Thammasat Int. J. Sc. Tech., Vol. 13, No. 1, January-March 2008

Running a Diesel Engine with Tyre Pyrolysis Oil Diesel Blends at Different Injection Pressures

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Abstract

Tyre Pyrolysis Oil (TPO) is produced from automobile waste tyres by vaccum pyrolysis method [1, 2]. The TPO has high energy content and has been already evaluated as a possible substitute for diesel fuel (DF). The TPO could be blended with DF and used as an alternate fuel for compression ignition engines. Early investigations reveal that the optimum blend was 30 percent TPO with DF in a diesel engine considering the availability, brake thermal efficiency and pollutant emissions. In this study, the effects on the performance and emission of a single cylinder four stroke air cooled diesel engine running on TPO-DF at 30 percent blend (TPO30) at different fuel injection pressures (210,220,230 and 250 bar) were investigated. Experimental results indicated that TPO30 with fuel injection pressure of 220 bar gave a better performance among all the injection pressures of TPO30 and DF. The performance, emission and combustion characteristics are reported in this paper.

Keywords: Tyre Pyrolysis Oil-Diesel Fuel (TPO-DF), 30% Tyre Pyrolysis Oil-70% DF blend (TPO30), Diesel engine, Injection pressure, Performance, Emission, Combustion analysis

1. Introduction

The increase in price of crude oil, government regulations on exhaust emissions and depletion of petroleum reserves stimulate the search for alternative fuels. The potential for finding other sources of energy from waste has also been encouraged. Already, investigations were carried out on the feasibility of using Flash Wood Pyrolysis Oil (WPO) in diesel engines [3]. It was reported that the Flash Wood Pyrolysis Oil is not suitable for fueling diesel engines, as a neat fuel. Flash Wood Pyrolysis Oil produces poor spray characteristics and does not self ignite, resulting in fuel modification. Attempts have been made to run a light duty diesel engines using blends of Wood Pyrolysis Oil (WPO) with different percentage of oxygenated compounds. In their work, reliable operations were recorded with WPO-diglyme blends with WPO content up to 44.1 percent in weight. No major trouble was observed on the critical components of the engine [4]. Attempts were also made on the use of Rubber Pyrolysis Oil [5]. All the above Pyrolysis oils have kinematic viscosity higher than DF. In reference [6], Experimental work was carried out in a one ton batch pyrolysis unit to produce oil, char and gas from waste automobile tyres through pyolysis process. 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, SO_2, particulate and total unburned hydrocarbons were determined in relation to excess oxygen levels. Throughout the combustion tests, comparison of the emissions was made with the combustion of DF. The oil was found to contain 1.4 % sulphur and 0.45 % nitrogen on a mass basis and have similar fuel properties to those of DF.

I. de Marco Rotriguez et al studied the behavior and chemical analysis of Tyre pyrolysis oil [7]. In their work it is reported that Tyre Oils are a complex mixture of organic compounds of 5-20 carbons and with a higher proportion of aromatics. The percentage of aromatics, aliphatics, nitrogenated, benzothiazol was 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 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 an 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 pyrolysis oil has a boiling point under 370 °C, which is the upper limit specified for the 95 % distilled product of diesel fuel. 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 products than commercial diesel fuel.

2. Present Work

2.1 Pyrolysis of waste automobile tyres

Pyrolysis is the process of thermally degrading a substance into smaller, less complex molecules. Pyrolysis produces three principal products: pyrolytic oil, gas and char [8,9]. The quality and quantity of these products depend upon the reactor temperature and design. 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 were washed and dried. They were fed into an extremely heated mild steel reactor unit 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.

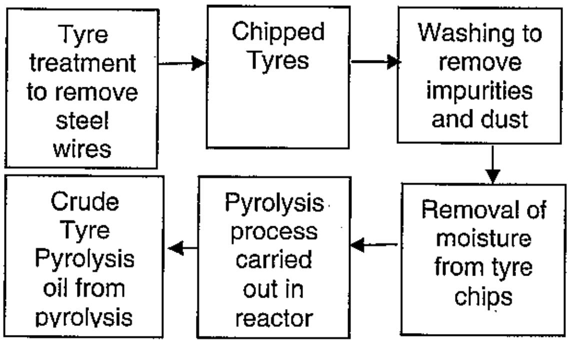


Figure 1. **Pyrolysis process of waste automobile tyres**

The process was carried out between 450 °C and 650 °C .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.

The non condensable gases were let out to the atmosphere. The TPO collected was crude in nature. About 2.09 kg of waste tyres feed stock was required per kg of TPO collected in this process. The products obtained in the process depend on the pyrolysis reactor temperature. The elemental composition of TPO is given in Table 1. Since the oil collected for this study was untreated, the TPO might contain low and high volatile fractions.

The properties of TPO were compared with conventional automotive petroleum fuels and is given in Table 2. From the table it is observed that the properties of TPO are comparable with that of diesel fuel. The viscosity of TPO is higher and 1.5 times greater than diesel fuel. The flash point and fire point of the TPO are closer to diesel fuel. In fact, the properties of TPO lie between the properties of diesel and gasoline. The sulphur and carbon content are also higher for TPO than DF [8]. The comparison of fuel properties of TPO with diesel and gasoline are given in Table 1.

Table 1. Elemental Composition of TPO

Elemental Composition (wt %)		Aproximate analysis (Dry air wt %)	
Carbon	: 84.17	Volatile matter	: 67.06
Hydrogen	: 13.12	Fixed carbon	: 28.13
Oxygen	: 2.46	Moisture content	: Nil
Nitrogen	: 0.22	Ash content	: 4.81
Sulphur	: 0.03	--	
Total	: 100.00	Total	: 100.00

Highly viscous fuel can be used in diesel engines in two ways.

a) Engine modification

i) Dual fueling (ii) Change of injection pressure (iii) Heated fuel lines

b) Fuel modification

i) Blending (ii) Transesterification (iii) Thermal cracking (iv) Hydrogenation to reduce polymerization

Table 2. Comparison of TPO with Petroleum fuels

Property	Diesel	Gasoline	TPO
Density@15 ^{0}C ,g/m^3	0.8226	0.74	0.92
KinematicViscosity, @ 40 ^{0}C cSt	2.58	-	3.77
Lower Calorific Value, MJ/kg	43.8	46	38
Flash point,°C	50	40	43
Fire point,°C	56	45	50
Sulfur content,%	0.29	-	0.72

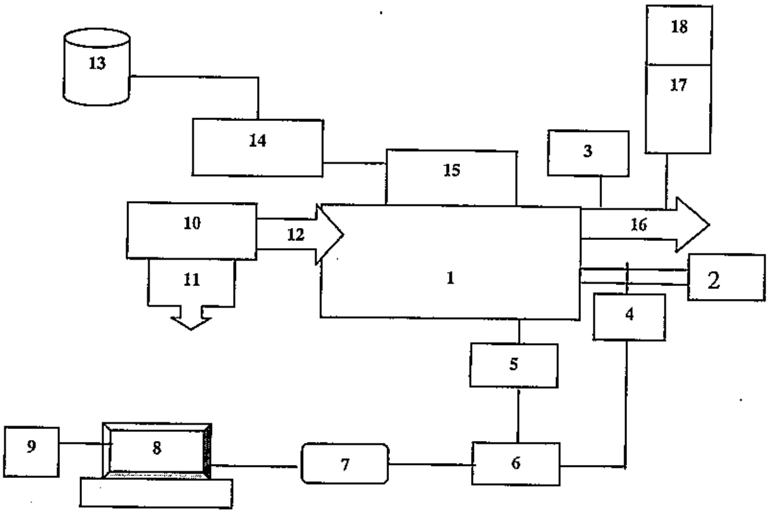
Table 3. Engine details

Name of the Engine	Kirloskar
General Details	Single cylinder, Four stroke, air cooled, CI Engine
Bore (mm)	87.5
Stroke (mm)	110
Compression ratio	17.5:1
Rated output @ 1500 rpm (kW)	4.4
Fuel Injection Pressure (bar)	210
Fuel injector	Nozzle Type: Multi hole No. of holes: 3 Nozzle opening pressure: 207 – 215 bar Needle lift (mm): 0.25 Spray–hole diameter (mm): 0.25 Cone angle: 110°
Injection timing (°CA)	23 BTDC

3. Engine and Test details

The schematic layout of the experimental set up is shown in Figure 2. The specifications of the DI engine are shown in Table 3. An electrical dynamometer was used to provide the engine load. An air box was fitted to the engine for airflow measurements. The fuel flow rate was measured on a volumetric basis using a burette and a stopwatch. A 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. 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. The specifications of the exhaust gas analyser and the smoke meter are shown in Table 4. Experiments were performed with two different fuels (DF, TPO30) from no load to full load. The mixture for TPO30 was prepared just before the experiments. Tests were carried out at the original injection pressure of 210 bar and then changed to 220 bar, 230 bar and 250 bar. Initially experiments were carried out using base diesel fuel (DF). All the experiments were conducted at a rated engine speed of 1500 rpm.



1. Engine
2. Dynamometer
3. Exhaust gas indicator
4. TDC Encoder
5. Pressure pickup
6. Pressure transducer
7. Charge Amplifier
8. C.R.O
9. Printer
10. Air Tank
11. Airflow meter
12. Inlet manifold
13. Fuel tank
14. Fuel pump
15. Fuel Injector
16. Exhaust Manifold
17. Gas analyzer
18. Smoke meter

Figure 2. Experimental setup

Table 4. Details of exhaust gas analyser

Exhaust gas analyser		**Model QRO 402, Make: QROTECH CO**	
Measuring item	**Measuring method**	**Measuring range**	**Resolution**
CO (%)	NDIR	0.00 - 9.99	0.01
HC (ppm)	NDIR	0 -15000	1
CO_2 (%)	NDIR	0.0 - 20.0	0.01
NO_x (ppm)	Electro chemical	0 - 5000	1

4. Results and Discussion

4.1 Performance

4.1.1 Brake thermal efficiency

Figure 3 shows the variation of brake thermal efficiency with brake power for DF and TPO30 operation at different fuel injection pressures. The results showed that the brake thermal efficiency increased when the fuel injection pressure increased from 210 bar to 220 bar for TPO30 as fuel. The brake thermal efficiency varied from 14.79 % at low load to 29.45 % at full load DF. The efficiency varied from 14.77 % at low load to 28.93 % at full load for TPO30 at 210 bar. It may be observed that the brake thermal efficiency is increased from 16.22 % at low load to 29.29 % at full load when the fuel injection pressure is increased to 220 bar. This may be attributed to the effective combustion taking place due to the finer spray formed in the combustion chamber. However, further increase in the fuel injection pressure beyond 230 bar results in a drop in brake thermal efficiency and this is noticed with the fuel injection pressure of 230 bar and 250 bar at full load. At higher injection pressures, the fuel droplets become finer and hence the fuel air mixture becomes too lean to auto ignite, which leads to ineffective combustion. The brake thermal efficiency decreased about 1.3 % at full load for the injection pressure of 230 bar, whereas the thermal efficiency decreased by about 1.6 % for TPO50 compared to the standard fuel injection pressure of 210 bar for TPO30 operation. All the thermal efficiencies for TPO30 at different fuel injection pressures were lower than DF operation.

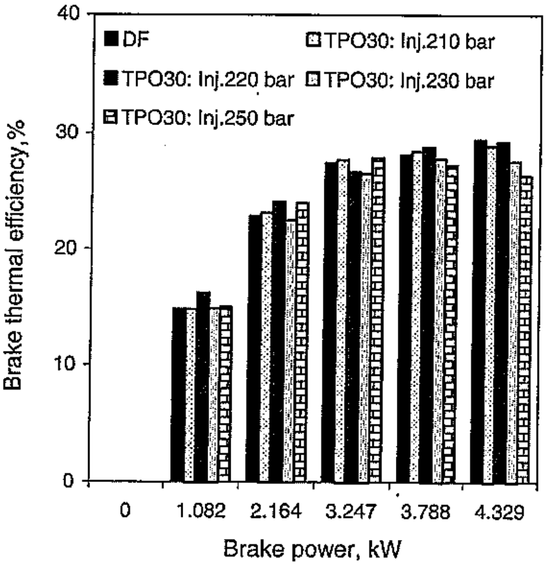


Figure 3. Variation of brake thermal efficiency with brake power

4.1.2 Brake specific energy consumption (BSEC)

Figure 4 shows the variation of BSEC with brake power for DF and TPO30 operation. Brake specific energy consumption is a more reliable parameter than brake specific fuel consumption when two different fuels are blended, since the calorific value and density of the two fuels are different. BSEC is calculated as the product of brake specific fuel consumption and calorific value of the blended fuel. It is observed that the brake specific energy consumption for the fuel injection pressure of 250 bar is the highest at full load. At 210 bar, the TPO30 blend generates coarse spray due to the increase in the viscosity of the blend. This leads to a decrease in the area of the spray formed, and results in improper combustion. As the injection pressure increased to 220 bar for TPO30 operation, the BSEC decreased. The probable reason is that the spray is able to cover more area in the combustion chamber and utilise the air effectively. When the injection pressure is beyond 220 bar, the spray may have more area but its depth of penetration decreases due to reduced momentum. This results in improper utilization of air in the combustion chamber [9]. On average the fuel injection pressure of 220 bar gave optimum brake energy consumption.

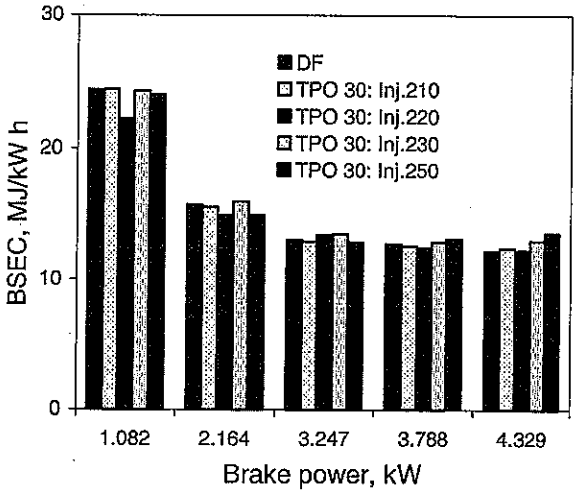


Figure 4. Variation of BSEC with brake power

4.1.3 Exhaust gas temperature

Figure 5 shows the variation of exhaust gas temperature with the brake power for DF and TPO30 operation. The exhaust gas temperature is lowest for the fuel injection pressure of 250 bar. The exhaust gas temperature is a function of engine loading for a particular fuel. As the load increases, the temperature also increases. The exhaust gas temperature for DF increased from 189.6 °C at no load to 424 °C at full load whereas for TPO30 it varied from 202.5 °C to

435 °C at an injection pressure of 210 bar. As the fuel injection pressure is increased to 220 bar for TPO30, the exhaust gas temperature increased from 222.5 °C at no load to 485 °C at full load. It may also be noticed from the figure that at the injection pressures of 230 bar and 250 bar, exhaust gas temperatures are lower than DF operation and TPO30 at 210 bar. The exhaust gas temperature increased from 180 °C at no load to 459 °C at full load for the fuel injection pressure of 230 bar, and for the fuel injection pressure of 250 bar for TPO30 operation, it increased from 184 °C at no load to 430 °C at full load.

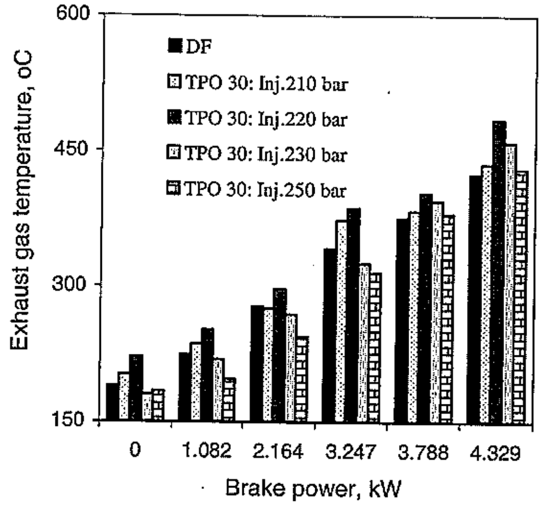


Figure 5. Variation of Exhaust gas temperatures with brake power

4.2 Emission study

4.2.1 Oxides of Nitrogen

The major pollutants from the exhaust of a diesel engine are oxides of Nitrogen and smoke. Figure 6 shows the variation of oxides of nitrogen (NO_x) for DF and TPO30 operation. NO_x increases with the increase in injection pressure for TPO30 from 210 bar 220 bar. The NO_x value for DF varied from 373.6 ppm at no load to 2221 ppm at full load, whereas it varied from 369.6 ppm to 2321 ppm for TPO30 at 210 bar. This may be attributed to better combustion that results in higher exhaust gas temperature and in turn higher NO_x formed. NO_x value increased from 372 ppm at no load to 2330 ppm at full load when the fuel injection pressure increased to 220 bar.

However, increasing the injection pressure to a value higher than 220 bar reduced the NO_x. This is reflected for the fuel injection pressure of 230 bar and 250 bar. The value varied from 326.5 ppm at no load to 1983 ppm full load for 230 bar. It also varied from 296.6 ppm at no load to 2257 ppm at full load for TPO30.

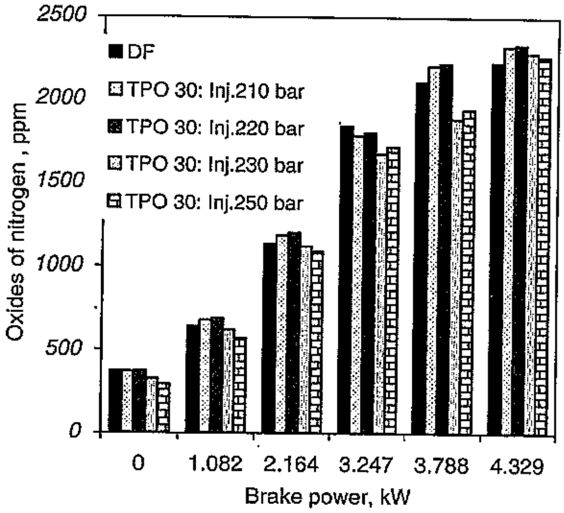


Figure 6. Variation of NO_x with brake power

4.2.2 Hydrocarbon emission

Figure 7 shows the variation of hydrocarbon emission (HC) with brake power for DF and TPO30 operation. The highest HC emission is at 250 bar for non-zero brake power (includes DF). Hydrocarbon emission for the fuel injection pressure of 220 bar is lower than 210 bar, 230 bar and 250 bar for TPO30. This may be attributed to more effective mixture preparation within the combustible limit. At the fuel injection pressure of 230 bar, the fuel air mixture becomes leaner than fuel air mixture at the fuel injection pressure of 220 bar which caused more HC. At the fuel injection pressure of 250 bar, the fuel air mixture becomes too lean during the combustion period and probably some of the fuel remains in the injector nozzle sac volume and escapes the combustion, which produces higher HC. TPO30 at the fuel injection pressure of 210 bar, produced HC varying from 19 ppm at no load to 28.5 ppm at full load. As the injection pressure increased for TPO30 to 220 bar, HC slightly decreased from 18.5 ppm at no load to 27 ppm at full load. For the fuel injection pressure of 230 bar, HC varied between 19.5 ppm at no load and 29 ppm at full load and for 250 bar it varied from 19 ppm at no load to 29.6 at full load.

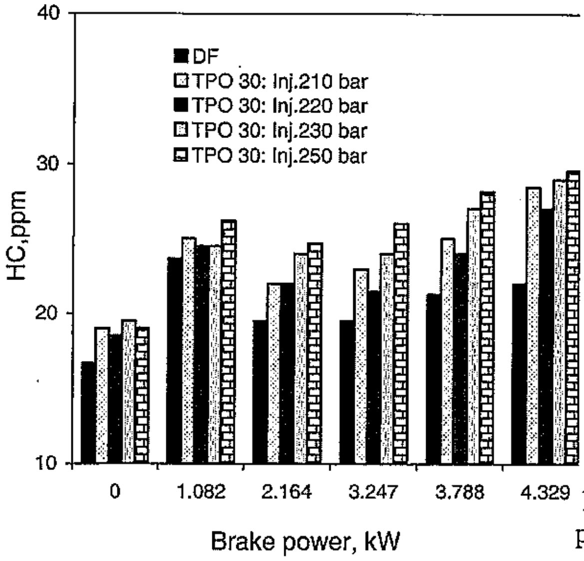


Figure 7. Variation of HC with brake power

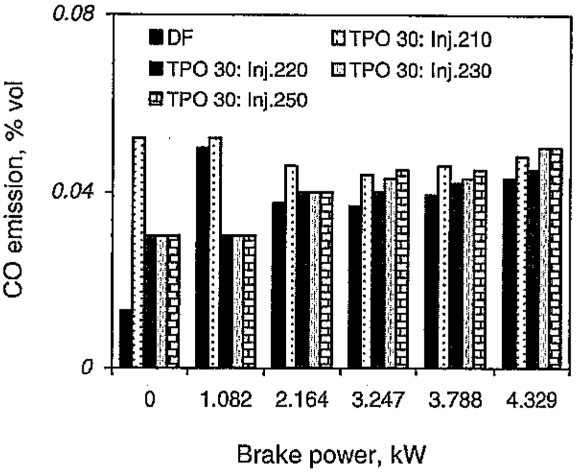


Figure 8. Variation of CO emission with brake power

4.2.3 Carbon monoxide emission

Figure 8 shows the variation of Carbon monoxide (CO) emission with brake power for DF and TPO30 operation. CO value ranged between 0.0013 % at no load to 0.016 % at full load for DF. It may be observed from the figure that CO emission for TPO30 at a fuel injection pressure of 210 bar is slightly higher than the fuel injection pressure of 220 bar, and the value lies between 0.052 % at no load to 0.048 % at full load. Further increase in the fuel injection pressure to 220 bar reduces the CO emission. There was no change in CO emission at the fuel injection pressure of 230 bar. The CO is higher for the injection pressure of 250 bar than DF and other injection pressures of TPO30 operation. The reason may be that, the fuel droplets may be too fine and incompletely mixed with air, which causes poor incomplete combustion.

4.2.4 Smoke emission

Figure 9 shows the variation of smoke density with brake power for DF and TPO30 operation. The smoke density for the injection pressure of 250 bar is the highest among all the injection pressure and also the base line data. The smoke density for DF varied between 0 BSU at no load to 1.45 BSU. The smoke value for TPO30 at the fuel injection pressure of 210 bar varied between 0.183 BSU at no load to 1.35 BSU at full load. Smoke reduced slightly between 0.1 BSU at no load to 1 BSU at full load for the fuel injection pressure of 220 bar. However, smoke values increased for the fuel injection pressure of 230 bar from 0.18 at no load BSU to 1.9 BSU at full load. This may be due to poor mixing of the fuel air mixture. In the case of 250 bar smoke varied from 0.6 BSU at no load to 2.5 BSU at full load.

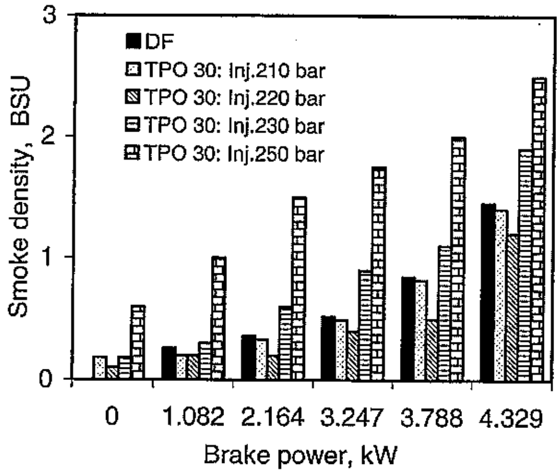


Figure 9. Variation of Smokewith brake power

4.3 Combustion Parameters

4.3.1 Pressure Crank angle diagram

Figure 10 shows the variation of cylinder pressure with crank angle for TPO 30 at different injection pressures and DF at full load. Cylinder pressure data obtained at full load indicated higher values for TPO30 at injection pressures 210, 220 and 230 bar compared to DF. It can be noticed that the combustion of TPO-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 TPO-DF blends results in a rise in the cylinder peak pressure. It is observed from the figure that the peak pressure is increased by about 1.8 bar. A maximum cylinder pressure of 73.3 bar is attained for the injection pressure of 220 bar. It is noticed that the cylinder pressure is lowest for the injection pressure of 250 bar. The peak pressures for the fuel injection pressures of 210, 220, 230, 250 bar and DF are 73, 73.3, 72.3 and 68.7 bar.

The ignition delay is measured as the difference between the start of ignition and the start of the injection [10]. During the ignition delay, the temperature, pressure and heat release decrease as a result of fuel evaporation and the start of cold temperature reactions in the air fuel mixture. The ignition delay is shortened as the injection pressure is increased. The ignition delay is reduced by 0.2° CA to 0.5° CA when the fuel injection pressure is increased from 230 bar to 250 bar. As the ignition delay is shortened, the accumulation of fuel in the premixed phase is more, and better combustion takes place due to better atomisation.

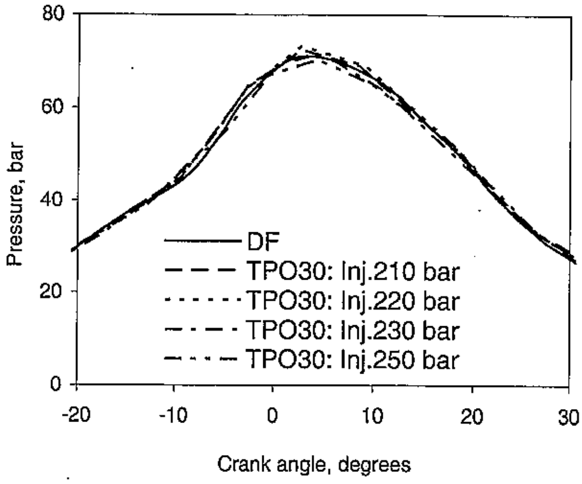


Figure 10. Pressure crank angle diagram

4.3.2 Cylinder peak pressure

Figure 11 shows the cylinder peak pressure with brake power for DF and TPO30 operation. It may be noticed from the figure that the cylinder pressure increased as the injection pressure is increased at 220 bar. The cylinder peak pressure for DF increased from 57.5 bar at no load to 71.2 at full load. It can also be noticed that cylinder peak pressure at fuel injection pressure of 210 bar increased from 58.7 bar at no load to 72.6 bar at full load. At fuel injection pressure of 220 bar for TPO30 operation, the peak pressure varied from 61.2 bar at no load to 73 bar at full load whereas for the fuel injection pressure of 230 bar it varied from 62.4 bar at no load to 72.3 bar at full load. For 250 bar, the peak pressure varied from 54.5 bar at no load to 68.7 bat at full load. 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]. Higher viscosity and lower volatility of the TPO30 blend may be the reason for this trend.

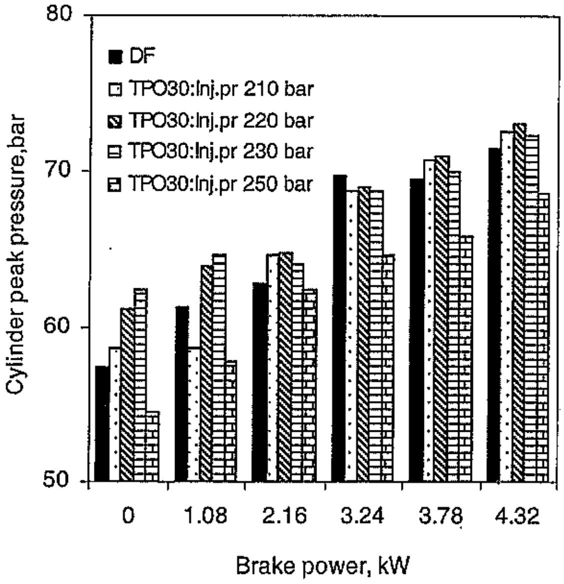


Figure 11. Variation of Cylinder peak pressure with brake power

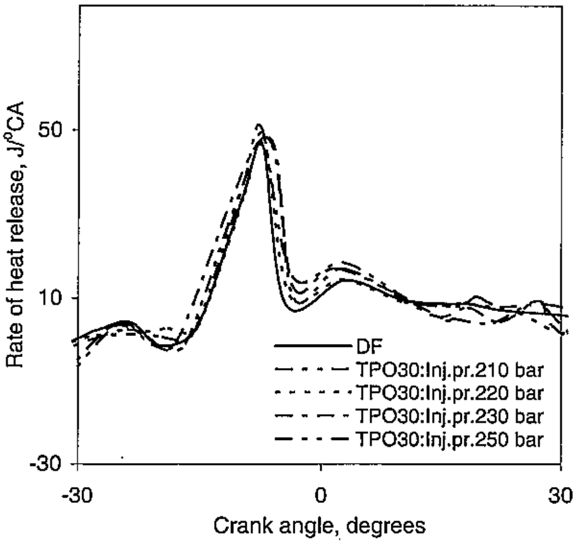


Figure 12. Variation of Heat Release Rate with crank angle

4.3.3 Rate of heat release

Figure 12 shows the heat release for DF and TPO30 at various injection pressures. It can be observed that the heat release takes place in two stages. The first stage is from the start of ignition to the point where the heat release rate drops. This stage occurs due to the ignition of fuel air mixture prepared during the delay period. The second stage starts from the end of the first stage to the end of combustion [10]. Fuels with longer ignition delay exhibit sudden pressure rise and high heat release at initial stages [9, 10, 11]. The maximum heat release was attained for the fuel injection pressures of 230, 220 bar followed by 250 bar, 210 and DF. The heat release curves for TPO30 operation also rose earlier than DF. High viscosity and longer ignition delay is the reason for this trend.

5. Conclusions

The TPO 30-DF blend at three injection pressures of 210 bar, 230 bar and 250 bar and DF were tested in a direct injection diesel engine. The performance, emission and the combustion characteristics of the engine at full load for the fuel conditions were investigated. The following results were obtained.

1. The engine was able to run up to the fuel injection pressure of 250 bar.
2. The brake thermal efficiency increased marginally for the fuel injection pressure of 220 bar. It reduced on average 1.5 percent from the efficiency of TPO30 injected at 210 bar to the fuel injection pressure of 250 bar.
3. Exhaust gas temperature increased for the fuel injection pressure of 220 bar for TPO30 operation. Further increasing the fuel injection pressure resulted in decreasing the exhaust gas temperature at full load.
4. NO_x increased up to the fuel injection pressure of 220 bar for TPO30 operation, compared to that of DF and beyond 220 bar, NO_x decreased compared to 210 bar, 220 bar and DF operation.
5. HC increased by 22 % and CO increased by 5 % compared to DF values at the fuel injection pressure of 220 bar for TPO30 operation at full load.. Smoke increased considerably, as the fuel injection pressure increased beyond 220 bar fuel injection pressure.
6. Heat release and maximum rate of pressure rise were higher for higher fuel injection pressures.
7. Ignition delay was longer for TPO30 operation compared to that of DF operation.

6. Acknowledgements

The Authors sincerely thank the Ministry of Environment and Forests, New Delhi for their financial grant (Project F.No.19-01/2005-RE /Dt.02.09.2005) to carryout this research work. The authors also thank the Management of Rajalakshmi Engineering College, Chennai and Anna University for providing the necessary infrastructure to conduct the study.

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