J Braz. Soc. Mech. Sci. Eng. (2017) 39:19–28
DOI 10.1007/s40430-016-0518-6

TECHNICAL PAPER

Investigation on performance, emission and combustion characteristics of variable compression engine fuelled with diesel, waste plastics oil blends

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Received: 9 December 2015 / Accepted: 26 February 2016 / Published online: 11 March 2016

Abstract Presently plastics are major contributors in solid waste which has higher thermal energy. Waste plastics can be converted into alternate fuel by pyrolysis which can replace diesel in compression ignition engines. The present study deals with the performance, combustion and emission characteristics of variable compression ratio engine fuelled with plastic oil, diesel and its blends with diethyl ether as an additive. Three blends 2.5, 7.5 and 12.5 % were tested in variable compression ratio engine. Waste plastic oil blend, pure plastic oil and diesel were considered for comparison. This study reveals that brake thermal efficiency increases for all the blends when compression ratio increases from 12 to 20. The specific fuel consumption of the blends and plastic oil were higher than the diesel. But the brake thermal efficiency for all the blends, plastic oil was comparatively lower than that of diesel. The regulated emissions of the variable compression ratio engine under varying loads and compression ratio for different blends were discussed.

Keywords VCR engine · Waste plastic oil · Diethyl ether · Performance · Emission

Technical Editor: Luis Fernando Figueira da Silva.

Electronic supplementary material The online version of this article (doi:10.1007/s40430-016-0518-6) contains supplementary material, which is available to authorized users.

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Abbreviations

BTHE	Brake thermal efficiency (%)
CO	Carbon monoxide (% vol.)
CO_2	Carbon dioxide (% vol.)
HC	Hydrocarbons (ppm)
NOx	Oxides of nitrogen (ppm)
SFC	Specific fuel consumption (kg/kWh)
aTDC	After top dead centre
bTDC	Before top dead centre
ACP	Averaged cylinder pressure
ASTM	American society for testing and materials
CA	Crank angle
CLD	Chemi luminescence detector
CR	Compression ratio
DEE	Di ethyl ether
FID	Flame ionization detector
NDIR	Nondispersive infrared sensor
PPM	Parts per million
RHR	Rate of heat release
VCR	Variable compression ratio
Vol.	Volume
WPO	Waste plastic oil

1 Introduction

Availability of fuel to all segments of society at a reasonable price is essential for development. Various researches are ongoing to find alternate fuels petroleum products. Due to the higher heating value, waste plastics are one of the most promising sources for alternate fuel production. The properties of the oil derived from waste plastics have properties similar to that of diesel. Studies were conducted on various edible and non-edible oils and its blends to find the combustion, performance and emission characteristics of compression ignition (CI) engines.

Polymer oil obtained from the plastic waste was used as a fuel in single cylinder diesel engine without any engine modification. The performance and the emission of the polymer oil, polymer oil blends were compared to baseline results of diesel. The experimental result showed that the carbon monoxide (CO), oxides of nitrogen (NOx) and smoke were significantly reduced for polymer oil blends. Unburned hydrocarbon (HC), brake specific fuel consumption (SFC) and brake thermal efficiency (BTHE) were found to have increased with polymer oil methanol blends [1].

A research established that the compression ignition engine could operate with 100 % waste plastic oil (WPO) and can be used as fuel in diesel engines. NOx emission was higher by about 25 % for WPO compared to diesel. It is also observed that engine fueled with WPO exhibits higher thermal efficiency up to 80 % of the load, the exhaust gas temperature was higher than diesel [2]. The toxic gas CO emission of WPO was higher than diesel. Smoke reduced by about 40–50 % in WPO at all loads [3].

The impact of WPO on the performance and emission characteristics of CI engine at varying load conditions was investigated. The experimental results showed that mechanical efficiency increases with increasing brake power for all fuel blends. The blends of WPO with diesel and varying engine load were found to have significant influences on the NOx, HC, CO and carbon dioxide (CO_2) emissions. The NOx emission increases with increase in percentage of WPO in blends and decreases with increase in engine load. The hydrocarbon emission was also decreasing with increase in the engine load [4].

Biodiesel derived from non-edible karanja oil was used as alternative fuel in a diesel engine. Performance of the engine with karanja biodiesel and its blends with diesel was generally comparable. The engine gave better performance with lower emission at high compression ratio (CR). It was also observed that the engine was operating smoother at higher compression ratios [5].

Due to high viscosity and carbon residue, use of vegetable oils in diesel engine results in inferior performance and increased smoke emission. This can be avoided by injecting a small quantity of diethyl ether (DEE) along with air. HC and CO emissions were also reduced due to DEE injection. But rate of heat release indicates an increase in the combustion rate due to the reduced ignition delay and combustion duration with DEE [6]. DEE was added with WPO and tested with single cylinder diesel engine without any modification. This research results showed that addition of DEE with WPO reduced the viscosity and supports atomization of fuel [7].

Another fuel additive cerium oxide and carbon nanotubes were used with diesel–biodiesel–ethanol blends in variable compression ratio (VCR) engine. It was noted that burning rate was accelerated by the catalyst carbon nanotubes which leads to decreased ignition delay and lower heat rate. Use of cerium oxide reduced NOx and oxidized CO resulted lower emissions [8].

A comparative study was conducted with VCR engine fuelled with diesel and Marula oil fuel under various CR at a fixed load of 80 %. The study revealed that CR 16:1 was optimum for engine torque and break power [9]. Another research was conducted in VCR engine with Tamanu oil and diesel by changing CR from 14 to 18. It was observed that BTHE increases for higher loads [10, 11].

The effect of four injection timings on performance, emission and combustion characteristics of CI engine fuelled with WPO was investigated. The results were compared with standard injection timing. This study revealed that the injection timing 14° before TDC decreases NOx, CO and HC while BTHE increases [12].

Pure biodiesel derived from Jatropha, diesel and its blends were fed to CI engine to compare the performance and emissions. It was noted that BTHE decreases with increment in biodiesel blend. The maximum efficiencies were recorded as 21.2 and 29.6 % for pure biodiesel and diesel respectively [13].

Rice bran oil methyl ester blends were used in direct injection CI engine to study the performance and emissions. The findings showed reduction in CO, HC and particulate matter with increase in NOx. BTHE was lower compared to the diesel [14].

Alcohol diesel blends like Diesel-E85 and Diesel–Methanol were tested in CI engine. During combustion two peaks were reported in the rate of heat release curves. This research established that fuel injection timing should be corrected if Alcohol-Diesel blends used in direct injection CI engines [15].

Used transformer oil (UTO) can be used as fuel for CI engine as it has required hydrocarbons and heating value. This was blended with diesel tested for combustion, performance and emission characteristics. The optimum blend was identified as UTO40 (40 % UTO). For UTO blends and UTO the emissions of HC and CO were comparatively higher than diesel [16].

Diesel like fuel was distilled from waste engine lubrication oil and compared with diesel for combustion, performance and emission in a CI engine. The results showed that torque, brake mean effective pressure and BTHE were higher than diesel but SFC was lower [17].

Based on the earlier research it is learned that non edible oil and waste oils were used to produce biodiesel. In few investigations additives like diethyl ether, alcohol and cerium oxide were used to improve the combustion characteristics. A good number of research works has been carried with fixed CR without any engine modification. In the current investigation an effort has been made to study the combustion, performance and emission characteristics of waste plastic oil-diesel blends with DEE as fuel additive in a VCR engine for three different compression ratios.

2 Experimental setup and methodology

2.1 Extraction of waste plastic oil

Figure 1 shows the extraction process of waste plastic oil by pyrolysis method. Waste plastic mainly consists of polyethylene terephthalate, high density polyethylene, low density polyethylene, polystyrene, polypropylene and polyvinyl chloride etc. These waste plastic are crushed into small pallets and supplied to the reactor for thermal degradation. In the absence of air these waste plastics were heated to the range of 300–900 °C where plastic vapor is formed. The outlet gas from the pyrolysis reactor was condensed into series of water cooled condenser and the liquid obtained was taken as fuel for the experiment. The other un-condensable gases were sent out into the atmosphere.

On volume basis 2.5, 7.5 and 12.5 % waste plastic oil was blended with diesel to form P2.5, P7.5, P12.5 blends respectively. Diethyl ether (2.5 % by volume) was added with these blends to improve the combustion. P100 represents the 100 % waste plastic oil. The properties of the tested fuels are listed in Table 1.

2.2 Experimental setup

The actual picture of the engine setup is shown in Fig. 2. A single cylinder four stroke variable compression ratio engine was used for the experimentation. The compression ratio was changed by varying clearance volume of the cylinder by a lever. The VCR engine has water cooling arrangement. The exhaust gas was sent through a shell and tube heat exchanger which acts as a calorimeter for exhaust gas. The exhaust pipe has a 45° tapping to measure the regulated emissions using AVL DI 444 exhaust gas analyser and AVL437C smoke meter.

To measure the combustion pressure, crank angle a piezoelectric pressure sensor was fitted in the cylinder head

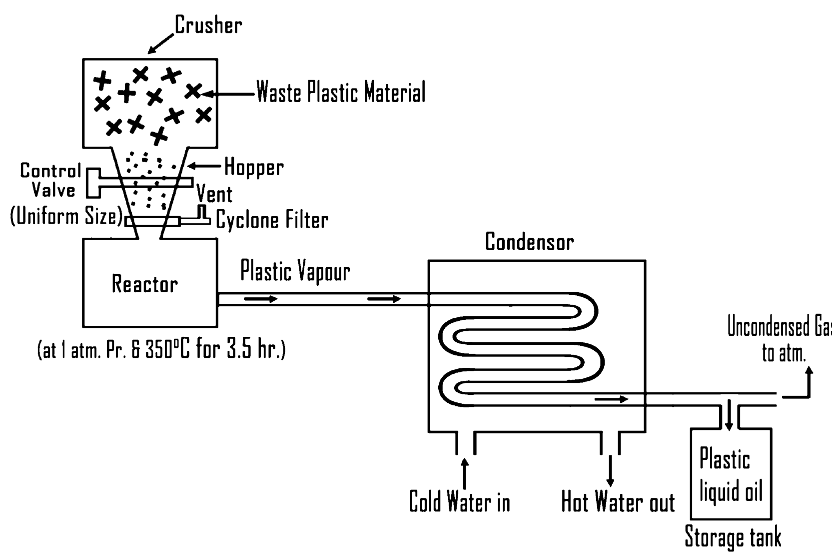

Fig. 1 Schematic diagram of production of fuel from waste plastic

Table 1 Properties of diesel fuel, blended oil and plastic oil-diethyl ether

S. no.	Fuel	Properties					
		Density (kg/m^3) (ASTM D1298)	Calorific value (MJ/kg) (ASTM D6751)	Flash point (°C) (ASTM D93)	Fire point (°C) (ASTM D93)	Kinematic viscosity 10^{-6} (m^2/s) (ASTM D445)	Cetane number (ASTM D7668-14a)
1	Diesel	840	44.8	50	56	2	42
2	P2.5	831	44.414	49	55	1.568	42.51
3	P7.5	824	44.091	48	54	1.79	43.03
4	P12.5	819	43.868	47	53	1.92	43.61
5	P100	790	43.340	42	45	2.52	51
6	DEE (additive)	714	33.857	−40	−41	0.23	126

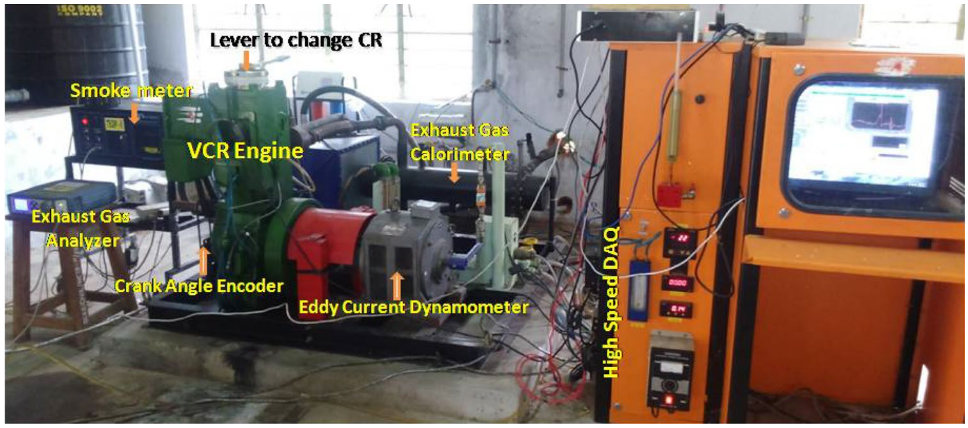

Fig. 2 Actual photographic view of test engine

Table 2 Specifications of the experimental setup

S. no.	Description	Parts with specification
1	Variable Compression Ratio engine	Model: CVCR, Single cylinder, diesel, 4-stroke, water-cooled, stroke 110 mm, bore 80 mm, Manual Crank Start, Forced Lubrication
2	Power	2.237–3.728 kW
3	Speed	1450–1550 rpm
4	Injection timing	23° CA before TDC
5	Maximum Load	10 kg
6	Injection pressure	200 bar
7	Compression ratio range	6:1–20:1
8	Piston bowl shape	Hemispherical
9	Lubrication oil	SAE 20W40
10	Dynamometer	Type: eddy current, air cooled with loading unit
11	Load measurement	Direct coupling, strain gauge, manual loading
12	Exhaust Gas Calorimeter	Type shell and tube, *K* type thermocouple, water cooling
13	Exhaust gas analyser	Model—AVL DI 444
14	Smoke meter	Model—AVL437C
15	Pressure sensor	Type: piezoelectric

and an encoder was fixed with timing gear. A computer with high speed data acquisition system was used to record the data like cylinder pressure, temperature, rate of heat release, load and all other temperatures at salient points. The specifications of the instruments used in experimental setup are given in Table 2.

2.3 Operating procedure

VCR engine was allowed to run with diesel for 15 min to precondition the experimental setup. The cooling water was allowed at constant rate of 60 ml/s. As a standard procedure, before changing any fuel blends the engine was operated 7–10 min to stabilize. The fuel was delivered by a fuel injection pump with the initial fuel delivery starting at 23° before TDC and injection pressure was maintained at 200 bar.

The standard data was recorded for the compression ratio of 16:1 at a rated speed of 1500 rpm with diesel. The data recorded were used as baseline data for comparison with waste plastic oil and blends. The compression ratio was changed as 12, 16 and 20 by changing the clearance volume of the VCR engine. A lever is provided in the VCR engine cylinder head with measurements to change the compression ratio. An eddy current dynamometer with a load cell was used to load the engine.

In each test, the speed of the engine, manometer readings, exhaust gas emissions such as smoke opacity, carbon monoxide, hydrocarbon, oxides of nitrogen, and carbon dioxide were recorded. From the observed measurements mass of fuel consumption, brake power, indicated power, brake thermal efficiency and specific fuel consumption were calculated. For each operating condition the performance, combustion characteristics and exhaust emission levels were measured.

The load, compression ratio, blends P2.5, P7.5, P12.5 and waste plastic oil was changed as per planned design of experiments (DOE) and experimental data was recorded following the above said procedure. Table 3 lists the experiments conducted as per full factorial design.

2.4 Error and uncertainty analysis

The measured quantity, measuring range, resolution, percentage uncertainties, measurement techniques and accuracy of the instruments used are given in Table 4. The experimental uncertainty, instrumental error, environmental condition, parallax error were also taken into account during the analysis.

The experimental accuracy was estimated by uncertainty analysis. The various parameters such as specific fuel consumption, brake thermal efficiency, carbon monoxide,

Table 3 Design of experiments

S. no.	Compression ratio	Load (kg)	Fuel
1	12	0	Diesel
2	16	2.5	P2.5 + DEE
3	20	5	P7.5 + DEE
4	–	7.5	P12.5 + DEE
5	–	10	WPO

smoke opacity, etc., were calculated using the percentage uncertainty of the respective instruments that are given in Table 4. The total uncertainty analysis of the experiment was calculated with the following equation.

Total percentage of the uncertainty = $[(BP)^2 + (BTHE)^2 + (CO)^2 + (CO_2)^2 + (HC)^2 + (O_2)^2 + (NOx)^2 + (\text{smoke opacity})^2 + (\text{crank angle encoder})^2 + (\text{load})^2 + (\text{pressure sensor})^2 + (\text{speed})^2 + (SFC)^2]^{1/2}$. The obtained value of total uncertainty lies in the acceptable range of ±1.581 %.

3 Results and discussion

3.1 Experimental results

As per planned design of experiments 75 combinations of tests were conducted. As a general behavior it is observed that brake thermal efficiency increases with load, compression ratio for all the fuels while specific fuel consumption decreases. Waste plastic oil and its blends closely match the brake thermal efficiency of the diesel.

Higher regulated emissions like CO, NOx and HC were observed for waste plastic oil and its blends than diesel. Smoke is a product of incomplete combustion. From the recorded data it is visible that waste plastic oil and its blends have higher smoke opacity than diesel. In this study CO_2 emission is higher for diesel as combustion performance is better than waste plastic oil and its blends.

3.2 Brake thermal efficiency

Brake thermal efficiency curves were drawn for varying loads at compression ratio 20 for all the tested fuels. Other curves were drawn for varying compression ratios 12, 16 and 20 at full load condition.

From Fig. 3 it is noted that for the compression ratio 20, brake thermal efficiency of all the fuels was in the range of 28.56–26.03 %. Which infers that, at higher compression ratio the waste plastic oil and its blends closely matches brake thermal efficiency of diesel. Due to higher compression ratio the temperature and pressure of the intake air are increased which supports the better combustion of the fuels.

Table 4 Details of instruments used and its uncertainties

S. no.	Instruments and measured quantity	Measuring range	Resolution	Accuracy	Measurement techniques	Percentage uncertainties
1	AVL Digas 444 gas analyzer—CO emission	0–10 % vol.	0.01 % vol.	<0.6 % vol.: ±0.03 % vol., ≥0.6 % vol.: 5 % of individual value	NDIR	±0.3 %
	CO_2 emission	0–20 % vol.	0.1 %vol.	<10 % vol.: ±0.5 % vol., ≥0.10 % vol.: ±5 % vol.	NDIR	±1 %
	HC emission	0–20,000 ppm vol.	≤2000:1 ppm vol., >2000:10 ppm vol	<200 ppm vol.: ±10 ppm vol., ≥200 ppm vol.: ±5 % of ind.val	FID	±0.1 %
	O_2	0–22 % vol.	0.01 %vol.	<2 % vol.: ±0.1 % vol., ≥2 % vol.: ±5 %vol.	Electro-chemical sensor	± 0.15 %
	NOx emission	0–5000 ppm vol.	1 ppm vol.	<500 ppm vol.: ±50 ppm vol., ≥500 ppm vol.: ±10 % of ind. val.	CLD	±0.5 %
2	AVL 437C smoke meter—smoke opacity	0–100 %	±1 % of full scale	0.10 %	NDIR	±1 %
3	Crank angle encoder—crank angle	0°–360°	1°	±1°	Magnetic pickup type	±0.2 %
4	Pressure transducer—cylinder pressure	0–100 bar	1 bar	±0.1 bar	Piezo electric sensor	±1 %
5	Load cell—load	0–20 kg	0.01 kg	±0.1 kg	Stain gauge type	±0.2 %
6	Speed sensor—speed	0–10,000 rpm	1 rpm	±10 rpm	Magnetic pickup type	±0.1 %
7	Temperature indicator	0–1200 °C	1 °C	±1 °C	*K* type thermocouple	±0.15 %

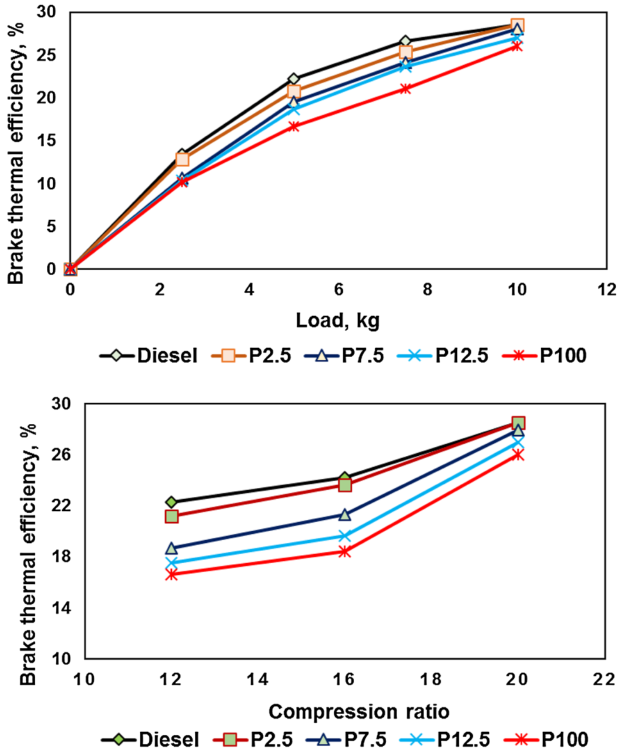

Fig. 3 Brake thermal efficiency versus load and compression ratio

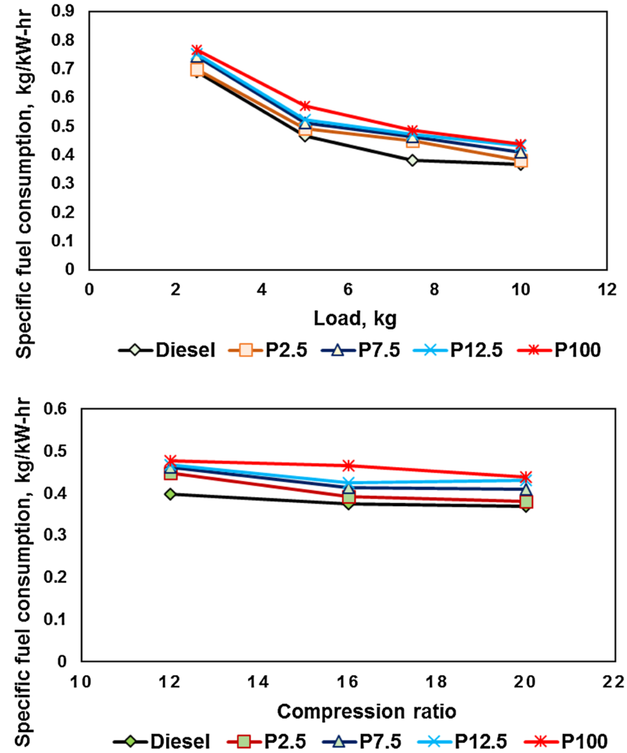

Fig. 4 Specific fuel consumption versus load and compression ratio

Brake thermal efficiency increases with load for all the fuels. Comparing with diesel, WPO and its blends provides lower efficiency. WPO, WPO blends have higher viscosity and lower calorific value. Atomization and vaporization of WPO, WPO blends are affected by these properties which results in the poor combustion.

Diethyl ether (DEE) is an ignition improver. DEE has the ability to absorb the heat and easily mixes with fuel. This property is helpful in vaporizing the high viscous WPO blends. Addition of DEE to WPO blends leads to similar behavior to diesel in combustion process.

3.3 Specific fuel consumption

Specific fuel consumption is the amount of fuel consumed by the engine to produce unit power per hour. SFC is an important performance indicator for internal combustion engine.

Figure 4 shows that SFC decreases with load for all the tested fuels. SFC decreases with increase in load and compression ratio. Cylinder temperature increases while increment in the load due to which combustion temperature also increases resulting in better combustion at higher loads and compression ratio. The fuel requirement for developing unit brake power comes down at higher loads and compression ratios. This is evident from the SFC noted for compression ratios 12–20.

At compression ratio 16, SFC for diesel, P2.5, P7.5 and P12.5 was noted in the range of 0.375–0.425 kg/kW h. It was observed that SFC for P100 was higher in all the cases. The reason for elevated SFC in P100 is due to high viscosity which affects the atomization and vaporization of the fuel. In the compression ignition engine, conversion of chemical energy into thermal energy was lesser while running with waste plastic oil. Hence the CI engine draws more fuel to meet the load that results in higher SFC for P100. Addition of DEE to P2.5, P7.5 and P12.5 reduces the above occurrence.

3.4 Carbon monoxide

Carbon monoxide is a product of incomplete combustion which comes under regulated emissions. Carbon monoxide requires a temperature of 1200 °C to convert CO_2 by oxidization. In minimal load the combustion temperature will be lower and emission of CO will be higher.

To meet maximum load, rich mixture is supplied to CI engine but same amount of oxygen is supplied for combustion of rich mixture resulting in higher CO emission. At part load CO emission will be lower than no load and full load. The reason for this behavior is usage of lean mixture and better combustion.

From Fig. 5 it is observed that CO emissions are lower for diesel in all the cases. Emission values of CO for P2.5,

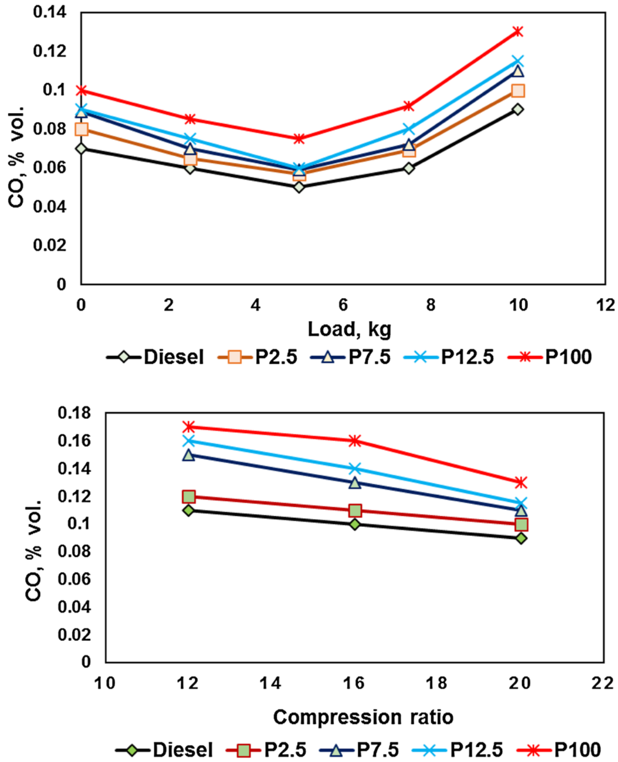

Fig. 5 Carbon monoxide versus load and compression ratio

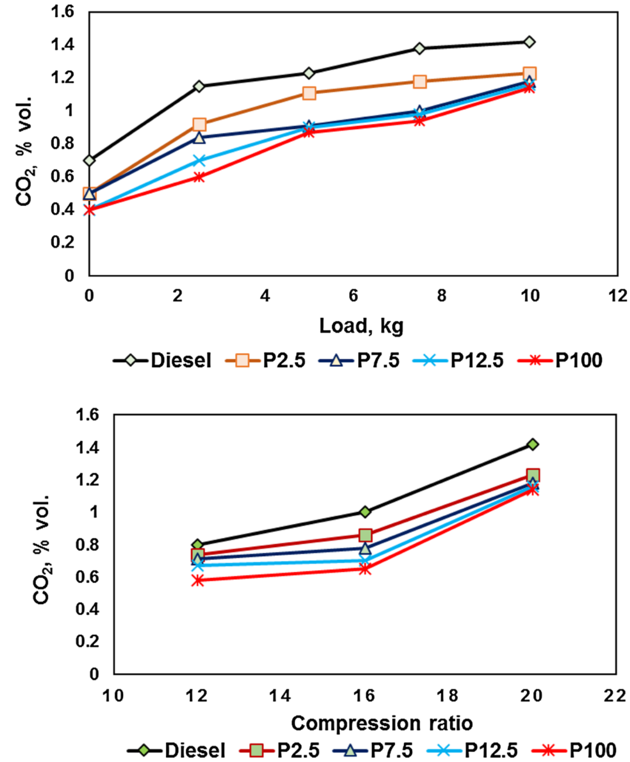

Fig. 6 Carbon dioxide versus load and compression ratio

P7.5 and P12.5 at part load were 0.057–0.06 % of volume. At the same load CO emission for diesel was 0.05 % of volume. The CO emission values have meager variation for diesel, P2.5, P7.5 and P12.5. The CO emission declines with increase in compression ratio; the reason is higher combustion temperature in cylinder. Addition of DEE to P2.5, P7.5 and P12.5 reduces CO emission less than P100 due to oxidization of blends and better combustion.

3.5 Carbon dioxide

Carbon dioxide is a greenhouse gas derived as product of combustion. Based on published research CO_2 contributes 12 % of exhaust gas second to nitrogen. It is evident from Fig. 6 that CO_2 emissions increase with load and compression ratio for all the tested fuels.

For a compression ratio 20, CO_2 emission of diesel is 1.42 % of volume. whereas for P100 (i.e. WPO) it is 1.14 % of volume. The blends P2.5, P7.5 and P12.5 also recorded lower CO_2 emission 1.23, 1.18 and 1.16 % of vol. Lower CO_2 emissions were noted for WPO and its blends comparing with diesel. The viscosity of the WPO and its blends are higher than diesel which affects the burning resulting incomplete combustion. Due to this lower CO_2 emissions and higher CO emissions recorded for WPO and its blends.

3.6 Smoke opacity

Smoke is *n* number of solid unburned HC particles coming out of combustion. Figure 7 infers that for higher load and compression ratio diesel and P2.5 emits same amount of HC. P2.5 consists of 95 % diesel, 2.5 % WPO and 2.5 % DEE by volume. The percentage of WPO and DEE is less in P2.5. The increase in plastic oil content in diesel increases the smoke opacity for P7.5 and P12.5. The higher viscosity and lower volatility of plastic oil lead to difficulty in atomizing the fuel and hence the incomplete combustion takes place.

Smoke opacity was 26 % for diesel and 47 % for waste plastic oil at full load due to non-availability of homogeneous charge inside the engine cylinder. It is also visible that smoke was emitted less during higher compression ratio and more at lower compression ratios. Also smoke increases significantly with increase in load because rich mixture was burnt in the cylinder.

3.7 Unburned hydrocarbon

Unburned hydrocarbons emitted from CI engine due to low combustion temperature and presence of lean or rich mixture. Fuel exhaust hydrocarbons are composed of original fuel molecules and partially oxidized hydrocarbons. The curves in Fig. 8 show that CI engine emits higher HC with

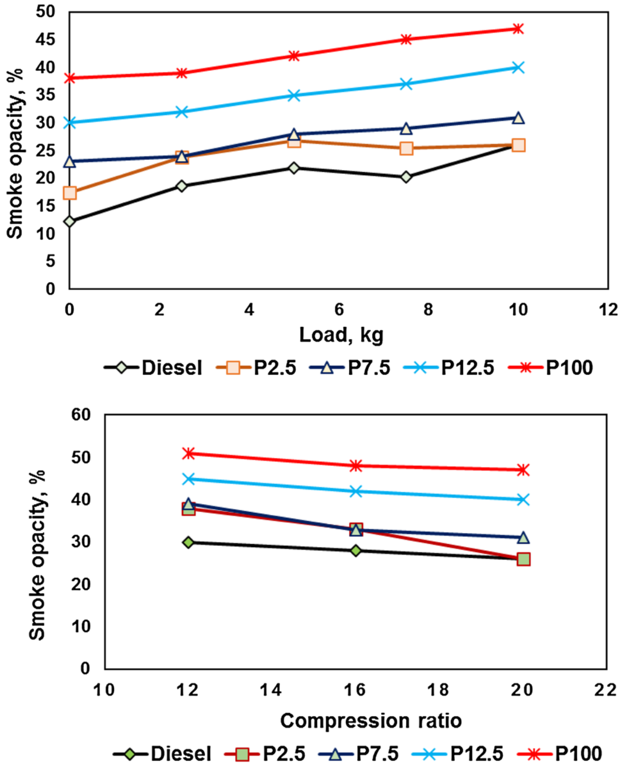

Fig. 7 Smoke opacity versus load and compression ratio

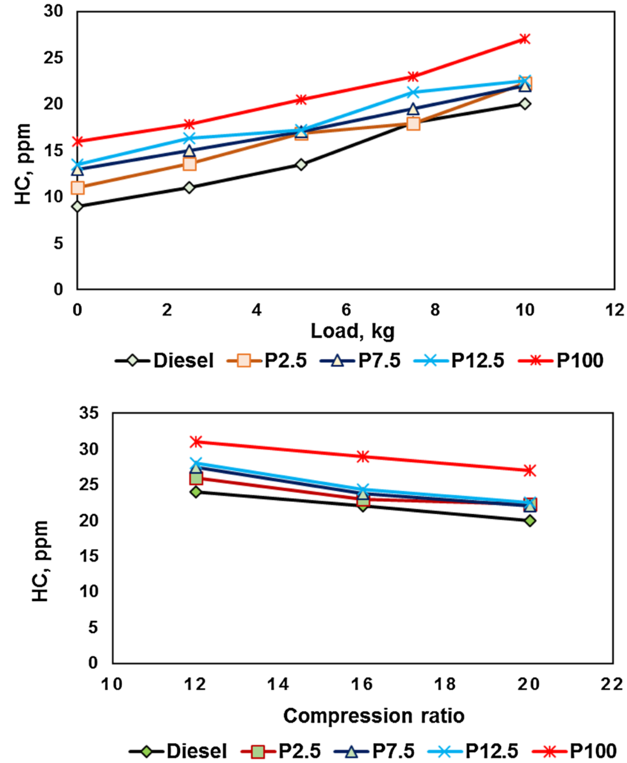

Fig. 8 Unburned hydrocarbon versus load and compression ratio

increase in load. At higher loads CI engine requires rich mixture, due to poor atomization and local rich mixture formation incomplete combustion takes place.

For compression ratio 16 HC emissions of 23, 23.8 and 24.3 ppm were noted for blends P2.5, P7.5 and P12.5, respectively. Diesel emission was noted as 22 ppm for the same compression ratio. Hydro carbon emission difference between diesel and WPO blends were very small. Diethyl ether which was added with P2.5, P7.5 and P12.5 blends to equal the properties of diesel. The same behavior was noted for compression ratio 20.

In the case of WPO and diesel HC emission was 27 and 20 ppm at full load. This was due to the following reasons, the fuel spray does not propagate deeper into the combustion chamber and gaseous hydrocarbons remain along the cylinder wall and the crevices.

3.8 Oxides of nitrogen

Oxides of nitrogen are produced by oxidization inside the cylinder at a temperature of 2200 K. Nitrogen requires very high energy to break its triple bond. When the high combustion temperature favors oxidization NOx is produced. NOx is a combustion product consisting of 10–30 % NO_2 and NO. The formation of NOx depends on oxygen content and cylinder temperature.

CI engines always run with lean air fuel mixtures and emit higher amounts of NOx. Emissions of NOx for WPO and its blends are higher with increase in load. Oxygen content in a fuel help better combustion and high rate of heat release. It also increases emission of NOx. Oxygen content of waste plastic oil is nearly 1.5 %.

To improve the combustion diethyl ether was added with WPO blends. DEE has higher cetane number, heat of evaporation and oxygen content. DEE addition to the WPO blends improve high rate of reaction.

Waste plastics oil is a ring structured aromatic fuel. Adiabatic flame temperature which is responsible for rate of heat release, will high for these types of fuel. From Fig. 9 it is evident that, for compression ratios 16 and 20 the difference in NOx emission levels was 30, 35, 50 and 40 ppm for diesel, P2.5, P7.5 and P12.5 respectively. The reason for lower difference in NOx emission among diesel and WPO blends was due to presence of major fraction of diesel in blends.

3.9 Averaged cylinder pressure and rate of heat release

Averaged cylinder pressure is vital parameter which directly indicates the power developed by the cylinder. The maximum pressure, rate of heat release and observed from Fig. 10 for various fuels at full load, compression ratio 20

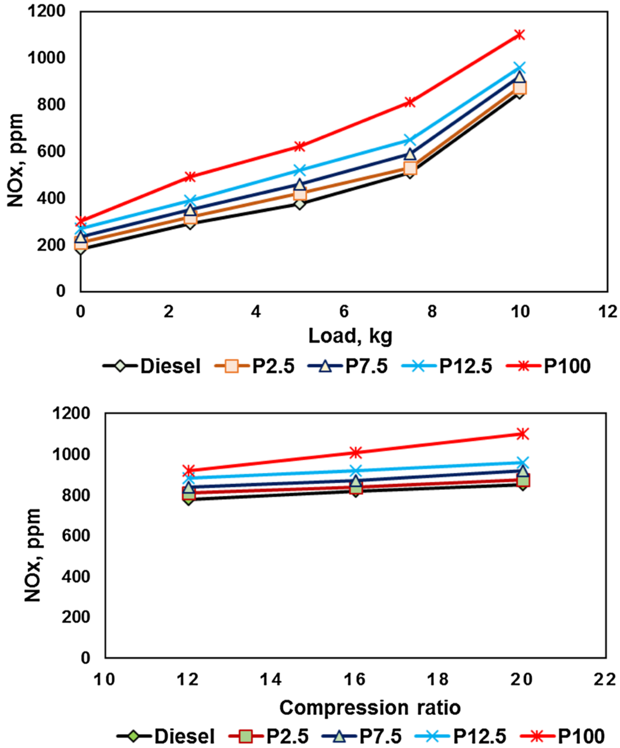

Fig. 9 Oxides of nitrogen versus load and compression ratio

their corresponding brake thermal efficiency is listed in Table 5.

Even though maximum pressure, rate of heat release were almost equal for diesel and P2.5, P7.5 brake thermal efficiency is superior for diesel. Higher calorific value of diesel offset the blends in results of brake thermal efficiency. The addition of diethyl ether to the blends yields closer rate of heat release and pressure for P2.5, P7.5.

Brake thermal efficiency of P12.5, P100 was lower than diesel, other two parameters also deviates from the diesel results. The higher concentrations of WPO, inferior calorific values are the reasons for lower efficiency in P12.5, P100. The occurrence of maximum pressure and higher rate of heat release at 13° after TDC for P100 was due to the longer ignition delay in waste plastic oil.

Addition of diethyl ether influences the combustion of WPO blends positively. Early burning of this additive result premixed heat release. Higher rate of reaction was achieved by adding DEE which increases the cetane number of WPO blends. DEE increases the ignition centers inside the combustion chamber. Hence DEE can be added to WPO blends to match the diesel in compression ignition engine as an alternate.

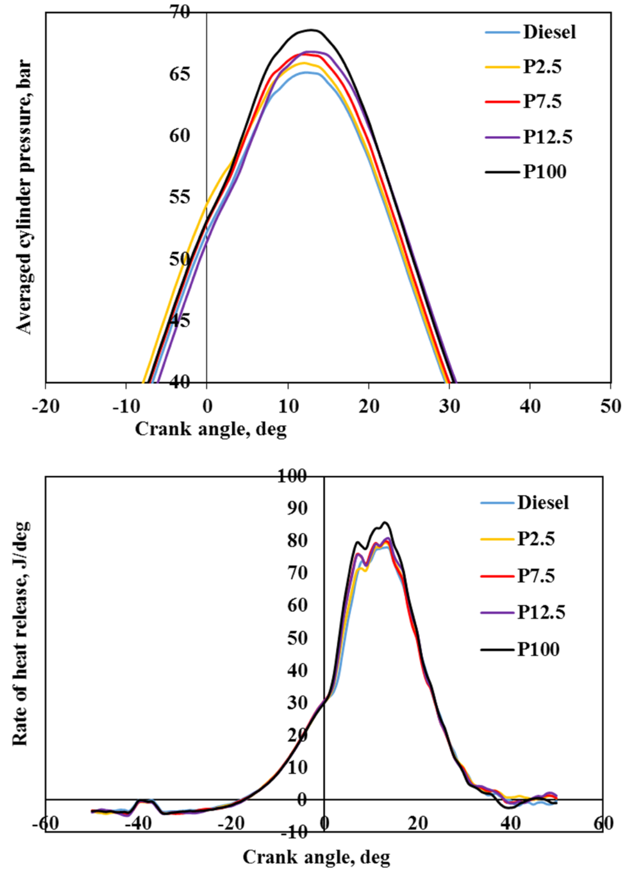

Fig. 10 Averaged cylinder pressure, rate of heat release versus Crank angle (CR 20)

4 Conclusion

Experimental studies on performance, combustion and emission for waste plastic oil and its blends were conducted with variable compression ratio engine. The results were compared with diesel. Waste plastic oil can be used as alternate to diesel at higher compression ratios without any modification in CI engine. Blending waste plastic oil and diesel with additive diethyl ether gives parallel results to diesel. Results of brake thermal efficiency, SFC, emissions and combustion characteristics of WPO blend P12.5 and P100 deviate from diesel due to higher viscosity and lower calorific value.

Brake thermal efficiency positive influenced by the addition of diethyl ether was evident from the results of P2.5, P7.5 and P12.5 comparing with P100. But specific fuel consumption was inferior to diesel in all the cases. CO_2 emission was lower for WPO and its blends on comparing with diesel. But the emission of CO was vice versa.

Table 5 Results of maximum pressure, HRR and BTHE for CR 20 at full load

Fuel	Maximum pressure bar	Maximum heat release J/°	Brake thermal efficiency (%)
Diesel	65.129 bar at 12° after TDC	78.08 at 13° after TDC	28.56
P2.5	65.905 bar at 12° after TDC	79.55 at 13° after TDC	28.52
P7.5	66.61 bar at 12° after TDC	79.09 at 13° after TDC	28
P12.5	66.81 bar at 12° after TDC	80.76 at 14° after TDC	27
P100	68.57 bar at 13° after TDC	85.85 at 13° after TDC	26.03

Unburned hydrocarbon and smoke emission was close to diesel in the case of P2.5, P7.5 and P12.5.

The maximum pressure and rate of heat release for P2.5, P7.5 were almost similar with diesel. Due to higher rate of heat release and combustion temperature NOx emission from WPO and its blends were high. Hence waste plastic oil can be blended with diesel and additives like DEE to get comparable results with diesel at higher compression ratios.

References

1. Ganapathi P, Robinson Y (2014) Performance and emission characteristics of a diesel engine fuelled with polymer oil–methanol blends. Int J Appl Environ Sci 9(4):1093–1102
2. Mani M, Nagarajan G, Sampath S (2011) Characterization and effect of using waste plastic oil and diesel fuel blends in compression ignition engine. Energy 36:212–219
3. Mani M, Subash C, Nagarajan G (2009) Performance, emission and combustion characteristics of a DI diesel engine using waste plastic oil. Appl Therm Eng 29:2738–2744
4. Kumar S, Prakash R, Murugan S, Singh RK (2013) Performance and emission analysis of blends of waste plastic oil obtained by catalytic pyrolysis of waste HDPE with diesel in a CI engine. Energy Convers Manag 74:323–331
5. Amarnath HK, Prabhakaran P (2012) A study on the thermal performance and emissions of a variable compression ratio diesel engine fuelled with Karanja biodiesel and the optimization of parameters based on experimental data. Int J Green Energy 9(8):841–863
6. Edwin Geo V, Nagarajan G, Nagalingam B (2010) Studies on improving the performance of rubber seed oil fuel for diesel engine with DEE port injection. Fuel 89:3559–3567
7. Devaraj J, Robinson Y, Ganapathi P (2015) Experimental investigation of performance, emission and combustion characteristics of waste plastic pyrolysis oil blended with diethyl ether used as fuel for diesel engine. Energy 85:304–309
8. Arul Mozhi Selvan V, Anand RB, Udayakumar M (2014) Effect of cerium oxide nanoparticles and carbon nanotube as fuel borne additives in diesteral blends on performance, combustion and emission characteristics of a variable compression ratio engine. Fuel 130:160–167
9. Jerekias G, Clever K (2011) Comparative performance analysis of Marula oil and petrodiesel fuels on a variable compression ratio engine. In: Proceedings of the IEEE African 2011: the falls resort and conference centre, Livingstone, Zambia, pp 13–15
10. Raj MT, Kandasamy MKK (2012) Tamanu oil: an alternative fuel for variable compression ratio engine. Int J Energy Environ Eng 3:18
11. Mohanraj T, Murugumohan Kumar K (2013) Operating characteristics of a variable compression ratio engine using esterified Tamanu oil. Int J Green Energy 10(3):285–301
12. Mani M, Nagarajan G (2009) Influence of injection timing on performance, emission and combustion characteristics of a DI diesel engine running on waste plastic oil. Energy 34:1617–1623
13. Datta A, Palit S, Mandal BK (2014) An experimental study on the performance and emission characteristics of a CI engine fuelled with Jatropha biodiesel and its blends with diesel. J Mech Sci Technol 28(5):1961–1966
14. Saravanan S, Nagarajan G, Rao GLN (2009) Feasibility analysis of crude rice bran oil methyl ester blend as a stationary and automotive diesel engine fuel. Energy Sustain Dev 13:52–55
15. Tutak W, Lukacs K, Szwaja S, Bereczky A (2015) Alcohol–diesel fuel combustion in the compression ignition engine. Fuel 154:196–206
16. Behera P, Murugan S (2013) Combustion, performance and emission parameters of used transformer oil and its diesel blends in a DI diesel engine. Fuel 104:147–154
17. Arpa O, RecepYumrutaş ZA (2010) Experimental investigation of the effects of diesel-like fuel obtained from waste lubrication oil on engine performance and exhaust emission. Fuel Process Technol 91:1241–1249