

The use of tyre pyrolysis oil in diesel engines

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The Use of Tyre Pyrolysis Oil in Diesel Engines

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Abstract

Tests have been carried out to evaluate the performance and emission characteristics of a single cylinder direct injection diesel engine fuelled by 10, 30 and 50 percent blends of Tyre pyrolysis oil (TPO) with diesel fuel (DF). The combustion parameters such as heat release rate, cylinder peak pressure and maximum rate of pressure rise were also analysed. For this work, TPO was derived from waste automobile tyres through vacuum pyrolysis in one kg batch pyrolysis unit. Results showed that the brake thermal efficiency of the engine fuelled by TPO-DF blends increased with increase in blend concentration and higher than DF. NO_x, HC, CO and Smoke emissions were found to be higher at higher loads due to high aromatic content and longer ignition delay. The cylinder peak pressure increased from 71.4 bar to 73.8 bar. The ignition delays were longer than DF. It is observed that it is possible to use Tyre Pyrolysis Oil in diesel engines as an alternate fuel in the future.

Key words: Diesel Engine, Tyre Pyrolysis Oil (TPO), Combustion, Performance and Emissions

Abbreviations: Diesel fuel (DF), Tyre Pyrolysis Oil (TPO), Hydrocarbon (HC), Nitrogen Oxides (NO_x), Parts per Million (ppm)

1. Introduction

Around the world, there are initiatives 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 is becoming more and more complex.

Waste to energy is the recent trend in the selection of alternate fuels. Fuels like alcohol, biodiesel, liquid fuel from plastics etc are some of the 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 in the world.

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The use of Tyre pyrolysis oil as a substitution to diesel fuel is an opportunity in minimizing the utilization of the natural resources. Several research works have been carried out on the pyrolysis of waste automobile tyres. Pyrolysis is the process of thermally degrading a substance into smaller, less complex molecules. Pyrolysis produces three principal products: such as pyrolytic oil, gas and char. The quality and quantity of these products depend upon the reactor temperature and design. In the Pyrolysis process, larger hydrocarbon chains break down at certain temperatures in the absence of oxygen that gives end products usually containing solids, liquids and gases. If the temperature is maintained at 550 °C, the main product is a liquid, which could be a mixture of various hydrocarbons depending on the initial composition of the waste material. At temperatures above 700 °C, the gas becomes the primary product due to further cracking of liquids. The gas is basically composed of CH₄, with C₂H₆, C₂H₄, C₂H₂, and other gaseous hydrocarbons however in lesser quantities. The quality and quantity of these products depend upon the reactor temperature and design. In the present work pyrolysis oil from waste tyres by vacuum pyrolysis is obtained. Though solid carbon black and pyrolysis gas are also obtained, the pyrolysis process will be much more prominent to produce liquid [1,4,8,9,12-15,19].

Adrian M. Cunliffe and Paul T. Williams (1998), studied the composition of oils derived from the batch pyrolysis of tyres in a nitrogen purged static-bed batch reactor, used to pyrolyse 3 kg of shredded scrap tyres at temperatures between 450°C and 600°C [1]. It was reported that pyrolysis of scrap tyres produced oil similar in properties to a light fuel oil, with similar calorific value, sulphur and nitrogen contents. 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. The oils contained significant concentration of polycyclic aromatic hydrocarbons some of which have been shown to be either carcinogenic and or mutagenic. 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. Throughout the combustion tests, comparison of the emissions was made with the combustion of diesel. The concentration of PAH increased from 1.5 to 3.4 wt. % of oil as the pyrolysis temperature increased from 450 to 600°C. The formation of PAH was attributed to a Diels–Alder type mechanism involving cyclisation of alkenes and dehydrogenation to form aromatic hydrocarbons. A range of potentially high value volatile hydrocarbons was identified in significant concentrations in the oils. It was found that tyres pyrolysed at 475 °C found to be optimum pyrolysis temperature and the Tyre pyrolysis temperature at this temperature has the chemical composition by % wt are: Carbon (84.6 %), Hydrogen (11.2), Nitrogen (0.5 %), Sulphur (1.4 %), Ash (0.002 %) and Oxygen by difference (2.2 %).

Isabel de Marco Rodriguez et al., (2001) studied the behavior and chemical analysis of Tyre pyrolysis oil [8]. In this 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. In this work, the percentage of aromatics, aliphatic, 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 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. The chemical composition of Tyre pyrolysis oil derived at 500 °C are: Carbon (85.6±0.5 %), Hydrogen (10.1±0.1%), Nitrogen (0.4±0.03 %), Sulphur (1.4±0.2 %), Ash (not available) and Oxygen by difference (2.5±0.5 %).

Used tires were thermally decomposed at 500°C and at a total pressure of 20 kPa in a process development unit consisting of a horizontal reactor vessel 3 m long and 0.6 m in diameter (Chaala and Roy, 1996). The chemical compositions of the Tyre pyrolysis oil are: Carbon (86.51 %), Hydrogen (10.10 %), Nitrogen (1.2 %), Sulphur (0.8 %), and Oxygen by difference (1.39 %). Saat Ucar et al, (2005) compared two pyrolytic oils derived from passenger car tyres and truck tyres from a fixed bed reactor. An optimum temperature at 650 °C, the chemical compositions of Tyre pyrolysis oil derived from truck tyres are: Carbon (86.47%), Hydrogen (11.73 %), Nitrogen (<1 %), Sulphur (0.83%), Ash (<1 %) and Oxygen by difference (not available). The chemical composition of Tyre pyrolysis oil derived from waste automobile tyres from bomb reactors are: Carbon (86.11 %), Hydrogen (10.92), Nitrogen (0.41 %), Sulphur (0.83 %), Ash (not available) and Oxygen by difference (1.73 %).

Studies have been carried out on wood pyrolysis oil as an alternate fuel in internal combustion engines [2,3,5,17]. Reliable operation was recorded with wood pyrolysis oil-diglyme blends without any modification in the engine.

In the present study, TPO-Diesel blends were used as a fuel in a single cylinder air cooled DI diesel engine. The performance, emission and combustion characteristics of the engine were analysed and compared with diesel fuel operation.

2. Experimental details

2.1 Pyrolysis of waste automobile tyres

In the present work, 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 fed in to a mild steel pyrolysis reactor unit. The pyrolysis reactor used was a full insulated cylindrical chamber of inner diameter 110 mm and outer diameter 115 mm and height 300 mm. Vacuum was created in the pyrolysis reactor and then externally heated by means of 1.5 kW heater. A temperature controller controlled the temperature of the reactor. The process was carried out between 450 °C and 650 °C in the reactor for 2 hours and 30 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 shown in Figure 1.

The non condensable gases were let out to atmosphere. The TPO collected was crude in nature. For an output of 1 kg of TPO about 2.09 kg of waste tyres feedstock was required. The product yields from the process are: Tyre Pyrolysis Oil (50 %), Pyro gas (40 %) and char (10 %). The heat energy required to convert the waste tyres into the products was around 7.8 MJ/kg. The residence time of the pyrolysis process was 90 minutes. The elemental composition of TPO is given in Table 1. The composition of TPO reconfirms and comparable with the values available in the early research works. Since the oil collected for this study was untreated, the TPO contains impurities, dust, low and high volatile fractions of hydrocarbons [10]. TPO was filtered by fabric filter and again filtered by micron filter. The efficiency of the filtration is 99 %.

2.2 Fuel composition and properties

TPO-DF blend gives different values of physiochemical properties, like heating value, viscosity, flash point, pour point etc compared to DF. These properties may affect the spray characteristics, performance, combustion and emissions of the engine. Therefore, some basic properties of TPO were measured and compared with conventional petroleum fuels as given in Table 2. The viscosity of TPO is higher by about 1.5 times than diesel. The flash point and fire point of the TPO are closer to diesel. Sulphur and carbon content are also higher for TPO than DF [10]. In the present work 10%, 30% and 50% of TPO was blended with DF on volume basis and observed for 15 days to check for any separation. No such separation was noticed.

TPO blended with DF is indicated as TPO xx. For example, 10 % TPO blended with 90 % DF is denoted as TPO 10.

3. Use of TPO as a Fuel in Diesel Engine

3.1 Engine setup

The schematic layout of the experimental set up is shown in Figure 2. The specifications of the engine are shown in Table 3. The test engine used was a single cylinder, air cooled direct injection stationary diesel engine (1). An electrical dynamometer (2) was used to provide the engine load. A Chromel Alumel thermocouple in conjunction with a digital temperature indicator (3) was used to measure the exhaust gas temperature. A TDC encoder (4) was used to detect the engine crank angle. A pressure pickup (5) mounted on the cylinder head, a pressure transducer (6) in conjunction with a KISTLER charge amplifier (7) and a Cathode Ray Oscilloscope (CRO) (8) were used to measure the cylinder pressure. A printer (9) was used to print the output of the CRO. An air box and inlet manifold (10, 12) were fitted to the engine and an air flow meter was used for airflow measurement (11). The fuel was admitted from the fuel tank (13) to the engine via the fuel injection pump (14) and the fuel injector (15) and the fuel flow was measured on volumetric basis using a burette and a stopwatch. An Infrared gas analyzer (17) was used to measure NO_x/HC/CO emissions in the exhaust with NO_x and HC measurement in ppm, and CO emission measured in percentage volume. Smoke was measured in Bosch Smoke Units (BSU) by a Bosch smoke meter (18). Initially experiments were carried out using base diesel fuel (DF). All the experiments were conducted at the rated engine speed of 1500 rpm.

3.2 Experimental Procedure

Performance, exhaust emission and combustion tests were carried out on the CI engine using blends of TPO-DF. All tests were conducted by starting the engine with DF only. After the engine was warmed up, it was then switched to TPO-DF blend. At the end of the test, the fuel was switched back to diesel and the engine was kept running for some time to flush out the TPO-DF blend by DF from the fuel line and the injection system, in order to prevent the fuel system from the accumulation of TPO-DF which may damage the system.

4. Results and Discussions

4.1 Combustion analysis

The ignition delay was evaluated as the time lag between the start of injection and start of ignition [3]. The later was inferred from the heat release curves as the point where the rate of heat release starts from Zero (after the evaporation of the injected fuel). The ignition delay is longer due to the higher viscosity of TPO-DF blends that results in poor atomization (3,6,7). The ignition delay increases with the TPO-DF blends. Figure 3 shows the heat release rate curves for TPO-DF blends and DF at full load. It indicates that the ignition delay for TPO 10, TPO 30 and TPO 50 is 1° , 1.6° and 2.5° CA respectively, which is longer than DF. The ignition delay for DF at full load is 6.5° . It can also be seen that the heat release rate is maximum with TPO 50 followed by TPO 30, TPO 10 and DF. Due to the longer Ignition delay the TPO-DF blends show a steeper rise in heat release in the premixed combustion with shorter duration compared to DF. It is also observed that the diffusion phase is longer for TPO-DF blends than DF. High viscous fuels exhibit longer ignition delay. During the premixed combustion phase, more fuel air mixture is prepared for TPO-DF blends.

The variation of peak pressure and the rate of pressure rise for the TPO-DF blends and DF are shown in Figure 4 and Figure 5. TPO includes the constituents having higher boiling points and lower boiling points than DF. However, the chemical reactions during the injection of TPO-DF blends at high temperatures resulted in the breakdown of unsaturated acids of higher molecular weight to products of lower molecular weight unidentified. These complex chemical reactions led to the formation of gases of low molecular weight on the peripheral region with a very dense inner core of liquids of higher molecular weight. Rapid gasification of this lighter oil is converted into volatile combustible compounds and thus ignited earlier there by increasing the peak pressure [18].

The peak pressure and maximum rate of pressure rise are highest for TPO 30 followed by TPO 50 and diesel. The peak pressure depends on the combustion rate in the initial stages, which is influenced by the ignition delay and the air fuel mixture and the amount of fuel that gets combusted during the premixed combustion phase [7]. Hence, higher viscosity and lower volatility of Tyre pyrolysis oil blends are the reasons for the increase in peak pressure and maximum rate of pressure rise in the case of blends. The peak pressure values of TPO-DF blends and DF at no load and full load are given in Table 3.

It may be observed from the table that, the peak pressure for TPO 50 is higher by about 3.65 bar while that of TPO 30 and TPO 10 are higher by 2.4 bar and 1 bar compared to DF.

4.2 Performance Study

4.2.1 Brake thermal efficiency

The brake thermal efficiency with brake power for TPO-DF blends is compared with the DF and shown in Figure 6. The brake thermal efficiency for DF at full load is 29.46 % while with TPO 10 and TPO 30 it is 28.68 % and 28.93 % respectively. The brake thermal efficiency for TPO 50 is 28.39 %. TPO 30 shows a better performance at all loads compared to TPO 10 and TPO 50. The reason may be additional lubricity. In general, the engine operated with TPO-DF blends give brake thermal efficiencies marginally higher than DF.

4.2.2 Brake specific fuel consumption

The variation of brake specific fuel consumption with brake power is shown in Figure 7. The TPO-DF blends show higher BSFC value than DF due to the lower calorific value of TPO-DF blends. The amount of fuel necessary to deliver the same power output with TPO-DF blends is higher with increasing the percentage of TPO.

4.2.3 Exhaust gas temperature

Figure 8 shows the exhaust gas temperature variation with brake power. It may be seen that the exhaust gas temperature increases with increasing load and TPO-DF blends. Poor volatility and high viscosity are the reasons for the higher exhaust gas temperatures for TPO-DF blends. The increase may also probably due to higher heat release rates of TPO-DF blends developed in the premixed combustion [17].

4.3 Emissions Study

4.3.1 NO_x Emissions

NO_x emissions are compared and depicted in Figure 9. The NO_x emissions are higher for TPO-DF blends than DF. The NO_x emissions are significantly influenced by two parameters, one is in cylinder gas temperature and the other is residence time. As mentioned earlier, because of the corresponding smaller cylinder volume, during the premixed combustion phase the peak pressure for TPO-DF blends were higher than DF, which is due to higher combustion temperature [16,17]. This is evident from the higher exhaust gas temperatures from the TPO-DF fuelled engine.

4.3.2 Hydrocarbon (HC) Emission

Figure 10 shows the variation of Hydrocarbon (HC) emissions for the tested fuels at different loads. HC emissions for TPO-DF are higher compared to DF at full load. Part load values for TPO-DF are marginally closer to DF. HC varies from 22.2 ppm to 24.76 ppm for DF. It can be observed that for TPO 10, it varies from 26.5 ppm to 25.5 ppm, for TPO 30 from 24 ppm to 28.5 ppm and for TPO 50 from 26.5 ppm to 30 ppm. Higher HC emissions are probably due to higher viscosity, density, poor volatility and fuel rich mixtures at higher loads. TPO is aromatic in nature and indeed results in higher unburnt hydrocarbon emissions. Part load values for TPO-DF are marginally closer to DF. At low loads locally over lean mixture is produced during the longer ignition delay period leading to incomplete combustion and hence higher HC is formed.

4.3.3 Carbon monoxide (CO) Emission

CO emission is higher for the TPO-DF blends as shown in Figure 11. CO for TPO-DF blends increases in concentration on an average of 12 % percent than DF. Diesel engines generally produce lower emissions of CO as they always run on lean mixture compared with gasoline engines, which operates nearer to stoichiometric mixtures [11]. Probably, during the combustion process, the presence of low molecular weight compounds which affect the atomisation process, resulting in local rich mixtures produce higher CO emission. At higher temperatures, radicals generated by the decomposition of high molecular weight compounds contained in oil react between themselves and form polymers by condensation. These polymers which exhibit coke-like structure, deposit into the combustion system of the engine [3,6]

4.3.4 Smoke

Smoke is nothing but solid soot particles suspended in exhaust gas [11]. Figure 12 shows the variation of smoke level with brake power at various loads for different tested fuels. It is observed that smoke is higher for TPO-DF blends at full load except for TPO 30. It was reported by Yoshiyuki that fuels with longer ignition delay with keeping aromatic content constant, exhibit lower particulate emissions and higher NO_x at full load. At the same time, as the aromatic content increased with constant cetane number, particulate emission increases at high load [16]. From the figure it can be observed that the smoke emission is slightly higher for TPO 10 and TPO 50 compared to DF, whereas TPO 30 is comparable with DF. This may be due to better and optimum fuel air mixture for TPO 30. As the TPO 50 has longer ignition delay and higher aromatic content, smoke is increased.

5. Conclusions

The following conclusions are drawn from the experimental results:

- Brake thermal efficiency of the engine increased with increase in TPO blend concentration than DF. Thermal efficiency for DF operation at full load is 29.3 %, In case of TPO 10 it is 29.6 %. The efficiency for TPO 30 and TPO 50 at high load is 29.77 % and 29.87 % respectively.
- No engine seizing, injector blocking was found during the entire operation of the engine running with different percentage of TPO-DF from 10% to 50%.
- Hydrocarbon emission is higher for TPO-DF blends than DF at peak load. TPO 10 exhibited approximately 3 % increase in HC at peak load. Incase of TPO 30 and TPO 50 operation the rise in HC at peak load is 15 % and 21 % respectively. This is due to the PAH present in the TPO.
- Carbon monoxide emission is also higher for TPO-DF blends than DF, but the values are less than 0.1 %.
- NO_x emission was higher for TPO-DF blends with increase in blend concentration than DF. TPO 10 exhibited approximately 0.5 % increase in NO_x at full load. Incase of TPO 30 and TPO 50 operation the rise in NO_x at full load is 4.5 % and 10 % respectively.
- Smoke is about 7 % higher for TPO 50 operation at full load compared to DF.
- Ignition delay is longer for TPO-DF than DF.
- Peak pressure and rate of pressure rise for TPO-DF blends are higher compared to DF.
- It is concluded that reducing the aromatic content and viscosity would help in using TPO as a fuel in diesel engines.

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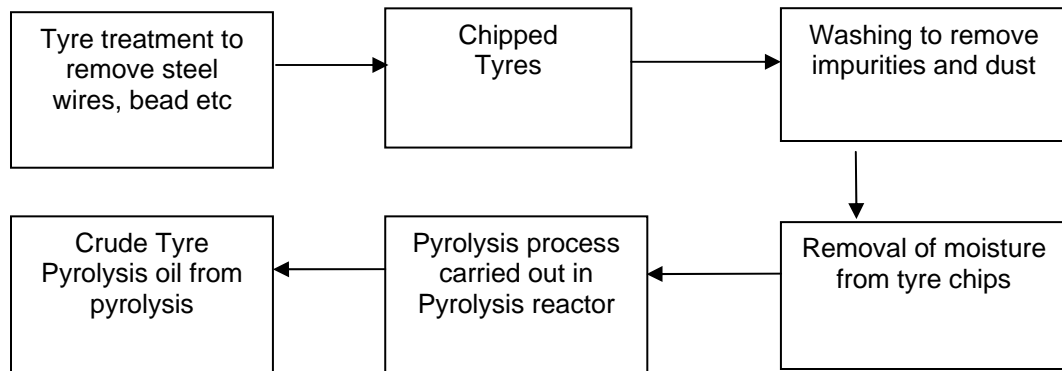
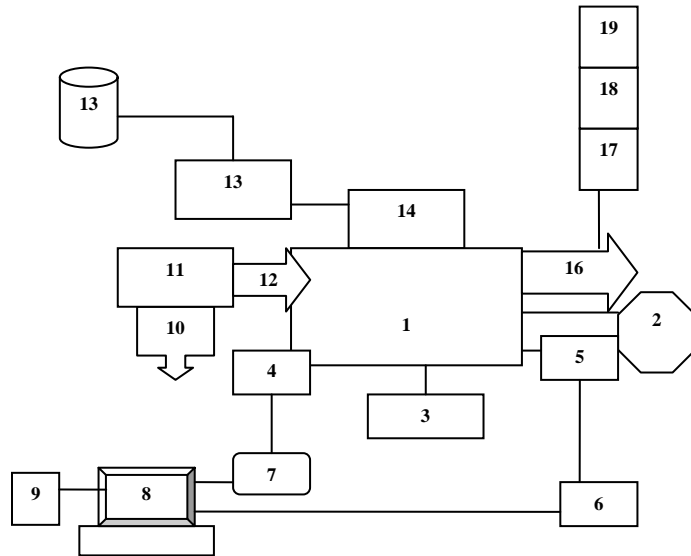


Figure 1 Pyrolysis process of waste automobile tyres



- | | | |
|--------------------------|---------------------|---|
| 1. Engine | 7. Charge Amplifier | 13. Fuel tank |
| 2. Dynamometer | 8. C.R.O | 14. Fuel Injection pump |
| 3. Exhaust gas indicator | 9. Printer | 15. Fuel Injector |
| 4. TDC Encoder Machine | 10. Air Tank | 16. Exhaust Manifold |
| 5. Pressure pickup | 11. Airflow meter | 17. NO _x ,CO and HC analyser |
| 6. Pressure transducer | 12. Inlet manifold | 18. Bosch Smoke Pump |

Figure 2 Experimental Setup

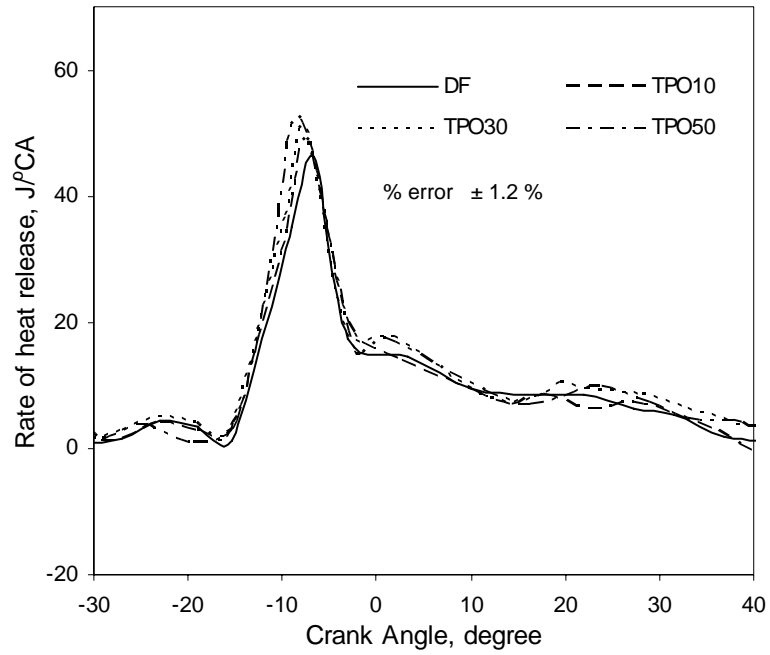


Figure 3 Variation of heat release rate with crank angle

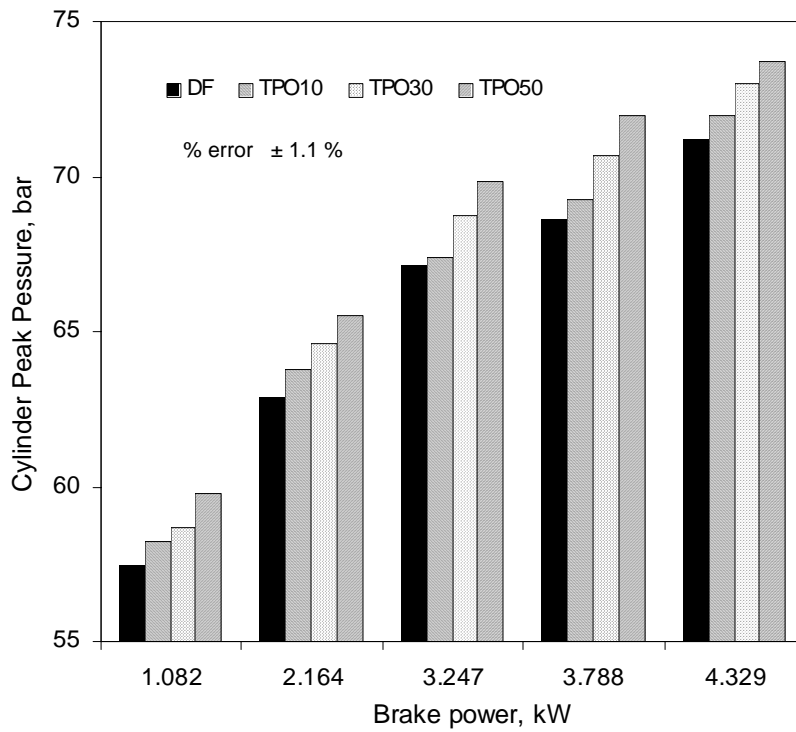


Figure 4 Variation of cylinder peak pressure with brake power

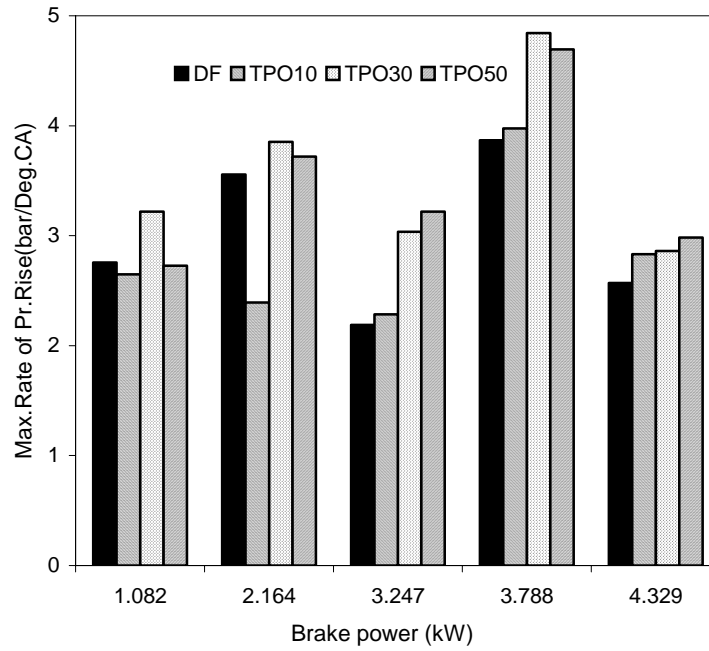


Figure 5 Variation of maximum rate of pressure rise with brake power

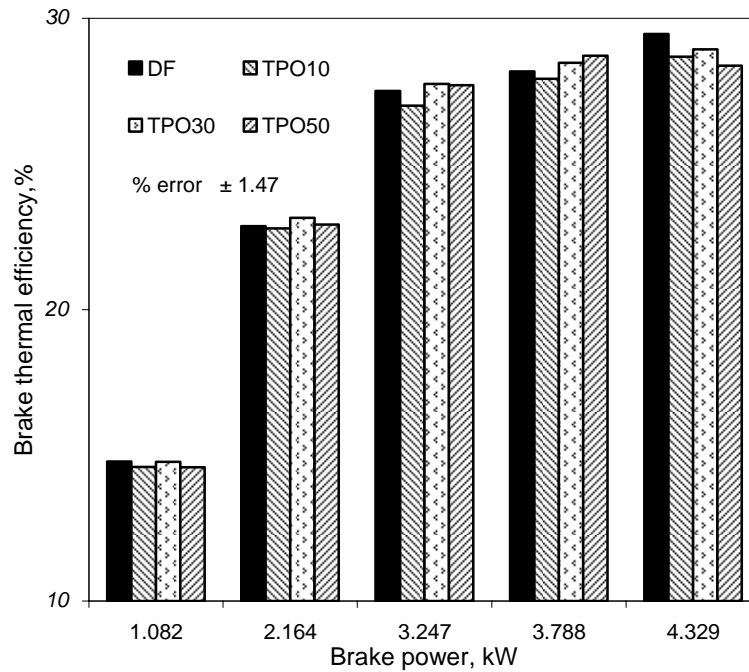


Figure 6 Variation of brake thermal efficiency with brake power

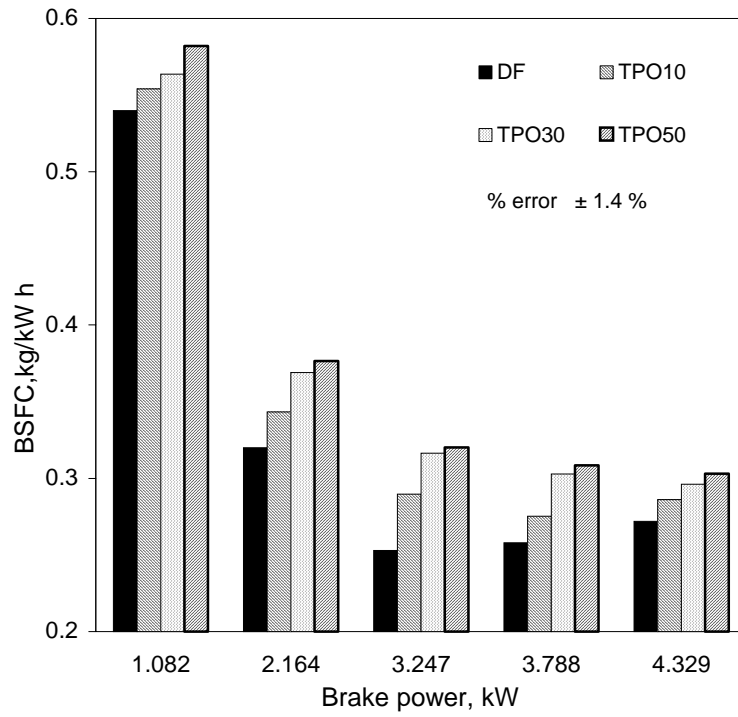


Figure 7 Variation of BSFC with brake power

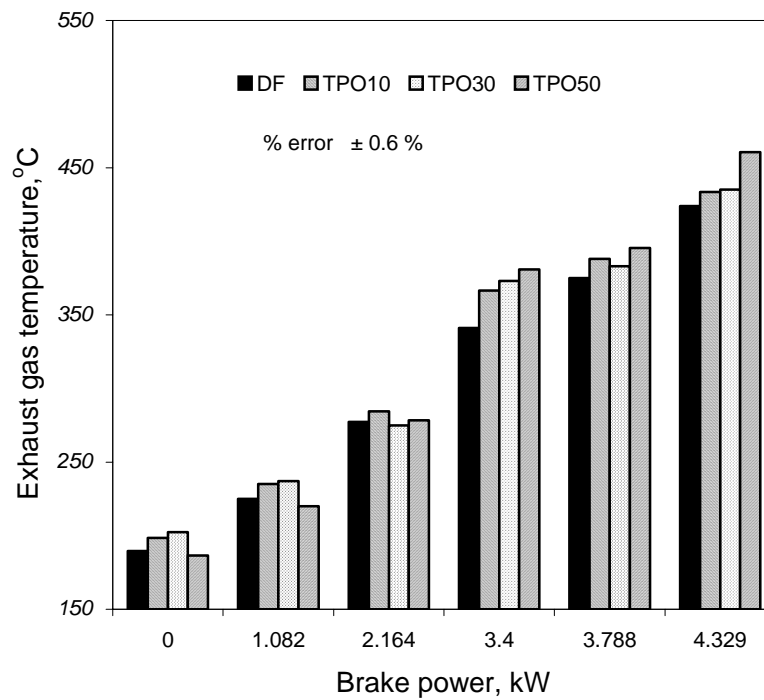


Figure 8 Variation of exhaust gas temperature with brake power

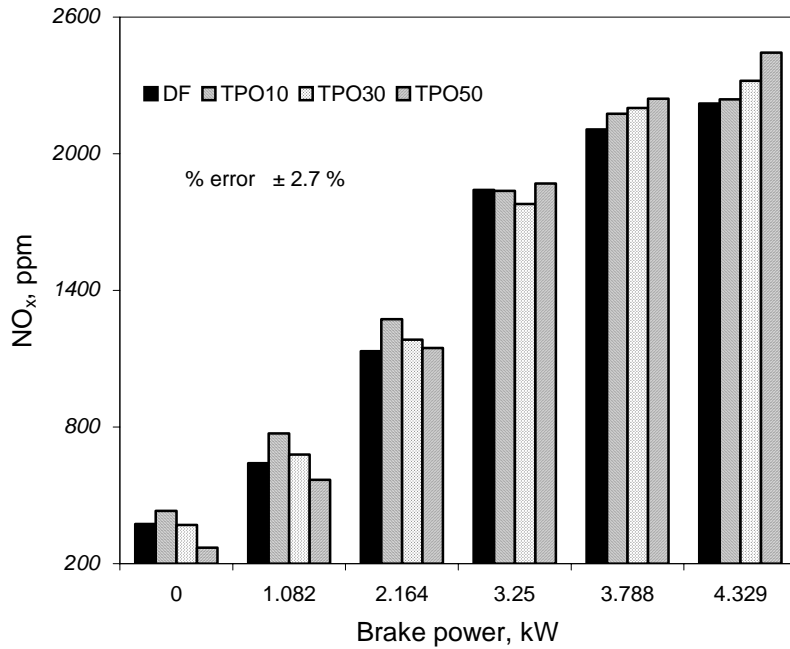


Figure 9 Variation of NO_x with brake power

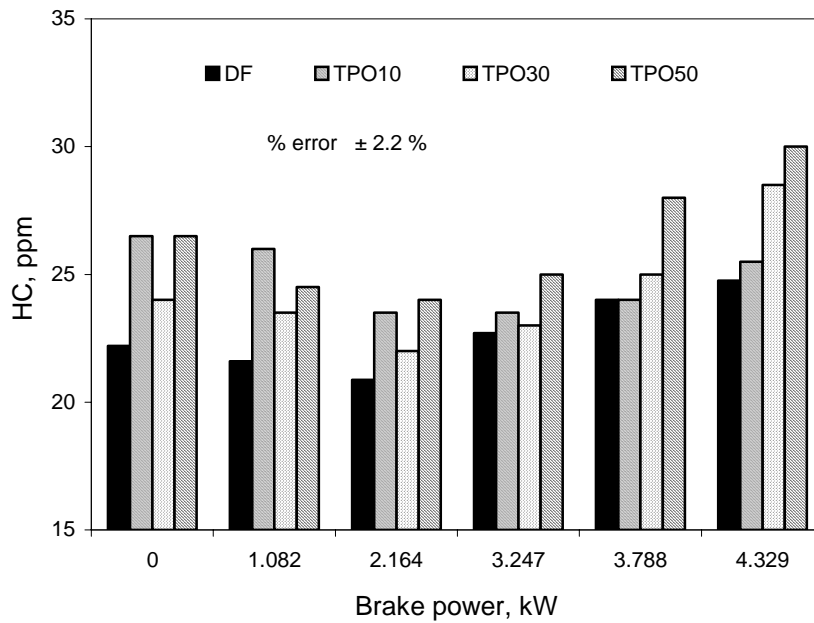


Figure 10 Variation of HC emissions with brake power

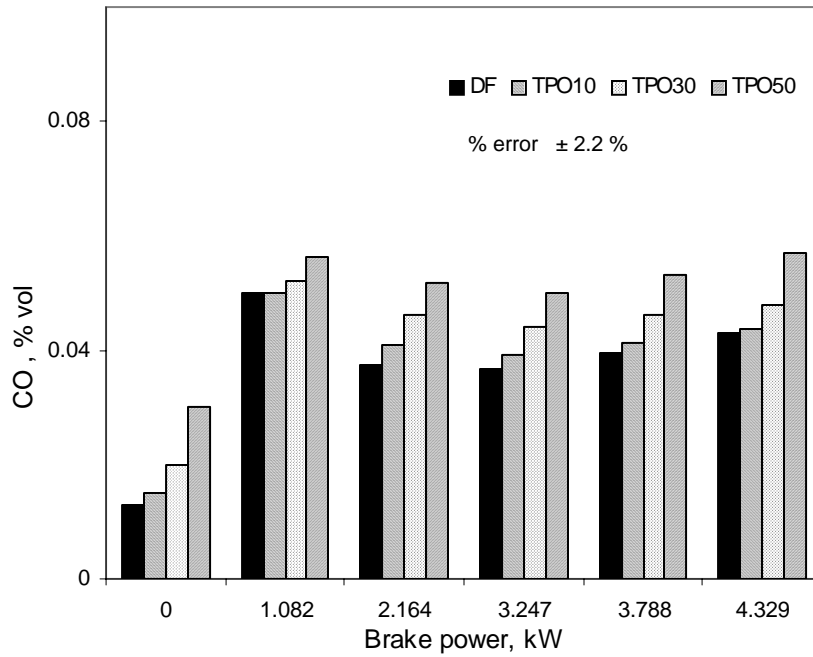


Figure 11 Variation of CO emission with brake power

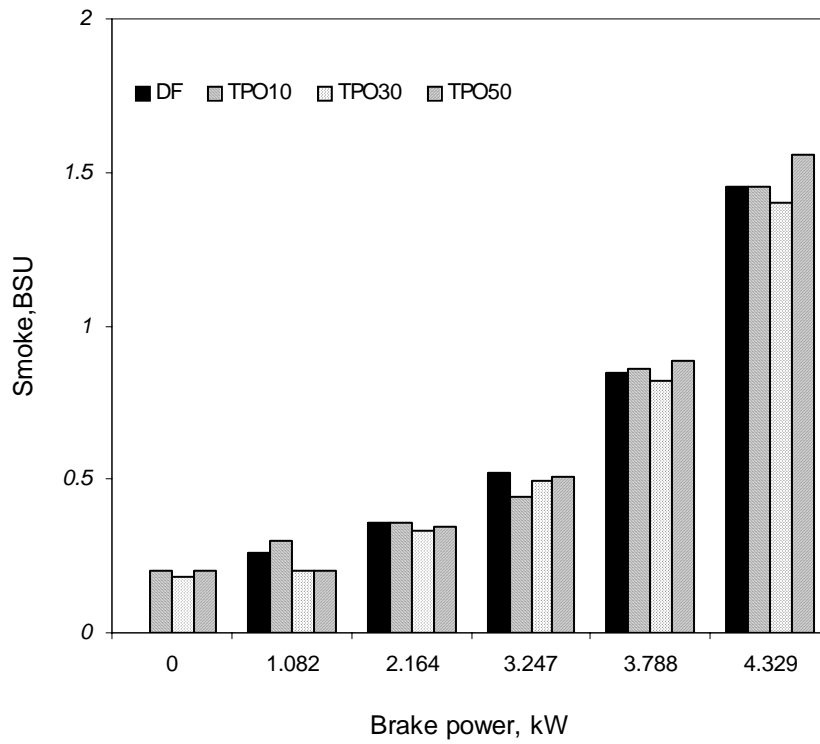


Figure 12 Variation of Smoke with brake power