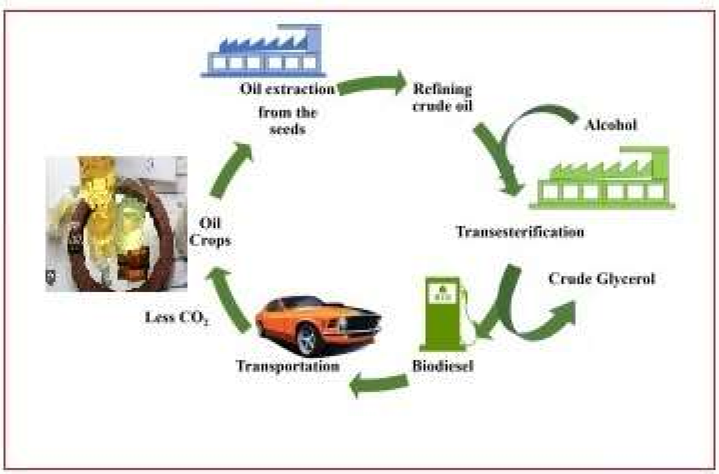
Analysis of Combustion, Performance and Emissions of a Diesel Engine Fueled by Blends of Waste Paraffin Oil

Saravanan Rajendran[1,*], Navaneetha Krishnan Perumal[2], Sivakumar Durai Balu[3], Rengasamy Mookan[4]

[1]Research Scholar, Department of Mechanical Engineering, Anna University, Chennai, Tamil Nadu, India
[2]Assistant Professor, Department of Mechanical Engineering, University College of Engineering, BIT Campus, Trichy, Tamil Nadu, India
[3]Assistant Professor, Department of Mechanical Engineering, University College of Engineering, BIT Campus, Trichy, Tamil Nadu, India
[4]Assistant Professor, Department of Petrochemical Technology, University College of engineering, BIT Campus, Trichy, Tamil Nadu, India
Corresponding author:saravanan040587@gmail.com

Graphical Abstract



Abstract

The oil that comes out of the transformer is to violate the environment after the completion of its durability. Disposal of these wastes into open land leads to environmental hazards. This research work intends to capitalise on the feasibility of converting waste paraffin oil from electrical transformers into an alternative fuel. The varying quantity of thermally cracked waste paraffin oil (20%, 40%, and 60% v/v) is mixed with 10% v/v of diethyl ether (DEE) and blended with commercial diesel to make 100% volume. The purpose of this work is to find out the performance of the blended fuel when compared to the commercial diesel fuel (CD). From the experimental data obtained, the performance and combustion characteristics were shown to be enhanced for WPDE60. The physicochemical properties of WPDE60 were found to be similar to

CD. Notable improvement was observed in the WPDE60 blend for BSFC, BTE, and in-cylinder pressure by 8.82%, 8.29%, and 4.3%, respectively, when compared to CD at full load conditions. Whereas emissions performance, such as unburned hydrocarbons, CO, and smoke density, were reduced by 18.82%, 4.9%, and 39.6%, respectively, and NOx emissions were increased by 3.3% compared to the commercial diesel. Based on the results obtained, WPDE60 fuel is resembled to the properties of commercial diesel, and that can be proposed as a fuel alternative for internal combustion engines.

Key Words: *Waste paraffin oil, Transformer oil, Di ethyl ether, Engine performance, Emissions characteristic, Diesel engine.*

Nomenclature

WPDE-Waste paraffin Diesel fuel	DEE-Diethyl Ether
FTIR -Fourier Transform Infrared Spectroscopy	NOx-Nitrogen Oxide
CD- Commercial diesel fuel	USD -United States Dollar
BSFC- Break Specific Fuel Consumption	HRR - Heat release rate
ASTM –American Society for Testing Material	ID- Ignition delay
BTE- Break Thermal Efficiency	HC–Hydrocarbon emission
CAGR-Compound Annual Growth Rate	TGA–Thermo gravimetric analysis

1. Introduction

Diesel engines began using biofuels when Rudolf Diesel presented the first diesel engine at the Paris World Fair in 1900. He felt that oil obtained from locally cultivated crops (peanut oil) might be employed to fuel his engine (Chalkley, 1917).Still today, using vegetable oil as a fuel source for longer periods of time in DI engines has the problems of reactivity of unsaturated hydrocarbons, lower volatility, and higher viscosity (Rengasamy et al. 2017). There are several biomass-based liquefied fuels that can be used to replace diesel, such as alcohol, biodiesel, and additional fluid energies (Banković-Ilić et al. 2012). There are typically additional modifications required to the diesel engine or fuel before it can operate on these exposed fills, both in terms of physical, chemical, and thermal properties. Hence, diesel, which is obtained from non-renewable hydrocarbon sources, is used as superlative fuel in diesel engines. Owing to versatility, availability, dependability, and high energy efficiency, fossil diesel has been widely used in various industries, including agriculture, transportation, etc. (Mofijur et al. 2013). In favourable features such as combustion quality, viscosity, volatilisation, relative density, and lubricity, the IC engine works well on diesel, as the air in the cylinder is compressed, the heat that is produced from the cylinder to burn the fuel. At the same time, fossil fuels have always been associated with resource scarcity, especially for producers who had long sought sustainable energy sources for crop yields (Demirbas, 2008). When it comes to greenhouse gas emissions and total global energy consumption, the transportation sector ranks third (after industry and construction), owing to the increase in vehicle engine demand, which directly relies on fossil fuels like gasoline and diesel. The demand for fossil fuel is predicted to climb by 60% by 2030 due to industrialisation, population growth, and improved living conditions (Bhuiya et al. 2016). Unrefined petroleum has been rapidly decreasing, resulting in an increase in the cost of rough energies, prompting the search for replacements (Nguyen et al. 2017). Nowadays, analysts are increasingly concerned about replacing petroleum products with suitable alternates, not only to avoid the use of petroleum products but also to decrease greenhouse gas emissions from the combustion of these fuels. In order to reduce the demand on diesel, the current research focuses on the possibility of replacing some portion of the diesel with thermally cracked waste transformer oil. As per Global Forecast to 2030, the transformer oil market will raise at a compound annual growth rate (CAGR) of 6.5% over the recent years 2021 to 2030. By the year 2030, the market for transformer oil is expected to touch USD 3.3 billion globally, from the current market of USD 1.9 billion. Hence, waste transformer oil can act as a potential energy source for fuel blend (Negm et al. 2017).

The transformer oil is a mixture of hydrocarbons made up of different hydrocarbon families consisting of paraffins, isoparaffins, naphthenes, and aromatics (Kaplan et al. 2010). The main and foremost constituent is linear long-chain paraffins. The fuel blend, which has a portion of direct use of transformer oil with diesel, was investigated by many researchers (Lahane et al. 2015), but the Initial Boiling Point (IBP) of the fuel blend comes down to being the issue. Whereas thermally cracked waste transformer oil shows the diesel-like properties (Arpa et al. 2013),since this oil has a high volatility and low viscosity, making it a possible fuel source. Other characteristics, such as density, calorific value, boiling point, and flash & fire points, are equivalent to diesel fuel. The addition of this thermally cracked used transformer oil to the commercial diesel will undoubtedly lower the viscosity and enhance the volatility of the overall mix (Estevez et al. 2022). The decreased viscosity and increased heating value will improve engine performance. The characteristics of fuel blends are nearly identical to those of diesel fuel. The greater volatility of the blend will result in finer atomisation and improved spray formation. Good ignition quality in terms of cetane number is one of the important characteristics of CI engines. Compression ignition engines require high diesel solubility and low viscosity, in addition to high volatility (Demirbas et al. 2015). Cyclic compounds of hydrocarbons, like naphthenes and aromatics, which are present in the transformer oil and which may be formed during thermal cracking operations, typically have a lower cetane index due to their shorter hydrocarbon chains. The fuels that have a lower cetane number show a delay in the ignition delay and peak rate of heat release in CI engines, which results in more noticeable premixed combustion, noise, and fuel consumption (Pham et al. 2021). The fuel that has a lower cetane number requires some ignition aid, such as additives. As a result, modest quantities of additives may be put in the engine to boost performance and reduce emissions (Noushabadi et al. 2020). Numbers of additives are present in the current market; among them, diethyl ether (DEE) is used in this study because of its high cetane number, a greater energy density, presence of higher oxygen, superior miscibility, a lower auto-ignition temperature, and varied flammability constraints characters. Literatures also find out that adding DEE to the emulsified fuel significantly reduces nitrogen oxide (NOx) emissions, smoke density, and ignition delays (Kaimal et al. 2018).

Any hydrocarbon having diesel-like properties can be combined with commercial diesel to reduce diesel fuel consumption considerably. As a consequence, the financial resources required for importing petroleum products are reduced, and as a result, the economy benefits and can be arrived at. In order to achieve this goal, Gnanamoorthi and Murugan. (2019) and Barik and Murugan. (2016) have examined the effect of diethyl ether on CI engines powered with oil obtained from waste plastic as an additive. Similarly, Hariharan et al. (2013) have evaluated the effect of diethyl ether on diesel engines fuelled by oil obtained from tire pyrolysis perations. (Dogana et al. 2012) have studied the result of fuel derived from pyrolysis of tire on engine combustion, performance, and exhaust emissions. In this trial, paraffinic hydrocarbon present in transformer oil was utilised as a source to make a fuel blend. To the best of our knowledge, this is a first trial report on combustion, performance, and emissions of diesel engine fuelled by the combination of diesel with DEE and thermally cracked waste transformer oil.

The main aim of the current study focuses on decreasing the commercial diesel consumption by blending some portion of thermally cracked transformer oil without compromising their performance in combustion, efficiency, and emission of IC engines. In this report, the varying quantity of thermally cracked waste paraffin oil (20%, 40%, and 60% v/v) is blended with commercial diesel along with 10% v/v of diethyl ether (DEE). Characterisation of fuel blend is made with FTIR (Fourier Transform Infrared Spectroscopy) analysis. In addition to FTIR, flash and fire point, cetane number, calorific value, density, and kinematic viscosity are also performed. The performance of the blended fuel, like combustion characteristics, performance of the engine, and emission characteristics, is compared to those of common diesel/commercial diesel (CD) fuel.

2. Materials and Methods

2.1 Materials

Waste transformer oil (paraffin oil) was collected from the Tamil Nadu Electricity Board (TNEP) substation in Tiruchirappalli. Hydrochloric acid (HCl) and diethyl ether were acquired from M/s Priya Science, Tiruchirappalli. Diluted HCl (1N) solution is used to remove the stain and rust from the waste paraffin oil. Double distilled water is used to remove corrosive material from waste paraffinic oil. Then, the oil is heated at 400°C are condensed and collected as stock solution. After the stock solution had been colong-chainom temperature, the additive, namely dietones. There, was added (10% v/v) and process, well Vapours ended oil is mixed with conventional diesel at varied concentrations. The various mixing protocol combinations (Table 1) were selected to represent the engine performance and emission characteristics of IC engines.

Table 1. Blending combinations of waste paraffinic oil, Di ethyl ether and normal diesel

Waste Paraffinic oil*	Di ethyl ether*	Commercial Diesel*	Designation
0	0	100	CD

18	1.8	80.2	WPDE20
36	3.6	60.4	WPDE40
54	5.4	40.6	WPDE60
91	9.0	0	WPDE100

**All numerical values in Vol %*

2.2 Characterization of fuel blend

The Fourier Transform infrared spectroscopy (FTIR) spectra were obtained utilising the Perkin Elmer Spectrum instrument (Model: Spectrum RX I) for verifying functional groups present in the fuel blends and neat diesel. The Perkin instrument is equipped with a deuterated tri-glycine sulphate (DTGS) detector. The instrument was handled in the diffuse reflectance mode at a resolution of 2 cm^{-1}in a range of 400 to 4000 cm^{-1}. The quality of the resultant fuel blends was expressed in terms of the values obtained by testing their physicochemical properties. Density, flash and fire point, viscosity, calorific value, and cetane number of fuel blends are examined in addition to FTIR analysis. American Standards for Testing Materials (ASTM) for testing of petroleum products were used to find the chemical and physical properties of fuel blends. Density was determined by using the ASTM D1298 technique, the kinematic viscosity with the ASTM D445 strategy, the calculated cetane index with the ASTM D-976 approach, the net calorific value with the ASTM D240 technique, the IKA C200-Bomb calorimeter, and the flash and fire point with the ASTM D92 technique. The obtained values were checked for repeatability and reported

2.3 Engine and Emission Tests

The engine performance is measured using an internal combustion 4-stroke, integrated electro-dynamic, single-cylinder diesel engine (Make and Model: Kirloskar TV1) with constant speed and water cooling systems. The engine testing procedure is represented by a detailed diagrammatic illustration in Fig. 1. The specifications of the engine parameter are presented in Table 2. The AVL 437 smoke meter is used to investigate the smoke (measurement range from 0 to 10 FSN Filter Smoke Number with a detection limit of 0.002 FSN or 0.02 mg/m^3). Similarly, the AVL 444 Di gas analyser (measurement range CO: 0-10 vol %; NOx: 0-5000 ppm; HC: 0-20000 ppm) is used to investigate the emission characteristics like carbon monoxide, nitrogen oxides, and unburned hydrocarbons. The readings of engine performance tests and exhaust emission tests were executed three times for the specific engine load, and the average values are presented here. Also, all the tests were done after warming up the engine at each stage. An uncertainty analysis study was conducted for the data obtained in this report based on Holman's theory. The accuracy of the instruments and uncertainty of its measurements are presented in Table 3. This study had an overall percentage of uncertainty of 2.79%.

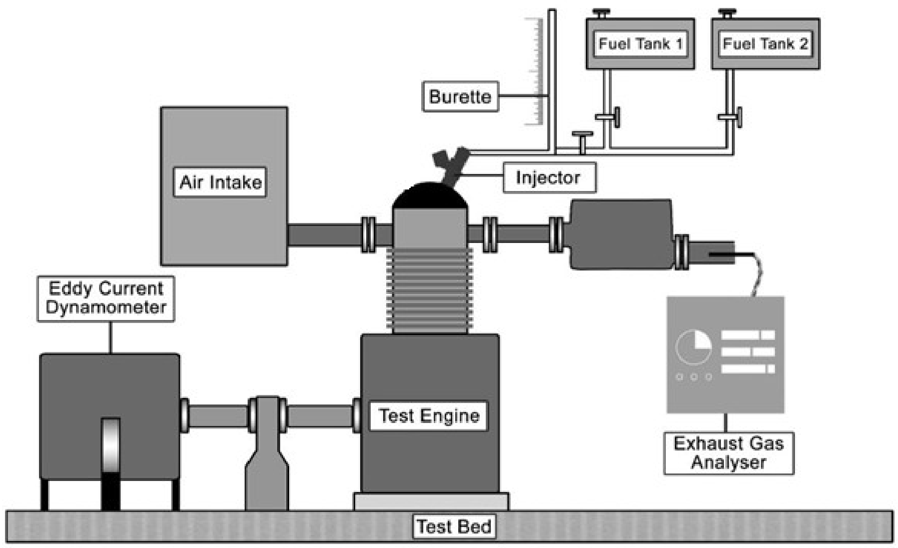


Fig. 1. Detailed schematic diagram of engine test set up

Table 2. Engine parameters and its specifications

Engine Parameters	Specifications	Units
Power	5.20	kW
Speed	1500.00	rpm
Cylinder Bore	87.50	mm
Stroke Length	110.00	mm
Connecting Rod length	234.00	mm
Compression Ratio	17.50	-
Swept volume	661.45	cc

Table 3. Instruments accuracy and uncertainty

Measurement	Instruments	Accuracy	Uncertainty
Cylinder pressure	Pressure transducer	±0.3 Kg	0.3
Exhaust gas temperature	Temperature indicator	±2° C	0.3
Speed	Speed Sensor	±10 rpm	1.0
Loading device	Load cell	±10 N	0.2
Fuel consumption	Burette	±0.2 cc	1.5
Crank angle	Crank angle encoder	±1degree	1.0
Exhaust gas analyzer	CO analyzer	±0.02%	0.2
	Unburned HC	±10 ppm	0.1
	NOxanalyzer	±12 ppm	0.2
Smoke density	Smoke meter	±1 FSN	1.0

3. RESULT AND DISCUSSION

3.1 Fuel blend properties

3.1.1 FTIR Analysis

Fig. 2 shows the FTIR spectra of the WPDE100 and commercial diesel to point out the responsible functional group present in the WPDE blends and commercial diesel. Table 4 depicts the practical gathering and compositional examination of both WPDE100 and commercial diesel fuel. When the commercial diesel is investigated using FTIR spectroscopy, the solid assimilating frequencies of 2921 and 2855 cm^{-1} of diesel fuel suggest the C-H extending frequencies of alkanes. Similar peak frequency was also obtained by Yadav et al. (2015). The tops at 1656 cm^{-1}show a location with C=C extending, indicating the existence of alkene. The height estimates of 1456 and 1378 cm-1 correspond to the C-H bending of the alkane within the power of the medium. The short and broad exceptional groups at 724 cm^{-1}correspond to C-H bending and C-H out-of-plane twisting vibrations, which denote the presence of alkanes. Similarly, when the WPDE100 is investigated using FTIR spectroscopy, the solid tops at 2954 cm-1, as well as the medium tops at 2854 cm-1, infer the C-H extending like commercial diesel (CD). The stature of 1656 cm^{-1}reacts to an alkene's C=C lengthening. C-H bending vibrations are seen in 1462 cm^{-1} and 1377 $cm^{-1}$of the particle's altered carbon chain. The similar results were also observed for transformer oil by Qasim et al. (2017). The small and broad peak at 3307 cm^{-1} and the sharp peak at 1020 cm⁻¹ were the distinct peaks that represent the WPDE as compared to the CD. The peak at 3307 cm⁻¹indicates the –OH stretching vibration of organic acid present in the WPDE blends. The sharp peak at 1020 cm⁻¹ value corresponds to the C-O vibration of ether (DEE), which was added with WPDE blends. The solid exceptional groups at 742 cm⁻¹ and 722 cm⁻¹correspond to C-H bending and C-H out-of-plane twisting vibrations, which indicate the existence of alkanes. As a result, the existence of hydrocarbon groups in WPDE100 means it is frequently used as a fuel.

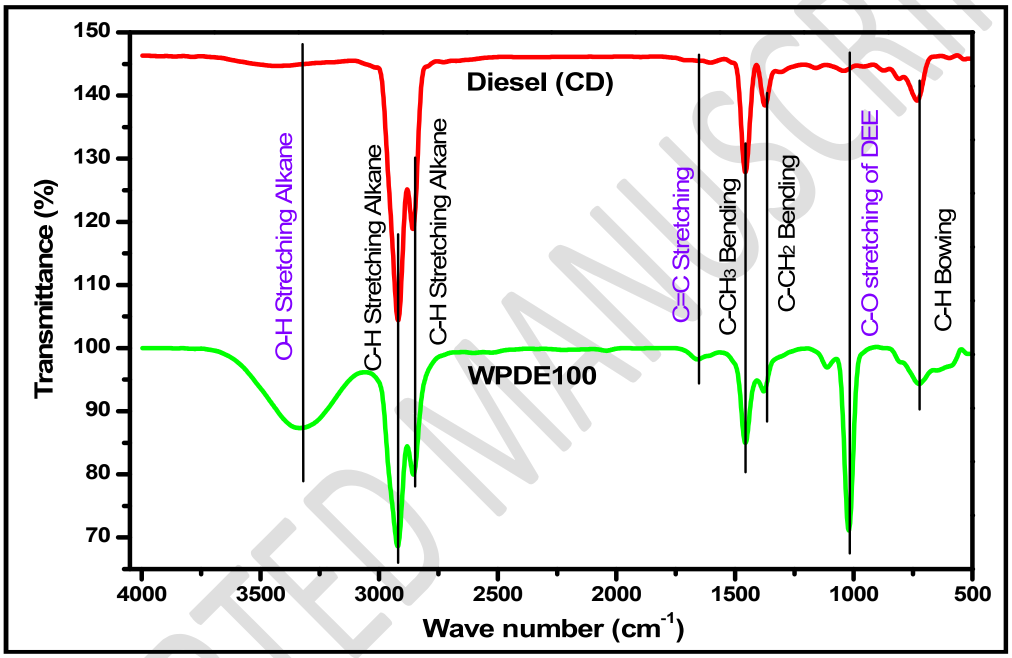


Fig. 2. FTIR Spectra of WPDE100 and Commercial Diesel (CD)

Table 4. FTIR spectrometry frequencies and its implication on functional group of Commercial Diesel and WPDE100

Commercial Diesel (CD)			WPDE100		
Frequency	**Bond Type**	**Family**	**Frequency**	**Bond Type**	**Family**
_	_	_	3307	-OH stretching	Acid
2921; 2855	C-H Stretching	Alkanes	2954; 2854	C-H Stretching	Alkanes
_	_	_	1656	C=C Stretching	Alkene

1456	C-H Bending	Alkane	1462	$C\text{-}CH_2$ Bending	Alkane
1378	C-H Bending	Alkane	1377	$C\text{-}CH_3$ Bending	Alkane
_	_	_	1020	C-O	Ether
724	C-H Bowing	Alkane	742; 722	C-H Bowing	Alkane

3.1.2 Physicochemical properties of fuel blends

The fuel properties of some important properties for commercial diesel and WPDE blends were inspected, and the acquired results are given in Table 5. The obtained density value of waste paraffin oil-blended diesel ranged from 816 to 819 kg/m³ at 15°C as compared to 835 kg/m³ at 15°C for commercial diesel. The standard value of density for commercial diesel as per ASTM D 4052 is from 815 to 845 kg/m³ at 15°C. The changes in density of WPDE20 to WPDE60 are due to composition variation of waste paraffin oil. Compared with WPDE60, the fuel blend WPDE20 shows higher density because waste paraffin oil, which has the value of low density, is present in higher amounts at WPDE60. The kinematic viscosity of the resultant WPDE blends was estimated as 2.26 mm²/s (centistoke) at 40°C for WPDE20, 2.24 mm²/s at 40°C for WPDE40, and 2.23 mm²/s at 40°C for WPDE60. Similarly, the kinematic viscosity of the commercial diesel was measured as 2.2 $mm^2\ s^{-1}$ at 40 °C. As the viscosity of the resultant WPDE blends is almost close to the commercial diesel. Hence, no need to carry out design modification in the present diesel engines. From the literature, it shows that poor ignition and poor atomisation may be due to the higher value of viscosity (Murugesan et al. 2009).The calorific value of the WPDE blends and CD are also reported in Table 5. The grass calorific value of the WPDE blends was measured as 39159 kJ/kg K, 39741 kJ/kg K, and 39803 kJ/kg K for WPDE20, WPDE40, and WPDE60, respectively. Whereas the grass calorific value of the commercial diesel was measured as 42460 kJ/kg K. The calculated cetane index of commercial diesel is reported as 50. As per the automotive diesel fuel specification (IS 1460–2017), the value should be 46 minimum. The calculated cetane index of the WPDE blends was higher than the minimum requirement specified by IS 1460–2017, also by commercial diesel. This increasing trend may be due to the presence of DEE and the paraffinic nature of waste transformer oil. The WPDE blends showed a flash point value in the range of 78 to 92 ºC, whereas the flash point of commercial diesel measured as 62 ºC. As per the automotive diesel fuel specification (IS 1460 – 2017) the minimum prerequisite of flash point for commercial diesel is ≥ 66 °C. From the above result, it is indicated that WPDE blends can be handled safely while transporting and storing. The similar trend was observed for fire point also.

Table 5. Properties of WPDE Blends and commercial Diesel

Properties	Units	WPDE20	WPDE40	WPDE60	Diesel (CD)
Density at 15 °C	kg/m^3	819	818	816	835
Kinematic viscosity at 40 °C	Cst	2.26	2.24	2.23	2.2
Gross calorific value	kJ/kg K	39159	39741	39803	42460
Calculated cetane no.	-	57.6	58.12	59.0	50.0
Flash Point	°C	92	83	78	68
Fire Point	°C	100	89	85	74

3.2 *Engine Performance*

3.2.1Break Specific Fuel Consumption

Calorific value of the fuel and fuel consumption of the engine are the two important factors to judge the performance of the engine (Vedharaj et al. 2013). Fig. 3.shows the relationship between the total brake-specific fuel consumption (BSFC) of WPDE blends and diesel (CD) for varying IC engine loads. In general, fuel consumption of the engine reduces steadily as load increases. The similar trend noticed by Prasanna Raj Yadav et al. for catalytically cracked waste transformer oil (Yadav et al. 2015). The similar observations were noticed in this study also. The volume of fuel injected and the viscosity of fuels are the influencing factors that affect specific fuel consumption. The commercial diesel has a brake-specific fuel consumption of 0.88 kg/kWh at minimum load conditions and 0.34 kg/kWh at the highest loading condition. The resembling trend was observed for the WPED20 blend. At full load conditions, the BSFC figures for WPDE40 and WPDE60 blends are 0.31 kg/kWh and 0.32 kg/kWh, respectively. The similar results obtained by Senthil et al. (2016) for the specific fuel consumption of transformer oil. WPDE60 blend has 8.82% lower specific fuel consumption than commercial diesel. The reason for the higher BSFC of the blend compared to the CD may be due to the combination of factors such as calorific value, density, viscosity, and presence of DEE. The same reasons were pointed out for the lower BSFC of commercial diesel compared to biodiesel and its blends study.

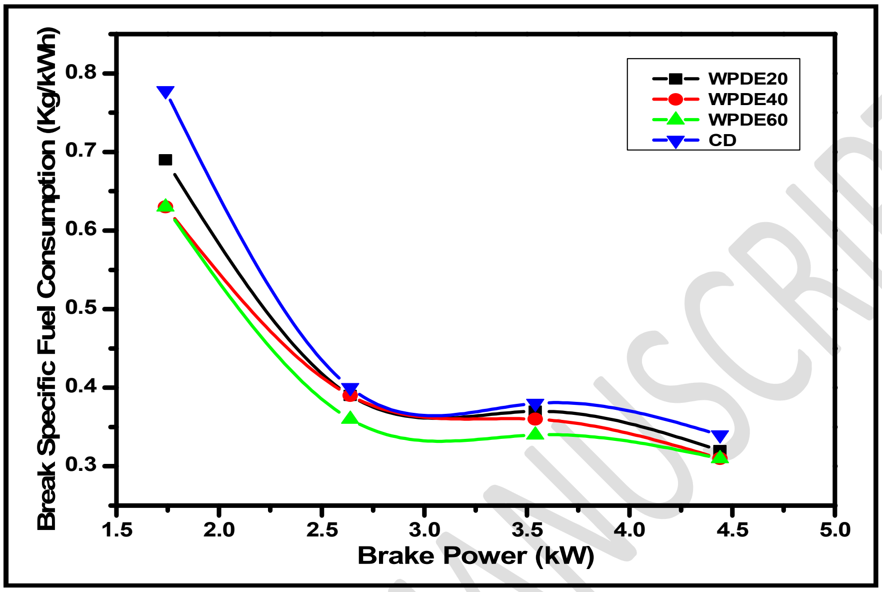


Fig. 3. Differences Brake specific fuel consumption with varying brake power for WPDE20, WPDE40, WPDE60 and CD

3.2.2 Break Thermal Efficiency

Fig. 4 illustrates the Brake Thermal Efficiency (BTE) of WPDE20, WPDE40, WPDE60, and diesel (CD) under various engine load conditions. The reduced specific fuel consumption of WPDE blend over the CD clearly showed the marginal improvement in brake thermal efficiency (BTE), especially for WPDE40 and WPDE60. Brake thermal efficiency is correlated with compression ratio because it reduces losses of energy and increases the power of greater loads (Pramod et al. 2021). In response to a load, the brake thermal efficiency progressively increases with raising engine load. There was a lower thermal efficiency for WPDE20 blends compared to diesel that was probably due to the lower calorific value, high viscosity, and low air–fuel mixing of WPDE blends. WPDE and its blends (WPDE20, WPDE40, WPDE60, and CD100) have BTEs of 24.89 percent, 26.7 percent, 27.83 percent, and 25.7 percent for a 100% load, respectively. The brake thermal efficiency of commercial diesel increases from 15.5% for lower engine loads to the maximum of 25.7% for high engine loads. Similarly, the BTE of WPDE60 varied from 17.02% to the maximum of 27.83% for high load. From the data, it was observed that an 8.29 percent increase in BTE was observed for the blend WPDE60 at peak load when compared to the neat diesel. It might be attributed to more oxygen presence (DEE) in the WPDE60 blend. This in turn increases the rate of burning. Further, high engine loads promote DEE evaporation and mixing, because the air is hottest at this stage. WPDE20 blend has 10.56% lower break thermal efficiency compared to CD. Reduction in fuel density and viscosity (Table 4) is also another factor that favours WPDE60 as superior to commercial diesel. The similar reasons are also observed by earlier literature for the improved brake thermal efficiency. From this interpretation, it is known that WPDE60 is an appropriate alternate fuel for diesel engines (Asokan et al. 2018).

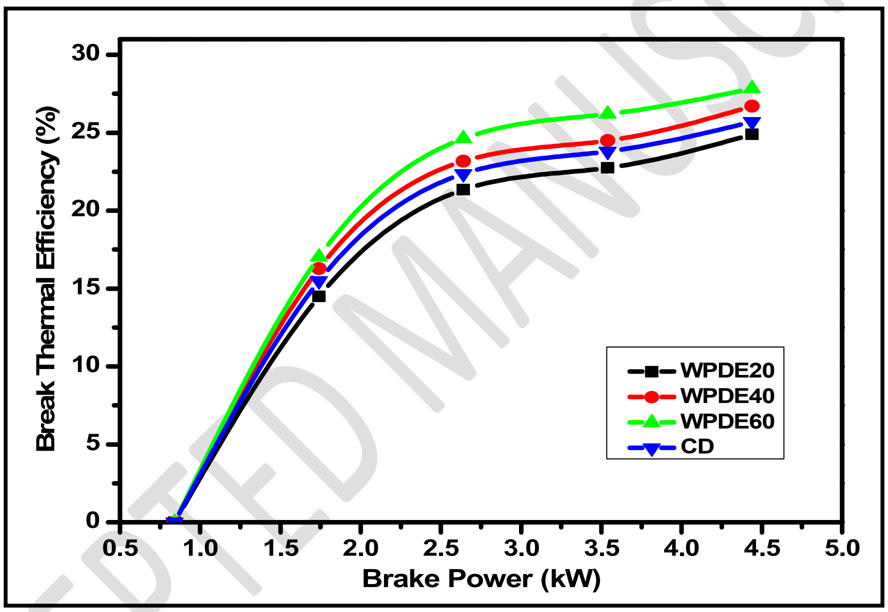


Fig. 4. Variations in Brake Thermal Efficiency against brake power for WPDE20, WPDE40, WPDE60 and CD

3.2.3 Rate of Heat Release

The combustion characteristics of any CI engine are manipulated by numerous factors like operating conditions of the engine, properties of fuel, design of combustion chamber, and injection timing. Heat release rate and in-cylinder pressure are the two combustion characteristics that play a crucial role in studying the combustion process. Fig. 5 depicts the rate of heat release of WPDE blends and neat diesel with regard to crank angle. During fuel combustion, the rate of heat release curve assists in determining how much energy can be turned into output. The maximum amounts of heat released for WPDE20, WPDE40, WPDE60, and diesel are 106.2677 J/CAD, 111.3697 J/CAD, 127.52058 J/CAD, and 128.4839 J/CAD, respectively. When compared to WPDE blends, the heat emitted by diesel (128.4839 J/CAD) is greater. The maximum heat release rate is achieved among the blended fuels is WPDE60 (127.52058 J/CAD). In comparison with other blends, the WPDE60 and diesel mixture exhibit minor variances with considerable heat release. The rate of heat release peak for WPDE20, WPDE40, and WPDE60 is nearly identical to that for diesel at maximum loads. WPDE40 produces a somewhat lower rate of heat release than diesel; this may be attributed to flow ability and inadequate spray characteristics of fuel (Vallinayagam et al. 2013). The heat release rate of WPDE60 is 0.75% lower as compared to CD. According to (Pandian B et al 224), this may be due to the presence of enough oxygen in the fuel blend (DEE) to enable combustion to occur more effectively. Calorific value, density, and viscosity of WPDE60 are also responsible for this promotion in the combustion process.

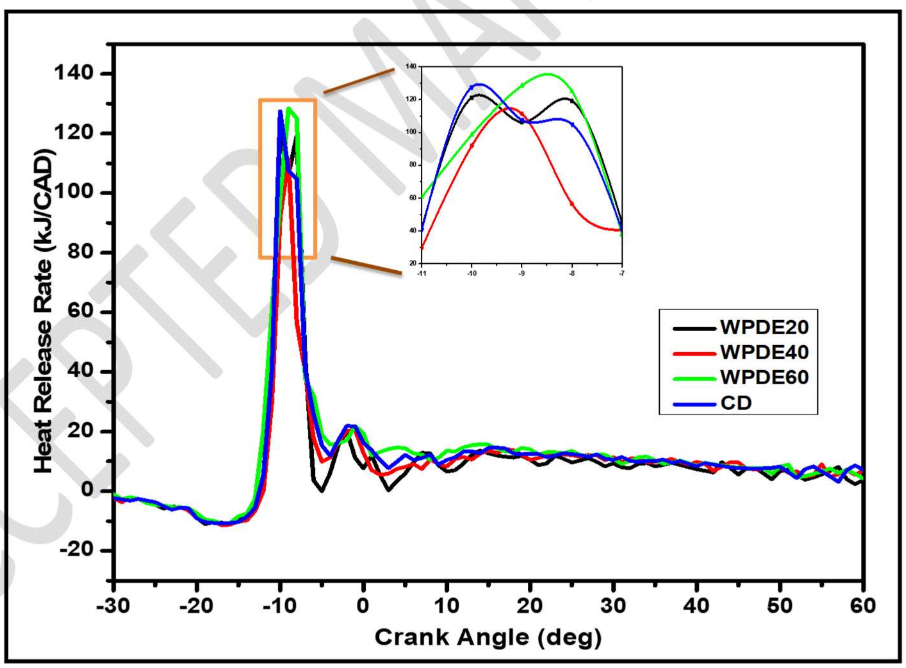


Fig. 5. Heat release rate with varying crank angle for WPDE20, WPDE40, WPDE60 and CD

3.2.3 Cylinder Pressure and Crank Angle.

Fig. 6 depicts cylinder pressure versus crank angle for commercial diesel and various WPDE blends at full load. WPDE blends follow the same trends as diesel follows for almost all the engine load conditions. It may be inferred from Fig. 7 that, with an increase in the thermally cracked transformer oil portion in the blend, in-cylinder pressure peak increases from WPDE20 to WPDE60. Further, WPDE20, WPDE40, WPDE60, and CD have a maximum cylinder pressure, respectively, of 57.63 bar, 59.02 bar, 66.30 bar, and 63.61 bar. The diesel engine has a cylinder pressure of 63.61 bars, just below the cylinder pressure of WPDE60 at full load conditions. It costs about 4.3 percent more than commercial diesel. Among WPDE blends, the WPDE60 attained the highest pressure (6 degrees after TDC). From Table 4, it was learnt that the calorific value of the WPDE60 is relatively comparable to the diesel; there is no difficulty in the release of energy. Furthermore, the viscosity and density value of the WPDE60 is more advantageous to better combustion. Hence, WPDE60 is reported to have higher in-cylinder pressure than commercial diesel. Same outcomes were also reported by Senthil et al. (2018) for the fuel and engine characterisation study of catalytically cracked waste transformer oil.

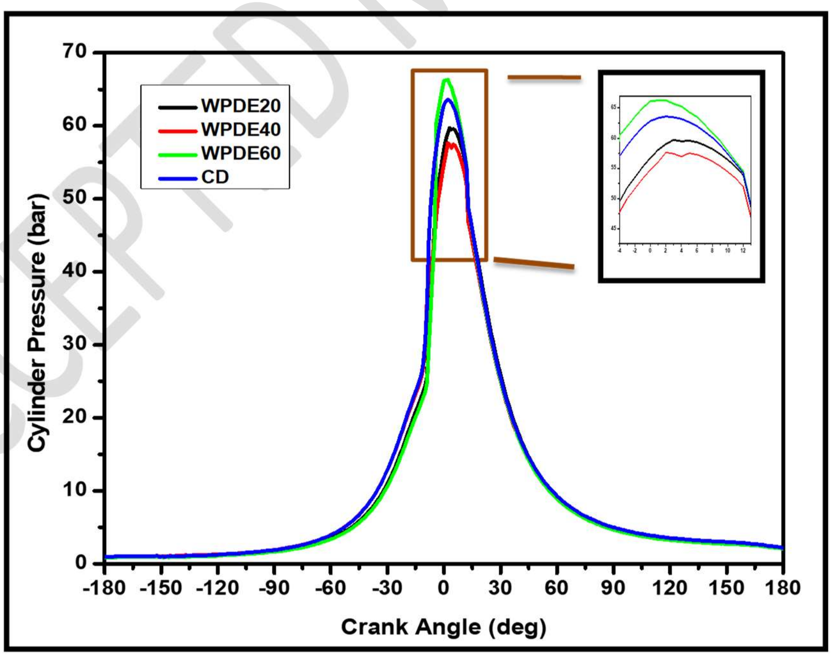


Fig. 6. Variation of in-cylinder pressure with crank angle for WPDE20, WPDE40, WPDE60 and CD

3.3 *Emission Analysis*

3.3.1. Unburned Hydro-carbon

Fig. 7 illustrates the unburned hydrocarbon emissions of WPDE20, WPDE40, WPDE60, and diesel (CD) under different engine load conditions. As per Rajan et al. (2020), hydrocarbon emissions are produced when fuel is unburnt or only partially burned. Inefficient combustion and lower cylinder temperature are the prime reasons for this unburned hydrocarbon generation. It may be noticed from Fig. 7 that increases in engine load increase the unburned hydrocarbon emissions. The WPDE40 and WPDE60 emit less hydrocarbon emission at higher loads compared to the WPDE20 and CD. At full load, the unburned hydrocarbon levels for WPDE20, WPDE40, WPDE60, and diesel are 12 ppm, 10 ppm, 9 ppm, and 11 ppm, respectively. Without any engine modification, the blend WPDE 40 and WPDE 60 emitted 9.09% and 18.82% fewer unburned hydrocarbons than the diesel at maximum loading. The reason may be due to the enhanced fuel properties of WPDE60. Other blends, namely WPDE 20, have a 25% greater hydrocarbon emission value than the WPDE 60 blend and 9.1% higher emissions than commercial diesel. The result obtained in this study very well matches with the heat release rate of WPDE60 than WPDE40 and WPDE20. Because a high rate of heat release due to the complete combustion results in lower unburned hydrocarbon emissions. The similar trend noticed by Prasanna Raj Yadav et al. for the analysis of the emission study on the catalytically cracked transformer oil blend with diesel.

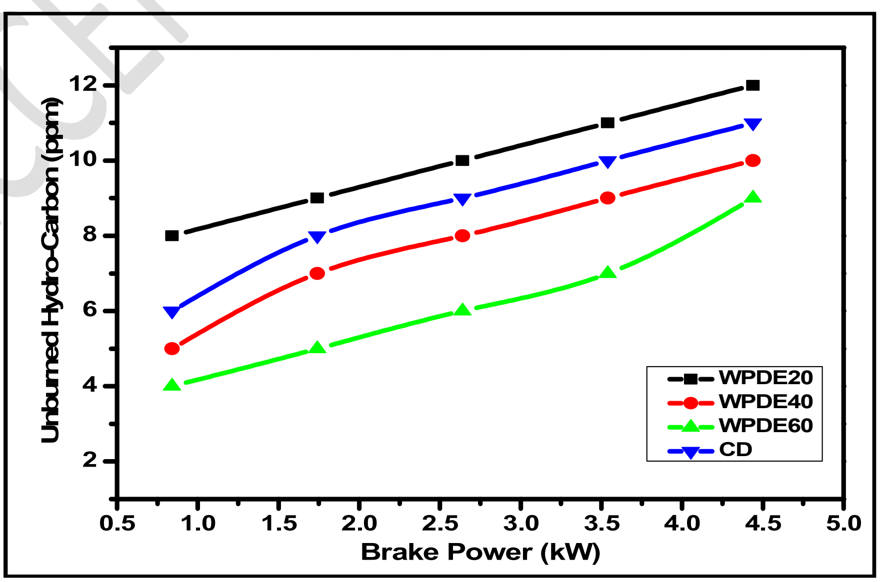


Fig. 7. Variations in emissions of unburned hydrocarbon against engine load for WPDE20, WPDE40, WPDE60 and CD

3.3.2. Carbon Monoxide

At various load conditions, the percentage of carbon monoxide emissions for WPDE blends and diesel can be seen in Fig. 8. Carbon monoxide is produced during combustion when there is an insufficient supply of oxygen. The significant factors responsible for the CO emissions include the air:fuel ratio, the physico-chemical properties of the fuel, and the atomisation of the CI engine. As noticed in Fig. 8, the trend shows that decreasing the carbon monoxide emission when increasing the load conditions from zero load to full load. The emission of carbon monoxide at 100 percent load for WPDE20, WPDE40, WPDE60, and Diesel is 0.04%, 0.03%, 0.02%, and 0.05%, respectively. WPDE20 blends emit a closer value of carbon monoxide emission compared to diesel. The WPDE60 blends release the least amount of carbon monoxide, about 4.9%, compared to the neat diesel. The WPDE60 blends suggest that they are the least polluting of carbon monoxide among the WPDE blends. The current findings are consistent with those of previous researchers (Paramvir Singh et al. 2019).The reason for the reduced CO emission forWPDE60 may be due to enhanced combustion processes, reduced fuel density, and the presence of oxygenated compounds (DEE). In addition, higher heat-release rates and in-cylinder pressure also contribute to the promotion of combustion, thereby reducing carbon monoxide emissions.

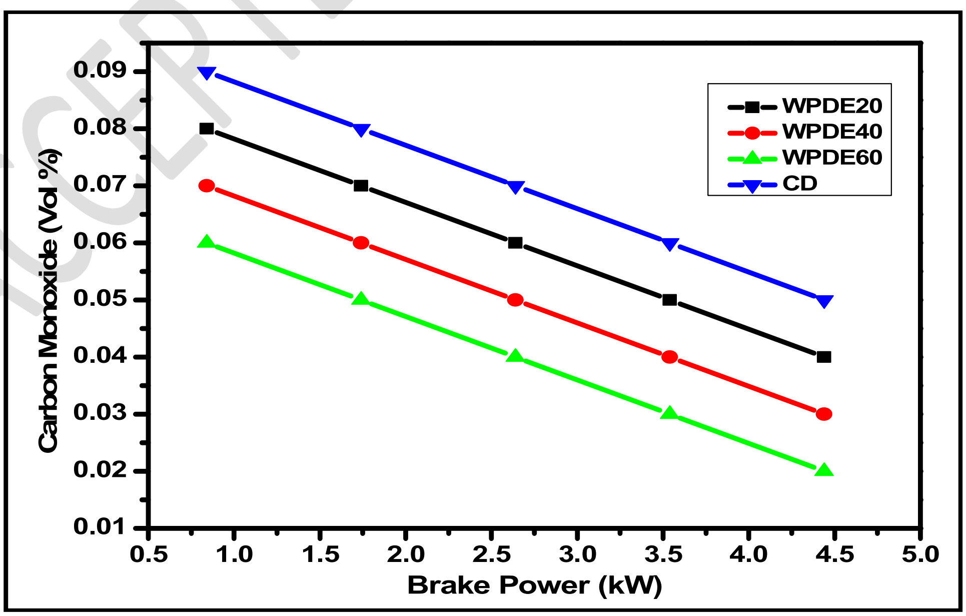


Fig. 8. Variations in emissions of carbon monoxide against engine load for WPDE20, WPDE40, WPDE60 and CD

3.3.3 Oxides of Nitrogen

Fig. 9 illustrates the variation of nitrogen oxide (NOx) emissions for WPDE20, WPDE40, WPDE60, and CD at various engine load conditions. According to the literature (Vendaraman et al. 2011), the NOx emission is mainly influenced by higher fuel residence time and surplus oxygen presence in the combustion chamber. Higher NOx release was observed for WPDE20, WPDE40, and WPDE60 than commercial diesel (CD) for almost all loading conditions. Nitrogen oxide concentrations at 100% loading for WPDE20, WPDE40, WPDE60, and CD are 173 ppm, 160 ppm, 150 ppm, and 145 ppm, respectively. At full load conditions, the increased NOx emissions compared to CD are 16.18%, 9.35%, and 3.3% for WPDE20, WPDE40, and WPDE60, respectively. Nitrogen oxides are produced more frequently with WPDE blends because of the substantial oxygen component. From the literature (Teoh et al. 2020), increasing braking power increases the temperature of combustion gas, which might increase NOx emissions per kWh. In addition, the increased in-cylinder temperature due to complete combustion dissociates more diatomic nitrogen into monoatomic nitrogen, which generates more NOx. Further, an increased amount of oxygen in the combustion chamber owing to the presence of DEE is also responsible for the higher NOx emission. Similar results trends were observed for most of the biodiesel-blended samples with diesel (Harigaran et al. 2023).

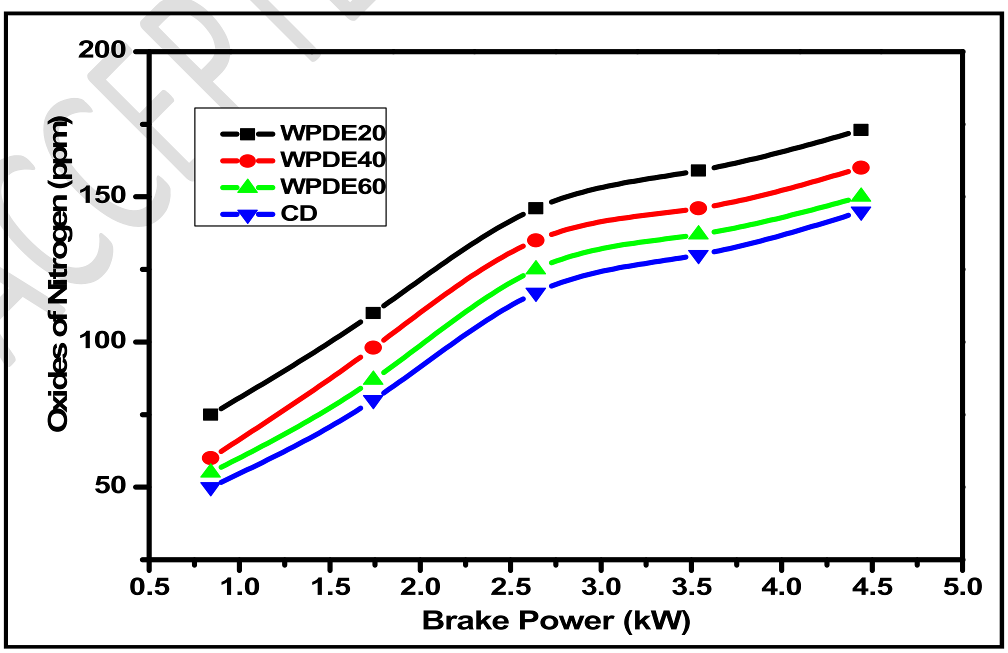


Fig. 9. Variations in oxides of nitrogen emissions against engine load for WPDE20, WPDE40, WPDE60 and CD

3.3.4. Smoke Density

The differences in smoke density at different loads for various WPDE blends and diesel are displayed in Fig. 10. The amount of oxygen present in fuel is the most important component controlling smoke density. Generally, smoke density and NOx emission analysis in CI engines are expected to work differently. That means, when there is an increase in NOx emissions for a particular engine, the smoke density emissions are expected to decrease (Zhang,Y et al. 2022). The similar trend was observed in this current study also. At full load condition, the smoke emissions from WPDE20, WPDE40, WPDE60, and diesel are 35.3 HSU, 32.6 HSU, 30.2 HSU, and 56 HSU, respectively. In the case of WPDE60, smoke density decreased by approximately 39.6 percent when compared to CD without any engine modification. Similarly, in the case of WPDE20 and WPDE40, smoke density decreased by roughly 32.5 percent and 34.8 percent, respectively. At full load, all WPDE blends released less smoke density than diesel, which may be caused by the presence of oxygen, which leads to breaking down the heavier hydrocarbon component of the WPDE blend. Further, oxygen molecules are believed to have permeated the fuel droplet, causing the soot within it to be oxidised to decrease the smoke emission (Ghiassi et al. 2016).

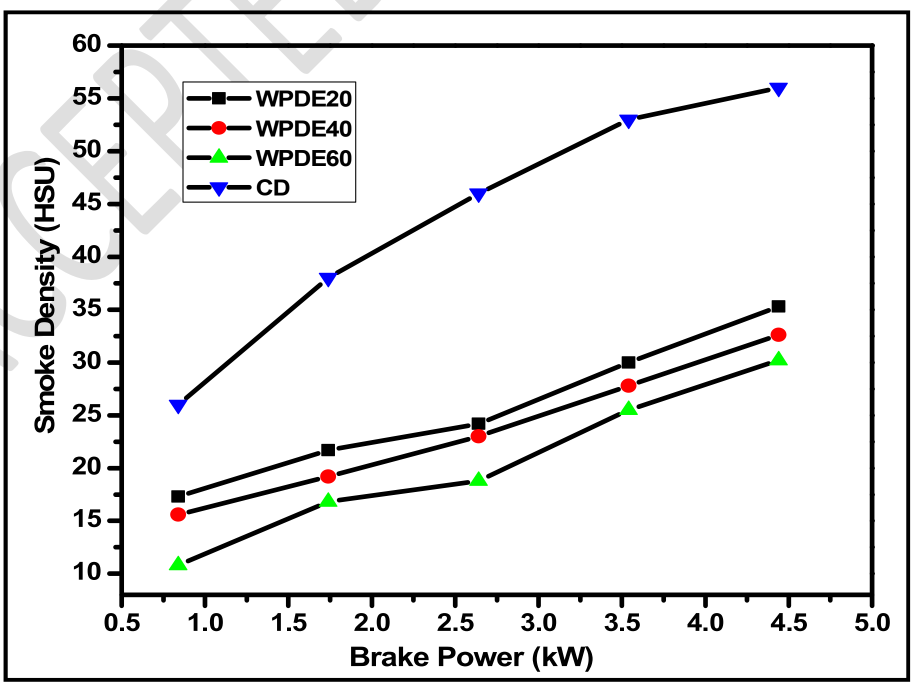


Fig. 10. Variations in smoke density against engine load for WPDE20, WPDE40, and WPDE60 CD

4. CONCLUSIONS

In this research study, a sincere effort has been made to utilise waste transformer oil, which has paraffinic hydrocarbons in nature, as a feasible alternate fuel source for a diesel engine, which would otherwise be disposed of as a waste product and harm the environment. From the current data obtained from this investigation, the combustion, performance, and emission characteristics of the diesel engine are summarised as follows:

- When considering specific fuel consumption. Among the WPDE20, WPDE40, and WPDE60 blends, the WPDE60 blend is lowered by 8.82% compared to CD at full load conditions. Hence, WPDE60 blend is considered the most efficient blend. The blend WPDE60 provides high brake thermal efficiency (27.83%) at peak load, compared to WPDE20, WPDE40, and commercial diesel, which have lower brake thermal efficiencies of 24.89%, 26.7%, and 25.7%, respectively. About an 8.29 percent increase in BTE was observed for the blend WPDE60 at peak load when compared to the neat diesel.
- As far as the rate of heat release is concerned, there is no notable difference between WPDE60 and diesel at maximum loads compared to other blends. At maximal load conditions, in-cylinder pressure peak was found to be raised by 4.3% with the WPDE60 blend when collated with diesel. The exhaust emissions, such as unburned hydrocarbons, carbon monoxide, and smoke density, have been reduced by 18.82%, 4.9%, and 39.6%, respectively, when compared to commercial diesel, at full load conditions.
- Whereas, at maximal load condition, NOx emissions were increased by 3.3% when compared to neat diesel. Finally, it is concluded that WPDE60 blend can be effectively used as an alternate fuel for commercial diesel without modifying engine configuration. Highlighting point in this work that waste disposal of transformer oil has been effectively managed and efficiently used.

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Competing Interest

There are no any conflicts of interest, according to the authors.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analysed in this research work

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