

## INFLUENCE OF DISTILLATION ON PERFORMANCE, EMISSION, AND COMBUSTION OF A DI DIESEL ENGINE, USING TYRE PYROLYSIS OIL DIESEL BLENDS

by

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*Conversion of waste to energy is one of the recent trends in minimising not only the waste disposal but also could be used as an alternate fuel for internal combustion engines. Fuels like wood pyrolysis oil, rubber pyrolysis oil are also derived through waste to energy conversion method. Early investigations report that tyre pyrolysis oil derived from vacuum pyrolysis method seemed to possess properties similar to diesel fuel. In the present work, the crude tyre pyrolysis oil was desulphurised and distilled to improve the properties and studied the use of it. Experimental studies were conducted on a single cylinder four-stroke air cooled engine fuelled with two different blends, 30% tyre pyrolysis oil and 70% diesel fuel (TPO 30) and 30% distilled tyre pyrolysis oil and 70% diesel fuel (DTPO 30). The results of the performance, emission and combustion characteristics of the engine indicated that  $\text{NO}_x$  is reduced by about 8% compared to tyre pyrolysis oil and by about 10% compared to diesel fuel. Hydrocarbon emission is reduced by about 2% compared to TPO 30 operation. Smoke increased for DTPO 30 compared to TPO 30 and diesel fuel.*

**Key words:** *diesel fuel, tyre pyrolysis oil, hydrocarbon, oxides of nitrogen, carbon monoxide*

### Introduction

Around the world, initiatives are taken at large scales to replace gasoline and diesel fuel due to the impact of fossil fuel crisis, hike in oil price and stringent emission norms. Millions of dollars are being invested in the search for alternative fuels. On the other hand, the disposal of waste tyres from automotive vehicles are becoming more and more complex. Fuels like alcohol, biodiesel, liquid fuel from plastic, *etc.* are some of the potential alternative fuels for the internal combustion engines. In order to prevent waste rubber and in particular discarded automobile tyres from damaging the environment, it is highly desirable to recycle this material in a useful manner. However, the total quantity of tyres currently recycled in a given year (excluding reuse, retreading, or combustion) is less than 7% of the annual tyre generation rate.

Bottrill *at al.* carried out experiments on a one-ton batch pyrolysis unit to produce oil, char, and gas from waste automobile tyres through pyrolysis process. A single oil droplet combustion study was carried out and also the oil was analyzed 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

$\text{NO}_x$ ,  $\text{SO}_2$ , particulate and total unburned hydrocarbons were determined in relation to excess oxygen levels [1, 2]. The oil was found to contain 1.4% sulphur and 0.45% nitrogen on mass basis and have similar fuel properties to those of diesel fuel.

I. de Marco Rodriguez *et al.* studied the behavior and chemical analysis of tyre pyrolysis oil (TPO) [3]. In this work it is reported that tyre oils is a complex mixture of organic compounds of 5-20 carbons with a higher proportion of aromatics. The percentage of aromatics, aliphatics, nitrogenated, benzothiazol was also determined in the TPO at various operating temperatures of the pyrolysis process. Aromatics were found to be about 34.7-75.6% when the operating temperature varied between 300 and 700 °C, while aliphatics were about 19.8-59.2%. In the same work, an automatic distillation test was carried out at 500 °C to analyse the potential use of TPO as petroleum fuels. It was observed that more than 30% of the TPO was easily distillable fraction with boiling points between 70 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 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.

Performance, emission and combustion characteristics of a light duty DI diesel engine run on wood pyrolysis oil (WPO) was reported by [4]. In this, a several long run tests were performed on a single cylinder with blends of WPO with different percentage of oxygenated compound, micro emulsions of WPO in diesel fuel and the results were compared with diesel fuel. It was reported that reliable operation was achieved with 44% of WPO in diethylene glycol dimethyl ether (diglyme). Similar results were obtained with two different emulsions with 30% of WPO in diesel fuel. Residuals were occasionally found to stick on the nozzle stem and sac volume. No trace of corrosion was detected. From the emissions point of view WPO diglyme blends produced lower hydrocarbon (HC) and oxides of nitrogen ( $\text{NO}_x$ ) than diesel fuel with comparable carbon monoxide (CO). It was also reported that no major trouble on the critical components of the engine was noticed.

Studies have been carried out on the feasibility of using WPO as an alternate fuel in internal combustion engines by [5]. It was observed that the plain wood oil did not produce self ignition in conventional engine and also resulted in poor spray characteristics. The major drawbacks of the use of wood oil in diesel engines were excessive carbon deposits, injection system clamping, incompatibility with engine lubricants and high acid aggressiveness. It was suggested that fuel improvement would be necessary if WPO is used as an alternate fuel for diesel engine.

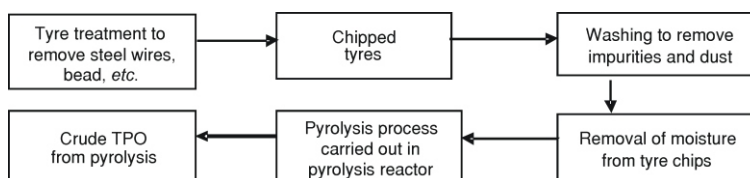
Investigations to assess the physical properties and composition of rubber pyrolysis oil showed that the gross calorific value and other properties were found to be similar to that of diesel oil [6].

## Present work

### 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 were washed, dried and were fed in an externally 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, outer diameter 115 mm, and height 300 mm. For external heating of the reactor a 2 kW power was supplied. The temperature of the reactor was controlled

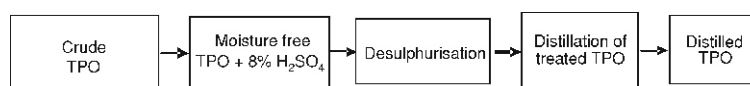
by a temperature controller. The process was carried out between 450 and 650 °C. The products of pyrolysis in the form of vapour were sent to a water cooled condenser and the condensed liquid was collected. The schematic diagram of the pyrolysis process of waste automobile tyres is given in fig. 1.



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

### *Distillation of TPO*

The modification of the crude TPO involves three stages, (1) removal of moisture, (2) desulphurisation, and (3) vacuum distillation. The schematic lay-out of the distillation of TPO is shown in fig. 2.



**Figure 2. Distillation of TPO**

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 and sulphur particles. A known volume of concentrated hydrosulphuric acid (8%) was mixed with the crude TPO and stirred well. The mixture was kept for about 40 hours and after that, the mixture was separated in two layers. The top layer had a thin fluid and the lower one had a thick sludge. The top layer was taken for vacuum distillation and the sludge was removed and disposed off.

### *Vacuum distillation*

Vacuum distillation process was carried out to separate the lighter and heavier fraction of HC 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 cooled condenser and the distilled TPO (DTPO) was collected separately. Non-condensable volatile vapours were left to the atmosphere. The distillation was carried out between 150 and 200 °C. In the distillation 80% of the TPO was distilled whereas 5% of TPO was left out as pyrogas and 15% was found as sludge. The time taken for obtaining 200 ml and 750 ml DTPO were 30 minutes and 100 minutes, respectively.

The DTPO has irritating odour like acid. 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 a heating value of about 7% higher than the crude TPO. This is due to the elimination of impuri-

ties, moisture, carbon particle, sulphur, and sediments. The kinematic viscosity is lower than that of crude TPO and diesel fuel (DF) as shown in tab. 1.

**Table 1. Comparison of DTPO with TPO, diesel, and gasoline**

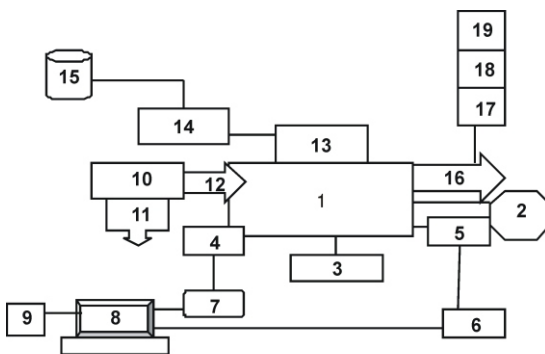
Property	Diesel	Gasoline	Crude TPO	DTPO
Density at 15 °C [kg/m <sup>3</sup> ]	890	740	935	871
Kinematic viscosity at 40 °C [cSt]	2	–	3.2	1.7
Gross calorific value [MJ/kg]	46		42	45
Flash point [°C]	50	40	43	36
Fire point [°C]	56	45	50	48
Sulphur content [%]	0.045	–	0.95	0.26
Ash content [%]	0.01	–	0.31	
Carbon residue [%]	0.35	–	2.14	0.02
Aromatic content [%]	–	–	60-70	–

## Experimental setup and test details

### Experimentation

The schematic lay-out of the experimental setup is shown in fig. 3. The specifications of the engine are shown in tab. 2. An electrical dynamometer was used to load the engine load. An air box was fitted to the engine for airflow measurements. 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 optical encoder with a signal conditioner was used to detect the engine crank angle.



**Figure 3. Experimental setup**

(1) Engine, (2) Dynamometer, (3) Control panel, (4) Pressure pickup, (5) TDC optical sensor, (6) Signal conditioner, (7) Charge amplifier, (8) CRO, (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<sub>x</sub> analyser, (19) Bosch smoke pump

**Table 2. Engine details**

Name of the engine	Kirloskar
General details	Single cylinder, four-stroke, air cooled, DI
Bore [mm]	87.5
Stroke [mm]	110
Compression ratio	17.5:1
Rated output at 1500 rpm [kW]	4.4
Fuel injection pressure [bar]	215
Injection timing [deg CA]	27 bTDC

An gas analyzer was used to measure  $\text{NO}_x$ , HC, and CO emissions in the exhaust. Initially experiments were carried out using base DF. All the experiments were conducted at a rated engine speed of 1500 rpm. After the engine is warmed up running with DF, it was then switched over to TPO 30 blend and subsequently to DTPO 30. At the end of the tests, the engine was run for a little time with DF to flush out the DTPO 30 from the fuel line and the injection system.

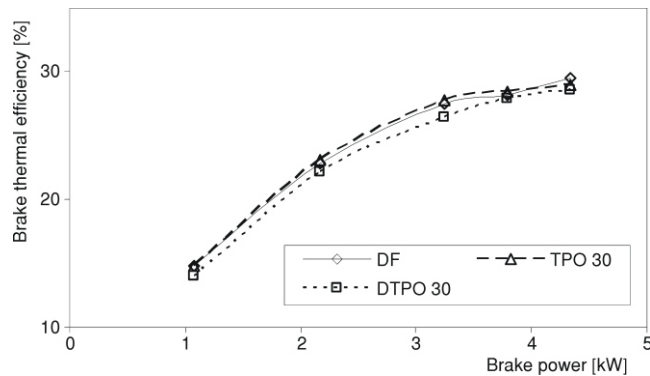
## Results and discussion

### Performance

#### Brake thermal efficiency

The brake thermal efficiency with brake power for TPO 30 and DTPO 30 blends are compared with the DF and is shown in fig. 4. The brake thermal efficiency for DF at full load is 29.5%. It can be observed that the engine fuelled with TPO 30 and DTPO 30 give thermal efficiencies of 29% and 28%, respectively, at full load. The thermal efficiencies of TPO 30 and DTPO 30 are lower compared to that of DF. DTPO 30 shows the lowest efficiency among the tested fuels. It may be observed from tab.

1 that the calorific value of DTPO is higher than TPO, but the viscosity of DTPO is lower than TPO. The higher heat release rate in the premixed combustion by the TPO 30 may be the reason for higher thermal efficiency compared to DTPO 30. Another possible reason may be that, after distillation, the DTPO 30 may contain both low volatile and high volatile fractions, which need to burn completely and require higher self ignition temperatures for ignition. Fractions with low self ignition temperatures may burn with prevailing temperature and fractions with high self ignition temperature do not burn and hence there may be incomplete combustion.



**Figure 4. Variation of brake thermal efficiency with brake power**

### Brake specific energy consumption

Brake specific energy consumption (BSEC) is a more reliable parameter than the 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.

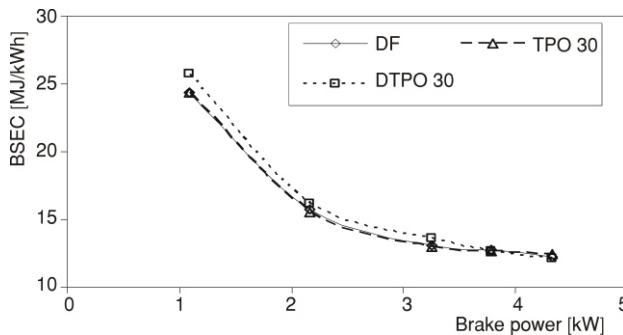


Figure 5. Variation of BSEC with brake power

Figure 5 shows the comparison of BSEC with brake power for the tested fuel.

It may be observed from fig. 5 that the BSEC varies from 24.3 MJ/kWh at low load to 12.2 MJ/kWh at full load, whereas it varies from 24.35 MJ/kWh at low load to 12.45 MJ/kWh at full load for TPO 30 and 25.8 MJ/kWh at low load to 12.5 MJ/kWh at full load for DTPO 30. As the density of DTPO 30 is lesser than TPO 30 and DF, more amount of energy is consumed to produce the same power output.

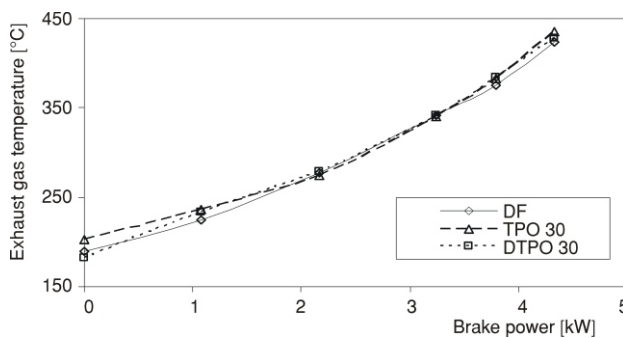


Figure 6. Variation of exhaust gas temperature with brake power

### Exhaust gas temperature

Figure 6 shows the comparison of exhaust gas temperature with brake power. The exhaust gas temperatures are higher for TPO 30 and DTPO 30 compared to that of DF. The exhaust gas temperature for DF varies from 190 °C at no load to 424 °C at full load. For TPO 30, the exhaust gas temperature varies from 202 °C at no load to 435 °C at full load whereas for DTPO 30 it varies from 182 °C at

no load to 428 °C at full load. Higher exhaust gas temperature for TPO 30 can be attributed to higher viscosity and poor mixture formation compared to DF. In the case of DTPO 30, the viscosity is lower than DF. The exhaust gas temperature for DTPO 30 is lesser than TPO 30. This may be attributed to higher latent heat of evaporation of DTPO.

### Emissions study

#### $NO_x$ emission

Figure 7 shows the variation of  $NO_x$  emissions with brake power.  $NO_x$  emissions are higher for TPO 30 compared to DF at full load.  $NO_x$  varies from 16.9 g/kWh at low load to 14.9 g/kWh at full load for DF, whereas it varies from 17.9 g/kWh at low load to 15.66 g/kWh at full load for TPO 30 and for DTPO 30, from 15.4 g/kWh at low load to 11.7 g/kWh at full load.

$\text{NO}_x$  emission is significantly influenced by the in cylinder gas temperature and availability of oxygen during the combustion. Fuels with longer ignition delay exhibit higher in cylinder temperature due to higher heat release at initial stages of combustion. This causes higher  $\text{NO}_x$  formation. Longer ignition delay of TPO 30 is the reason for higher  $\text{NO}_x$  [7]. In the case of DTPO 30,  $\text{NO}_x$  emission is lesser compared to that of TPO 30 and DF at low loads and reduced significantly at part load and full load conditions. The reason may be that the latent heat of evaporation higher than TPO and hence the cylinder temperature decreases. This may in turn result in lower  $\text{NO}_x$  or DTPO 30 compared to TPO 30 and DF.

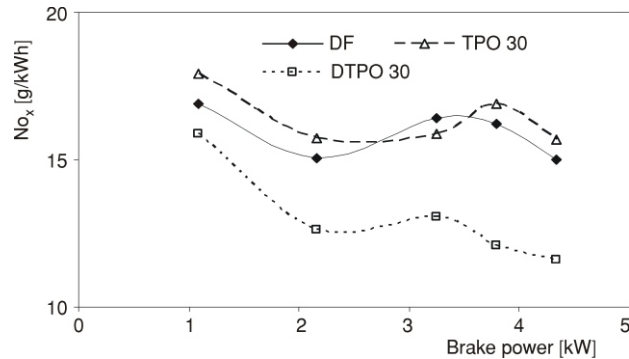


Figure 7. Variation of  $\text{NO}_x$  with brake power

#### Hydrocarbon emission

Figure 8 shows the variation of HC emissions for the tested fuels at different loads. HC emissions for TPO 30 is higher compared to DF at full load. HC varies from 0.23 g/kWh at low load to 0.06 g/kWh at full load for DF. It may also be observed that, for TPO 30 it varies from 0.25 g/kWh at low load to 0.08 g/kWh at full load, whereas for DTPO 30, it varies from 0.24 g/kWh at low load to 0.07 g/kWh. Higher HC emission for TPO 30 is probably due to higher viscosity, density and poor volatility and fuel rich operation at high load condition. In the case of DTPO 30, the viscosity is lower compared to DF. Although, the fuel air mixture completely burns, the presence of aromatic compounds leads to higher HC emissions compared to that of DF. However, the HC emissions are slightly lesser than TPO 30 blend.

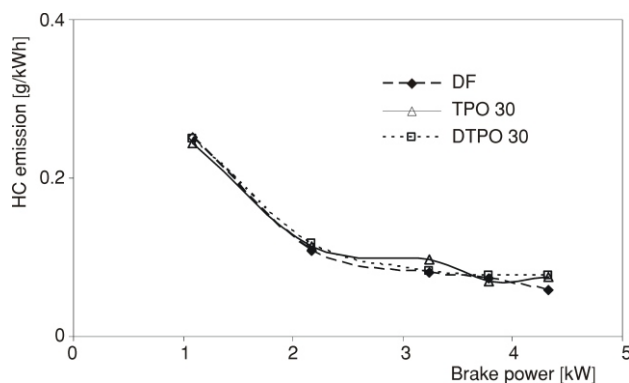


Figure 8. Variation of HC emissions with brake power

#### Carbon monoxide emission

Figure 9 shows the variation of CO emission for the tested fuels at different loads. Diesel engines generally produce lower emissions of CO as they always run on lean mixture compared with spark ignition engines, which operate nearer to stoichiometric mixture. CO emission for TPO 30 blends is found to be higher than DF. CO varies from 11.4 g/kWh at low load to 2.5 g/kWh at full load for DF. It may be observed that CO varies from 11.9 g/kWh at low

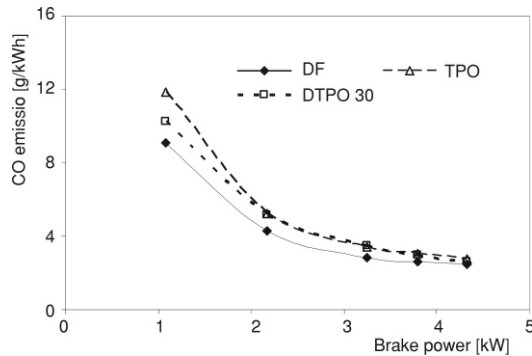


Figure 9. Variation of CO emission with brake power

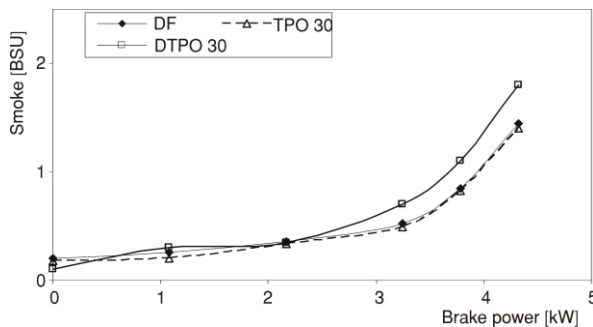


Figure 10. Variation of smoke with brake power

content is increased with constant cetane number, particulate emission of TPO 30 increases at high load. It can be noted that the smoke emission of TPO 30 is comparable with DF and the fuel quality has no adverse effect on smoke. However, DTPO 30 exhibits higher smoke compared to DF. Lower in cylinder temperature as a result of higher latent heat of evaporation of DTPO 30 may be the reason for higher smoke.

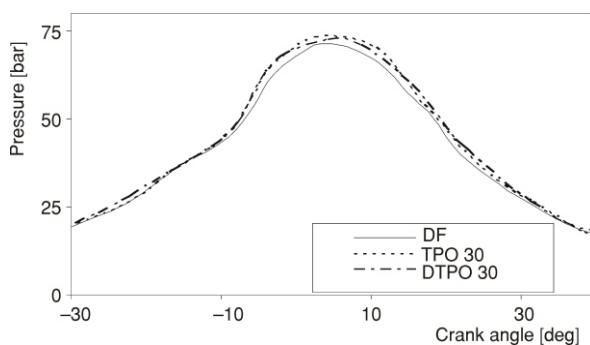


Figure 11. Variation of pressure with crank angle

load to 2.8 g/kWh at full load for TPO 30 and 10.3 g/kWh at low load to 1.16 g/kWh for DTPO 30. Higher values of CO can be attributed to the poor mixture preparation, inefficient combustion due to higher viscosity and poor volatility of TPO 30. In the case of DTPO 30 after distillation the availability of more gasoline fractions may cause higher CO than DF. But CO emission is lesser than TPO 30.

### Smoke emission

Smoke is nothing but solid soot particles suspended in exhaust gas [8]. Figure 10 shows the variation of smoke level with brake power at various loads for different tested fuels. Smoke varies from 0 to 1.45 BSU for DF. It may be observed that smoke varies from 0.15 to 1.35 BSU for TPO 30 and from 0.1 to 2 BSU for DTPO 30. It was reported by Yoshiyuki *et al.* [9] that fuels with longer ignition delay keeping aromatic content constant, exhibit lower particulate emissions and higher  $\text{NO}_x$  at high load. At the same time, as the aromatic

### Pressure crank angle diagram

Figure 11 indicates the variation of cylinder pressure with crank angle at full load. Cylinder pressure is higher for TPO 30 and DTPO 30 compared to DF. It can be noticed that the combustion of TPO-DF blends takes place earlier than DF. The peak pressure of a compression ignition (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 dependent on the delay period and the mixture preparation.

The early combustion of TPO-DF blends results in an increase in cylinder peak pressure. TPO 30 shows the ignition delay longer by about 1.6 deg CA than DF and the peak pressure is increased by about 1.8 bar. DTPO 30 shows the ignition delay by about 1 deg CA longer than DF and the peak pressure for DTPO 30 is decreased by 2 bar at full load compared to DF.

### Cylinder peak pressure

The variation of cylinder peak pressure with brake power for the tested fuels at different loads is shown in fig. 12. 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. The cylinder peak pressure for DF varies from 58 bar at low load to 71 bar at full load. It can be noticed that the cylinder peak pressure increases from 59 bar at low load to 73 bar at full load for TPO 30. For DTPO 30 the cylinder pressure varies from 57 bar at low load to 69 bar at full load. In the case of TPO 30, the peak pressure at all loads is high and this is attributed to higher viscosity and lower volatility which results in a longer ignition delay of the TPO 30 blends.

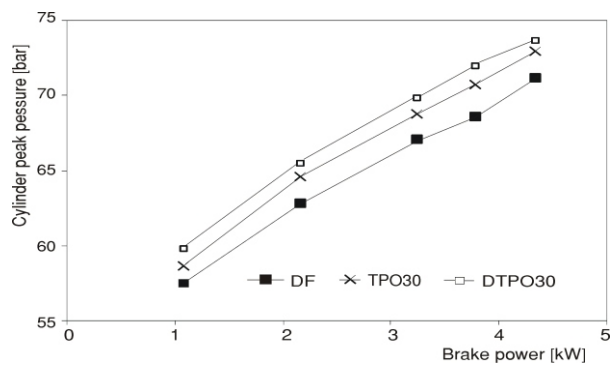


Figure 12. Variation of cylinder peak pressure with brake power

### Rate of heat release

Figure 13 shows the heat release pattern of the tested fuels 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. The second stage starts from the end of the first stage to the end of combustion. DF shows the lowest heat release rate at initial stage and longer combustion duration. It may be seen that the maximum heat release rate for DF and TPO 30 is 46.3 and 50.7 J/deg CA, respectively, whereas the maximum heat release rate for DTPO 30 is 42.2 J/deg CA. The heat release rate for DTPO 30 is lesser than DF and TPO 30. This may be attributed to higher latent heat of evapora-

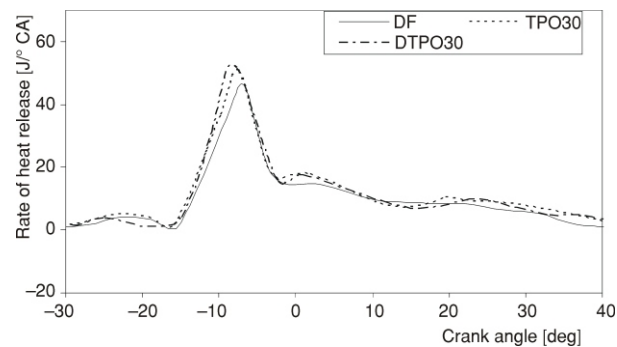


Figure 13. Variation of heat release rate with crank angle

tion of DTPO 30 which evaporates inside the cylinder by absorbing the heat from the cylinder wall and the gas inside the cylinder and exhibit a lower heat release rate.

## Conclusions

The following conclusions are drawn based on the experimental results obtained while operating a single cylinder air cooled diesel engine fuelled with TPO 30 and DTPO 30 blends.

Tyre Pyrolysis oil derived from the waste automobile tyres appears to be similar like diesel fuel. It can be blended with conventional diesel fuel. Distillation of TPO improved the heating value and reduced the sulphur content and viscosity of TPO.

The brake thermal efficiencies of the engine fuelled with TPO 30 and DTPO 30 are comparable with DF operation.

$\text{NO}_x$  emissions are higher for TPO 30 blend compared to DF. Distillation of TPO improved the fuel quality and the  $\text{NO}_x$  is reduced by about 8% compared to TPO and by about 10% compared to DF.

Compared to DF operation, HC emission increased by about 15% for TPO 30 and 13% for DTPO 30, respectively. But, in the case of DTPO 30 operation HC is reduced by about 2% compared to TPO 30 operation. This may be due to the removal of impurities and low high volatile fractions.

CO also increased with increase in TPO 30 and DTPO 30 blends but it is lesser than 0.1%. In the case of DTPO 30 the CO emission is higher by about 3% compared to TPO 30.

Smoke increased for DTPO 30 compared to TPO 30 and DF.

Peak pressures are higher for TPO 30 and DTPO 30 blends compared to DF.

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