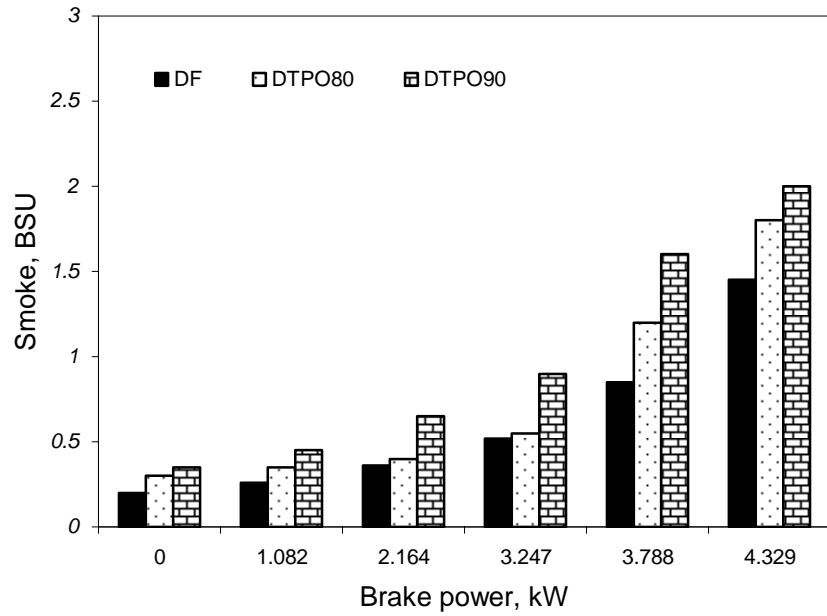


Figure 10 Variation of Smoke with brake power

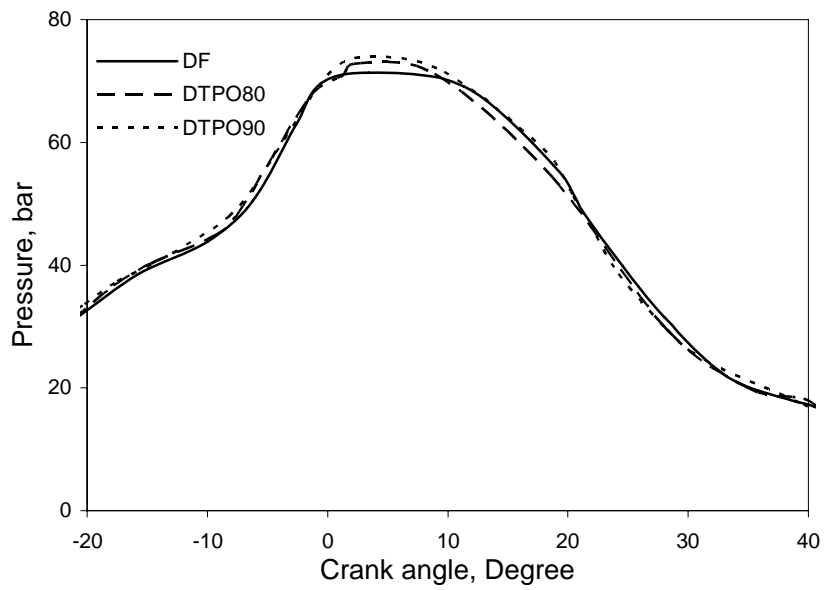


Figure 11 Variation of pressure with crank angle

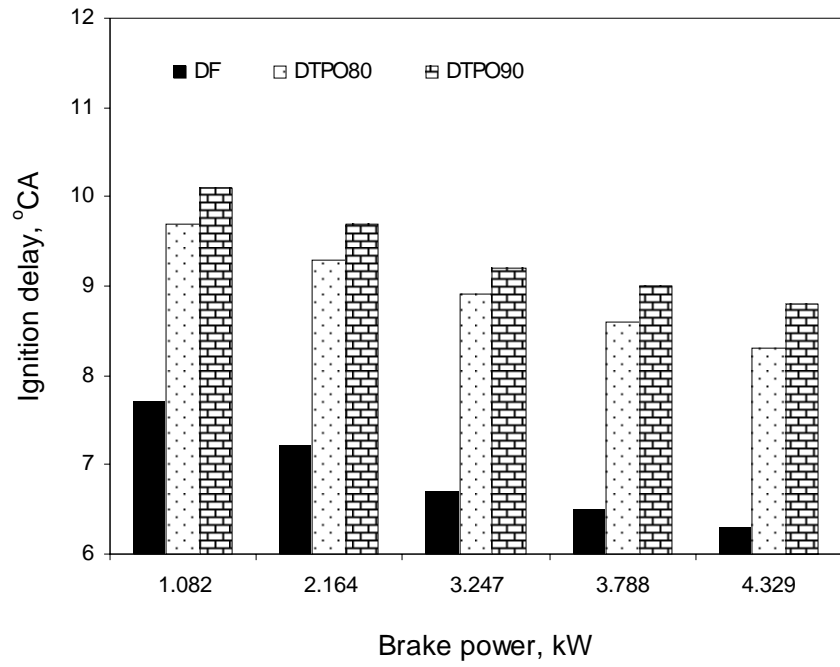


Figure 12 Variation of ignition delay with brake power

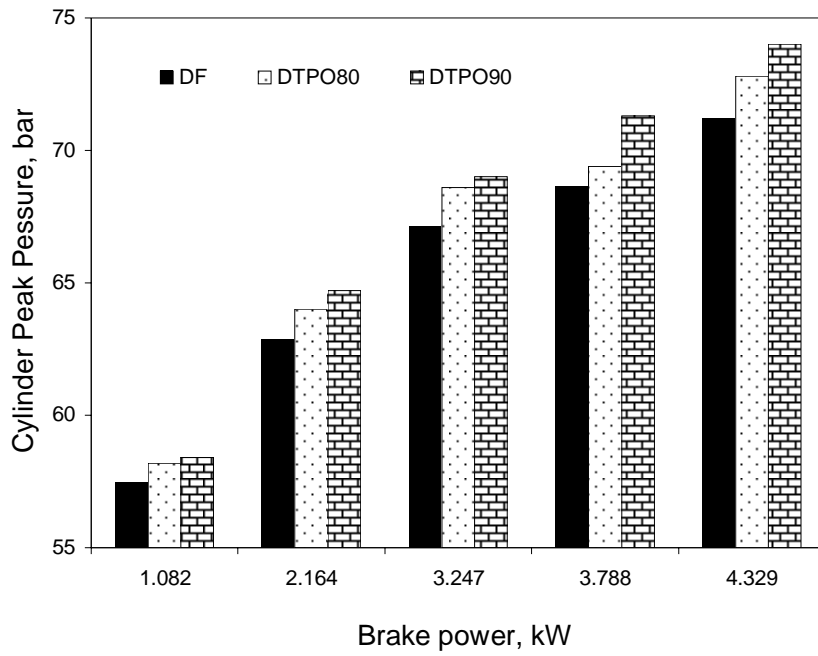


Figure 13 Variation of cylinder peak pressure with brake power

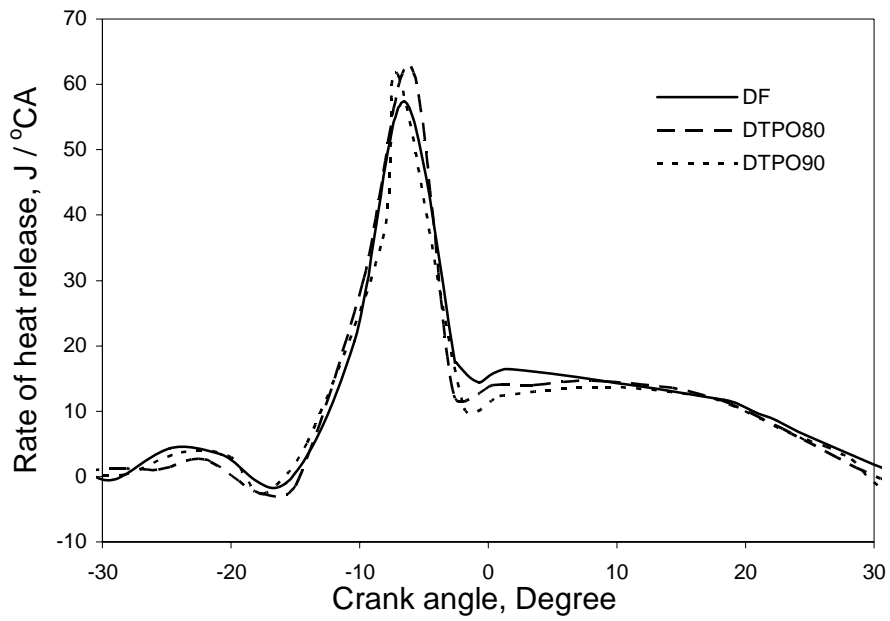


Figure 14 Variation of heat release rate with crank angle

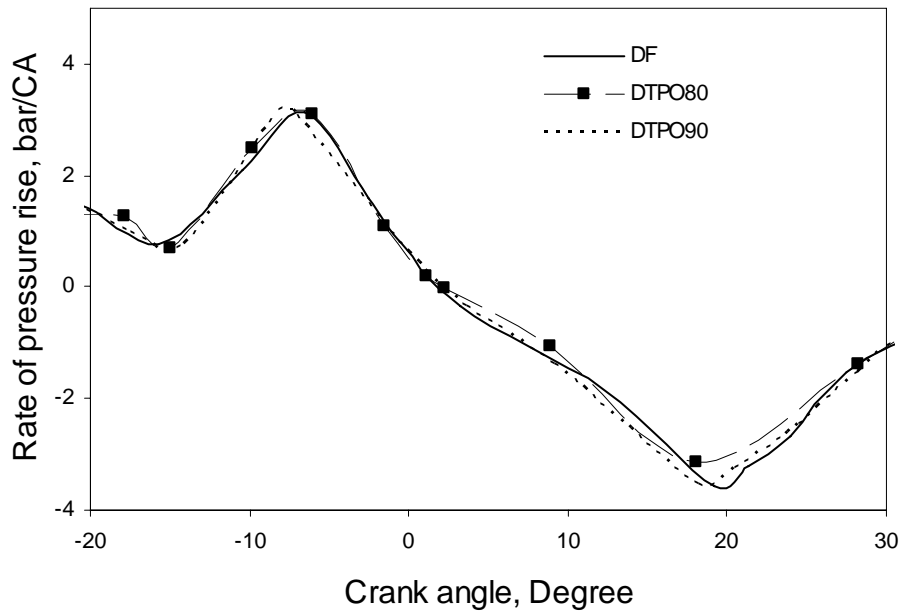


Figure 15 Variation of rate of pressure rise with crank angle

Table 1 Comparison of DTPO and its blends with Diesel

Property	Diesel	Crude TPO	DTPO	DTPO80	DTPO90	
Density @ 15 ⁰ C kg/m ³	830	935	871	860	865	
Kinematic Viscosity, cst @ 40 ⁰ C	2	3.2	1.7	1.76	1.73	
Gross Calorific Value MJ / kg	46.5	42.83	45.78	45.9	45.8	
Flash Point, ⁰ C	50	43	36	39	37	
Fire Point, ⁰ C	56	50	48	49	48	
Sulphur Content, %	0.045	0.95	0.26	0.21	0.23	
Ash Content, %	0.01	0.31	---	--	--	
Carbon Residue, %	0.35	2.14	0.02	--	--	
Aromatic content, %	26	64	--	--	--	
Distillation temperature, ⁰ C	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