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Performance, Combustion and Emission Characteristics of Direct Injection Diesel Engine with Plastic Oil Extracted from Compact Discs

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Abstract—Crude oil availability is a major concern all over the world because of geopolitical constraints. Further, the emissions from engines running on crude oil products are the major source of environmental issues. Hence, scientific community is putting significant research efforts to identify alternative to crude oils which can effectively run the internal combustion engines with reduced emissions. It is obvious that plastic wastes also have severe environmental effects because of the disposal problems. In this research, an attempt is made to investigate the performance and emission characteristics of direct injection diesel engine while using plastic oil which is derived from the waste compact discs. Various properties of fuels are tested according to American society for testing and material standards (ASTM). The performance, combustion and emission characteristics of plastic oil fuelled engine are analyzed at various load conditions from no load to full load. The results indicate that the brake thermal efficiency of the engine employing plastic oil is a slightly lower than that of the engine when diesel is used. Combustion characteristics of plastic oil are almost similar to that of diesel fuel. The results of the experiments further show that the smoke, unburned hydrocarbon and carbon monoxide increase where as oxides of nitrogen decrease when plastic oil is used.

Keywords: diesel engine, plastic oil, heat release rate, unburned hydrocarbon, pyrolysis

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1. INTRODUCTION

Most of the countries including India don't have sufficient source of fossil fuels and hence, they export from other countries. Global warming is one of the major concerns in the last couple of decades [1]. Global warming causes the increase in temperature of the earth surface. Due to that, human survival, polar life and wildlife are severely affected. Petroleum contains majorly carbon particles which generate carbon dioxide that has to be linked to global warming [2, 3]. Apart from this, one of the main drawbacks of using petrol and diesel is the environmental pollution. The combustion of air and fuel mixture produces harmful gases like unburned hydrocarbon (UBHC), carbon monoxide (CO),oxides of nitrogen (NO_x) and smoke [4]. These gases have significant adverse effects on environmental health. Considering the availability of petroleum source and environmental issues, it is essential to develop fuels from sustainable alternative sources [5].

Compression ignition engine or diesel engine is absolutely essential device that is used in several sectors such as automobile, agricultural, marine and power generation because of higher thermal efficiency and better conversion rate of torque and power output as compared to spark ignition engine [3–5]. Instead of diesel fuel, some alternate fuels are developed such as alcohols, biodiesel, natural gas etc., and they are found to be promising alternate fuels for compression ignition engine.

Alcohol fuel is attempted in diesel engines in the form of blend (diesel and alcohol) and dual fumigation mode [6–8]. In blend, both diesel and alcohol are mixed together before injected into the cylinder chamber. Natural gas is another potential alternate fuel used in diesel engine vehicles. It contains the methane, butane, propane and ethane. Based on the geographical study, availability of natural gas is not same across the world. In addition to that, specific arrangements are required for production and transportation of natural gas [9–11]. One of the promising alternate fuels is biodiesel which can be easily produced from natural sources like vegetable seeds, corn, sugar beet and wheat. One of the major differences between the fossil fuel and biodiesel is the percentage of oxygen present [12, 13]. Bio sources can provide clean energy and eco-friendly fuel. It is predominantly used in marine engine and heavy duty vehicles. Density of bio diesel is

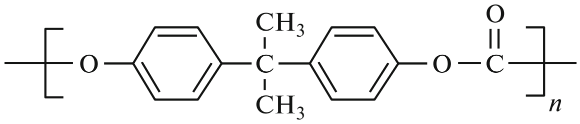

Fig. 1. Structure of polycarbonate.

lower than that of water and it can be stored for a long duration without any stability issues [14–16].

Besides alcohol, natural gas and biodiesel,alternate fuels derived from waste resources are also explored. In the modern world, use of plastics is ever increasing. Basically plastics are synthetic polymers which have a representation of polyethylene, polypropylene, polystyrene and polyvinyl chloride [17–19]. Plastics are largely utilized in house hold works, automobile body constructions, electronics applications, aerospace industries etc.,Because of large scale usage of plastics, the disposal becomes a challenging task as plastics are not environmental friendly. However, plastics can yield oils which are suitable for diesel engine [20–22]. Quite number of works concerning plastic oil as alternate fuel for diesel engine is reported in the literature.

Chintala et al. [23] compared the performance of plastic oil and diesel and have reported that the brake thermal efficiency with plastic oil is almost same as that with diesel fuel. It is also observed that the plastic oil generates slightly higher UBHC, CO as compared to diesel whereas the NO_x emission is found to be less. Kaimal & Vijayabalan [24] tested two fuels. i.e. rice bran methyl ester and plastic oil. The combustion analysis revealed a delay in heat release rate with both the fuels which resulted in reduced brake thermal efficiency (BTE) as compared to diesel fuel. The longer ignition delay with plastic oil is also reported by Kalagaries et al. [25]. The results also indicate higher NO_x with plastic oil in comparison with diesel fuel.

To improve the performance, Venkatesan et al. [26] employed blend of diesel and plastic oil and found enhanced performance and combustion characteristics when 30% plastic oil blend was used. Dhamodaran et al. [27] tested plastic oil in diesel engine under different operating conditions. The experiments were conducted at different injection timings (21°, 23°, and 25° before top dead centre (BTDC)) and with exhaust gas recirculation of 10, 20, and 30%. It is found that EGR with 21° BTDC injection timing could reduce all the emissions. The lower BTE with plastic oil is also reported by Kumar et al. [28].

From the literature review, it is found that oil derived from waste plastic materials have a potential to be an alternative fuel for diesel engines. However, literature reveals only limited number of investigations; especially the combustion characteristics are not entirely studied. Further, the quantity of oil that could be derived from waste plastic material is not yet reported. Driven by this scenario, the present work aims at investigating the performance of diesel engine with 100% plastic oil derived from used compact discs (CD). Extensive experimental trials are conducted to explore the performance, combustion and emission characteristics. This is the first attempt in which oil is derived from used CDs. The quantification of derived oil is also reported.

2. PRODUCTION OF PLASTIC OIL

2.1. Source of Fuel

Plastic oil can be made from waste CDs. CDs are generally manufactured by using a material called Polycarbonate. It has a very good optical coherence, higher contact resistance and ductility at atmospheric temperature. Polycarbonate is widely used electrical and electronics equipment production, glazing industries, construction industries, automobile sparts, sports equipment, safety equipment and food/drink containers. The most serious deficiencies of polycarbonate are poor wearability and chemical resistance. The structure of polycarbonate ($C_{16}H_{14}O_3$) is shown in Fig. 1.

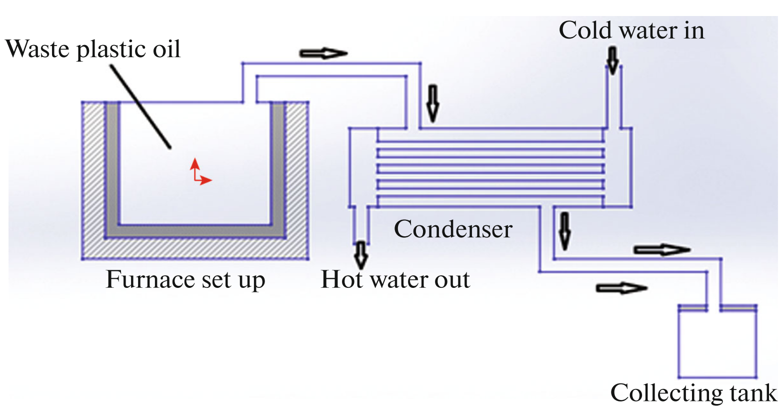

Fig. 2. Pyrolysis of waste plastic oil setup.

2.2. Pyrolysis Process

This section narrates the derivation of oil from CDs. CDs are made up of tri-layer composite of protective layer of acrylic plastic film. The middle reflective layer of aluminium/silver film has a thickness of 55–70 μm and the bottom layer contains polycarbonate substrate of 20 μm thick. Initially, CDs were carefully dipped into 30% acetic acid solution for a minimum 30 minutes to dissolve the outer labels carrying movie names, games names etc. Dissolution was accelerated by shaking the contents thoroughly. Then they were dried thoroughly and crushed into arbitrary sizes and shapes. The crushed parts were then charged into the pyrolytic reactor.

The schematic of pyrolysis process is shown in Fig. 2. The pyrolytic reactor is nothing but a furnace whose temperature is maintained at 450–750°C. After a period of time, the charged CDs start to evaporate which obviously yields hot plastic oil which can then be passed to the condenser setup. The oil cooled by the condenser can be collected in the small tank. The unwanted materials in the CDs are settled in the furnace chamber. The collected waste plastic oil sample is shown in Fig. 3. It is found that 1 kg of CDs could yield 400 ml of oil.

Fig. 3. Sample of CDs oil.

2.3. Fuel Properties

The properties of plastic oil and diesel were measured as per American Society for Testing and Materials (ASTM) standard and are indicated in Table 1.

3. TEST SET UP

The Engine used in this work is a single cylinder, four stroke, direct injection, water cooled diesel engine. No modification was attempted in diesel engine as the properties of derived oil found to be similar to that of diesel fuel. The engine has a compression ratio of 16 : 1 and the rated power is 3.5 kW. The stroke length and bore are 120 mm and 80 mm respectively. The engine was coupled with an eddy current dynamometer to conduct load test. The engine specification is given in Table 2. Figure 4 shows a photographic view of the test rig. For measuring combustion parameters, piezoelectric transducer was used. The data collection was performed with the help of DAQ system and data were noted by LabVIEW software. The emission characteristics were measured using AVL Digas 444N [CO, UBHC, NO_x] and smoke meter.

The engine was tested at 1500 rpm under a loading of 0, 25, 50, and 100% with the following fuel blends. 100% diesel, WPO 10% (waste plastic oil 10% + diesel 90%), WPO 20%, WPO 40%, WPO 60%, WPO 80%, and WPO 100%.

3.1. Uncertainty Analysis

The uncertainty analysis was performed using Eq. (1).

$$\frac{\Delta S}{S} = \sqrt{\left(\frac{\Delta x_1}{x_1}\right)^2 + \left(\frac{\Delta x_2}{x_2}\right)^2 + \ldots + \left(\frac{\Delta x_n}{x_n}\right)^2}, \qquad (1)$$

where,

$\frac{\Delta S}{S}$ – uncertainty testing value,

Δx – accuracy of the measuring instrument,

x – minimum output value measured.

The total uncertainty present is found to be ±1.556.

The various percentages of uncertainties and accuracy level of the instrument employed are given in Table 3.

Table 1. Properties of plastic oil and diesel

Fuel properties	ASTM standard	CDs oil	Diesel Fuel
Chemical structure		$C_{16}H_{14}O_3$	$C_{10}H_{22}$
Density at 40°C (g/cm^3)	ASTM D4052	0.660	0.834
Specific gravity at 40°C (g/cm^3)	–	0.835	0.87
Flash point (°C)	ASTM D93	32	60–80
Kinematic viscosity at 40°C (mm^2/s)	ASTM D445	3.9	1.91–4.1
Ash content (%)	ASTM D482	0.0023	0.02
Heating value (MJ/kg)	ASTM D3338	42	40–45
Cetane number	ASTM D613	51	48

Table 2. Technical specification details of test engine

Make	Kirloskar
No of cylinder	One
Bore & Stroke	80 mm & 120 mm
Compression ratio	16 : 1
Rated power	3.5 kW & 1550 rpm
Type of cooling	Water cooling
Ignition	Compression ignition
Fueling method	Direct injection
Static injection timing	23° BTDC

4. RESULT AND DISCUSSION

The performance, emission and combustion characteristics of plastic oil are discussed in comparison with diesel as given below.

4.1. Performance Characteristics

4.1.1. Brake thermal efficiency. To evaluate the engine performance, it is necessary to evaluate the BTE.Fig. 5 shows a steady raise in BTE as the load increases. At full load condition BTE of diesel fuel is 31.4% whereas plastic oil is 30.4%. BTE of various blends of plastic oil is lower than that of pure diesel fuel. Decrease in BTE of plastic oil is mainly due to lower calorific value and addition of plastic oil with diesel fuel results in a decrease of rate of vaporization of fuel.The plastic oil in diesel engine influences the fuel spray formation which affects the BTE.BTE of plastic oil is 3% less as compared to pure diesel.

4.2. Combustion Characteristics

Different types of alternate fuels have a consequence on combustion attributes including the heat release rate and in cylinder pressure in diesel engine.

4.2.1. Heat release rate. Figure 6 shows the heat release rate for diesel fuel and plastic oil at part load (50% load) condition. The negative portion at the start of the combustion is because of the fuel evaporation during the injection of fuel inside the combustion chamber. From Fig. 6, it can be observed that the start of combustion of plastic oil is delayed when compared to diesel fuel. The maximum rate of heat release of plastic oil is 79.9 J/deg CA whereas it is 84.1 J/deg CA for diesel fuel.The longer ignition delay and lower heat release rate for plastic oil are due to its higher viscosity.The longer ignition delay period results in admission of more amount of fuel in the combustion chamber which extends the premixed combustion phase. This leads to lower heat release rate.

4.2.2. In-cylinder pressure. Cylinder pressure majorly depends on fraction of fuel burned during premixed burning stage. As mentioned already, the higher viscosity of plastic oil results in longer ignition delay and hence, more fuel is available at the onset of combustion. This may lead to sudden rise in pressure. However, due to delay in onset of combustion, maximum pressure attained is found to be less in case of plastic oil as compared to diesel. As shown in Fig. 7, the maximum pressure obtained for a diesel fuel is 56.1 bar whereas it is 52.7 bar for plastic oil at full load condition.

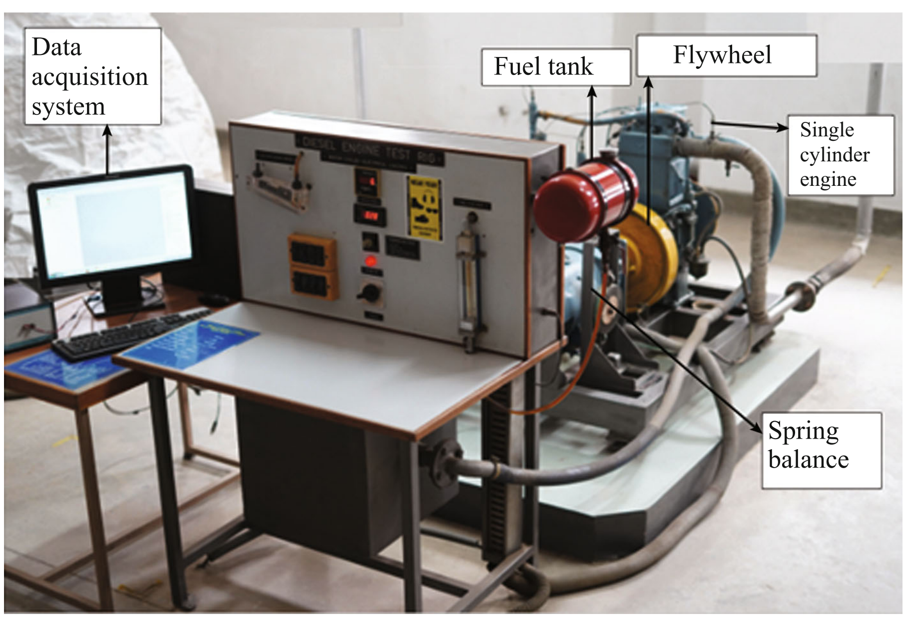

Fig. 4. Experimental setup of DI diesel engine.

Table 3. Uncertainties of instruments

Device	Range	Accuracy level	Uncertainties percentage
AVL Digas 444N			
CO	0–15% vol	–0.02 to +0.02%	–0.5 to +0.5%
UBHC	0–30000 ppm vol	–8 ppm to +8 ppm	–0.267 to +0.267 ppm
NO_x	0–5000 ppm vol	–5 ppm to +5 ppm	–0.05 to +0.05 ppm
Smoke meter	0–100%	–1% to +1%	–0.2% to +0.2%
AVL 437C			
Tachometer(Speed)	0–50000 rpm	–10 rpm to +10 rpm	–0.1% to +0.1%
Load (kg)	0 – 20 kg	–0.5 kg to +0.5 kg	–1% to +1%
BTE			–0.1 to +0.1
Burette	0–30cc	–1 cc to +1 cc	–1% to +1%
Crank angle encoder	0–360°		–0.2% to +0.2%

4.3. Emission Characteristics

There are no aromatic hydrocarbons included in plastic oil and thus emission from alternate fuel combustion is barely harmful to the human's health and environment.

4.3.1. NO_x emission. The emission characteristics in terms of NO_x of diesel and plastic oil are shown in Fig. 8. From no load to full load conditions, NO_x emission increases steadily in all cases. As the load increases, more amount of fuel is admitted inside the combustion chamber which increases the pressure and temperature of the engine. The NO_x production is directly proportional to the temperature. Fig. 8 also indicates that NO_x emission is lowered with plastic oil as compared to the conventional diesel fuel at full load conditions. This reduction of NO_x emission of plastic oil is due to lower combustion temperature and cylinder pressure. It is already known that the heat release rate of the engine is on lower side when plastic oil is employed. This is the reason for lower cylinder temperature in case of plastic oil.

4.3.2. Smoke emission. It is observed that rich fuel air mixture is required to meet the high load demands. Formation of soot particles in the engine exhaust is the source of smoke formation in diesel engine. Smoke is formed mainly due to incomplete combustion of the fuel and insufficient air/oxygen available during combustion. Smoke increases when an engine runs at full load condition because of higher quantity of fuel admitted and less amount of oxygen present at full load condition. When there is abundance of fuel, incomplete combustion occurs and smoke formation increases. As shown in Fig. 9, diesel has 67.2% of smoke and plastic oil has 68.9% at full load condition. It is observed that smoke intensity of plastic oil is slightly higher than the diesel fuel. The reason for increasing smoke intensity in plastic oil is lack of oxygen inside the combustion chamber and incomplete combustion at full load condition.

4.3.3. UBHC emission. Similar to smoke, UBHC emission also prevails due to incomplete combustion. If excess oxygen presents inside the combustion chamber the hydrocarbon emission formation gets reduced. However, the presence of higher quantity of plastic oil experiences lack of oxygen and hence, incomplete combustion. This can be referred from Fig. 10. For diesel fuel, UBHC varies from 30 to 49% whereas in case of plastic oil varies from 55 to 79%.

4.3.4. CO emission. CO formation in internal combustion engine is mainly due to lack of oxygen. Since diesel engines operate on lean air fuel mixture, the CO emission is generally low. In general, more oxygen available in lean mixture operating region hence, CO emission is lowered in diesel engine. However, the same cannot be said for plastic oil. As discussed in

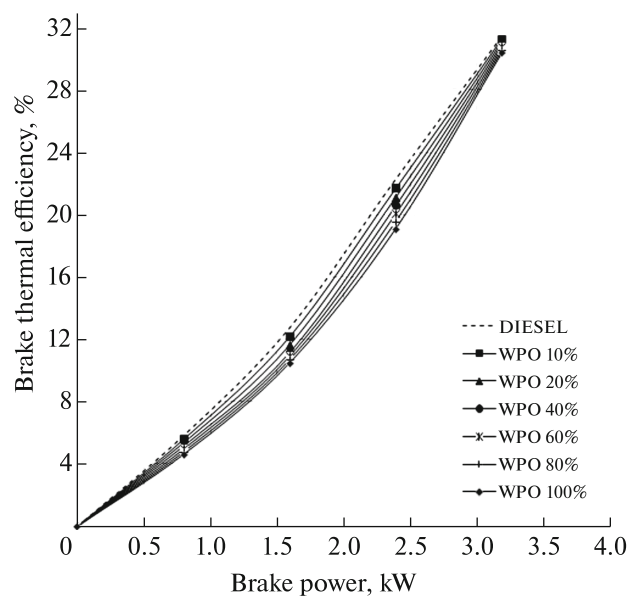

Fig. 5. Brake thermal efficiency with respect to load.

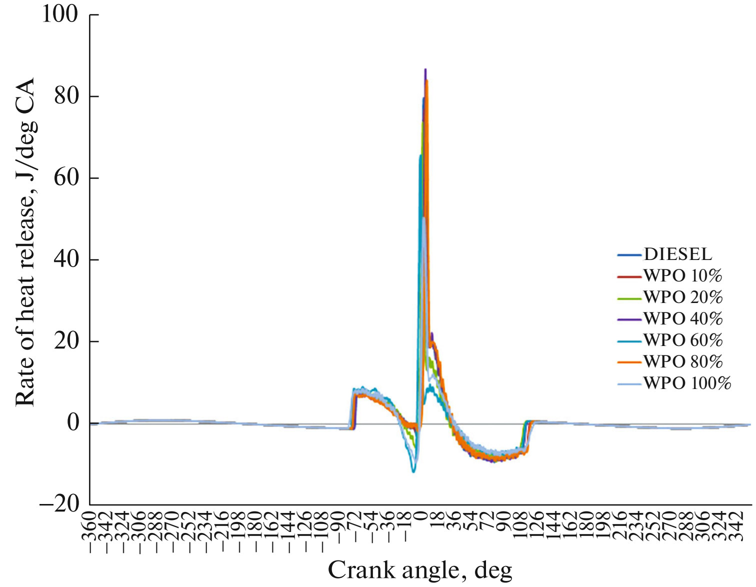

Fig. 6. Heat release rate with respect to load.

detail, plastic oil suffers from lack of oxygen and this leads to higher CO emission. According to Fig. 11, CO emission for diesel fuel is 0.07% and the same for plastic oil is 0.14% at full load conditions.

5. CONCLUSIONS

In this study, oil is extracted from the used CDs and the extracted oil is employed as alternate fuel for diesel engine without any major modifications. Engine can run with 100% plastic oil at full load conditions. The present investigation aims at carrying out the performance, combustion and emission tests on diesel engine with plastic oil and the results are compared with diesel fuel. Based on the outcomes of the research, the following conclusions are drawn:

• Although oil extracted from CDs has the potential to be employed as alternate fuel for diesel engines, the brake thermal efficiency is found to be less as compared to diesel.

• Because of longer ignition delay with plastic oil, the heat release rate and cylinder pressure are less than that found with diesel. At the same time,fuel blends exhibit better combustion characteristics than pure diesel fuel.

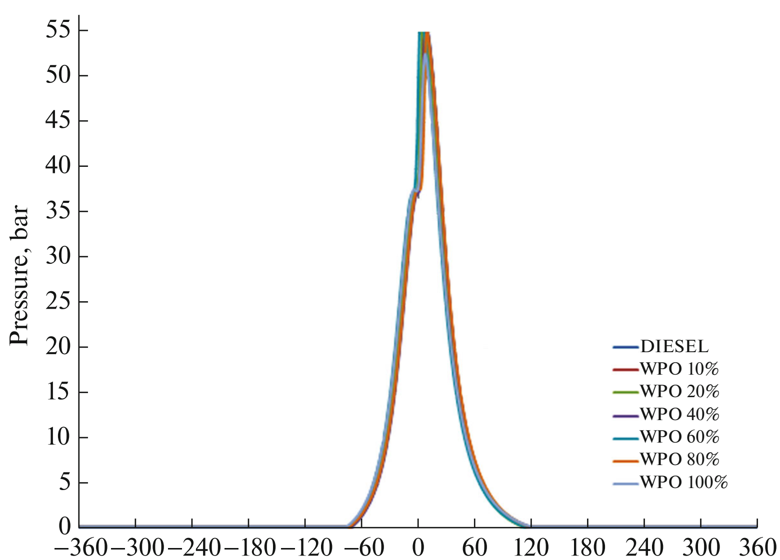

Fig. 7. In cylinder pressure with respect to load.

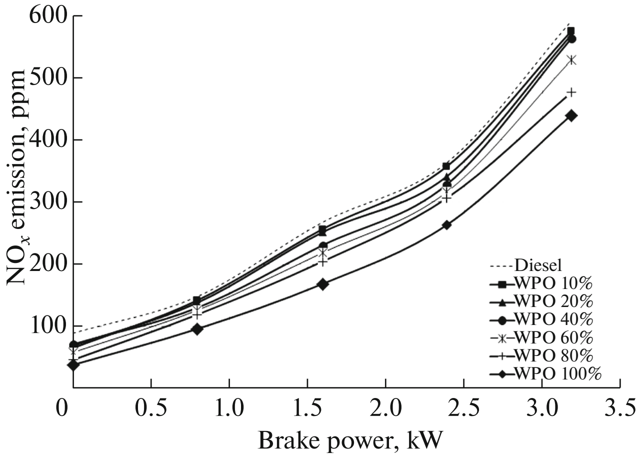

Fig. 8. Oxides of nitrogen with respect to load.

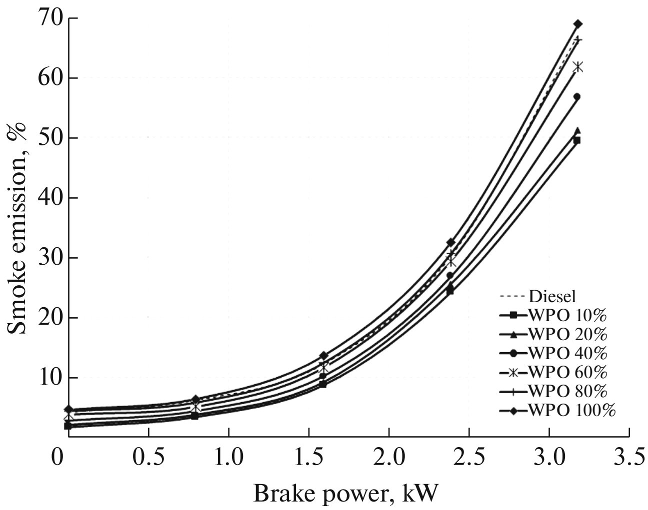

Fig. 9. Smoke emission with respect to load.

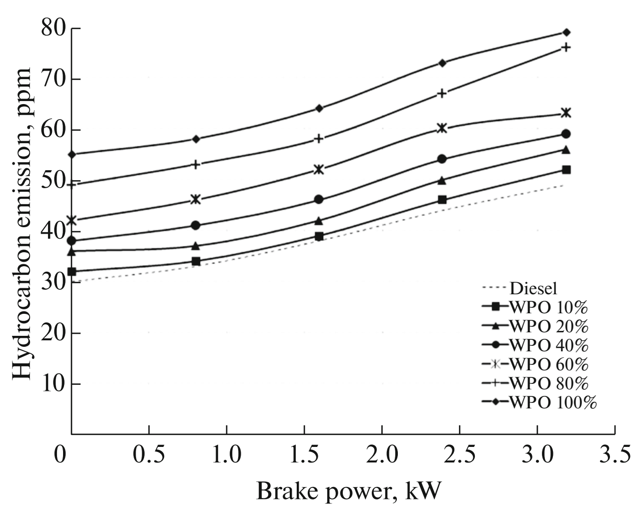

Fig. 10. Hydrocarbon emission with respect to load.

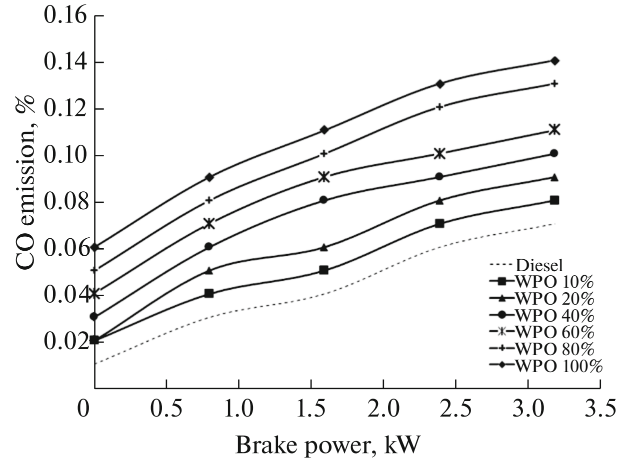

Fig. 11. Carbon monoxide emission with respect to load.

• Compared to diesel fuel, a significant reduction in NO_x emission is observed for plastic oil blended with diesel fuel. On the other hand of UBHC, CO and smoke emission are considerably higher with plastic oil.

• The oil extracted from CDs using pyrolysis method is simple process and economically viable one. Further, it is demonstrated that considerable amount of oil can be extracted from CDs.

NOMENCLATURE

BTE:	Brake thermal efficiency
BTDC:	Before top dead centre
CD:	Compact discs
CO:	Carbon monoxide
NO_x:	Oxides of nitrogen
UBHC:	Unburned hydrocarbon
WPO:	Waste plastic oil
$\frac{\Delta S}{S}$:	Uncertainty testing value
Δx:	Accuracy of the measuring instrument
x:	Minimum output value measured

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. Vinoth Kanna, I., Arulprakasajothi, M., and Eliyas, S., *Int. J. Ambient Energy*, 2021, vol. 42, p. 1794. https://doi.org/10.1080/01430750.2019.1614994
2. Chen, Y., *J. Traffic Transport. Eng. (English Ed.)*, 2018, vol. 5, p. 318. https://doi.org/10.1016/j.jtte.2018.05.001

3. Othman, M.F., Adam, A., Najafi, G., and Mamat, R., *Renew. Sustain. Energy Rev*., 2017, vol. 80, p. 694. https://doi.org/10.1016/j.rser.2017.05.140
4. Ragupathi, K., and Mani, I., *Energy Sources Part A: Recovery Util. Environ. Effects*, 2021, vol. 43, p. 932. https://doi.org/10.1080/15567036.2019.1632987
5. Sehatpour, M.H., Kazemi, A., and Eddin Sehatpour, H., *Renew. Sustain. Energy Rev*., 2017, vol. 72, p. 295. https://doi.org/10.1016/j.rser.2017.01.067
6. Saccullo, M., Nygren, A., Benham, T., and Denbratt, I., *Fuel*., 2021, vol. 294, p. 120478. https://doi.org/10.1016/j.fuel.2021.120478
7. Nour, M., Attia, A.-A., and Nada, S.A., *Energy Convers. Manage*., 2019, vol. 185, p. 313. https://doi.org/10.1016/j.enconman.2019.01.105
8. Çelebi, Y. and Aydın, H., *Fuel*., 2019, vol. 236, p. 890. https://doi.org/10.1016/j.fuel.2018.08.138
9. Hall, C. and Kassa, M., *Renew. Sustain. Energy Rev*., 2021, vol. 148, p. 111291. https://doi.org/10.1016/j.fuel.2021.121012
10. Felayati, F.M., Semin, Cahyono, B., Bakar, R.A., and Birouk, M., *Fuel*., 2021, vol. 300, p. 121012. https://doi.org/10.1016/j.fuel.2021.121012
11. Bayat, Y. and Ghazikhani, M., *J. Cleaner Prod*., 2020, vol. 271. https://doi.org/10.1016/j.jclepro.2020.122450
12. Senthilkumar, P. and Sankaranarayanan, G., *J. Energy Inst*., 2016, vol. 89, p. 504. https://doi.org/10.1016/j.joei.2015.07.006
13. Shehata, M.S., Attia, A.M.A., and Abdel Razek, S.M., *Fuel*., 2015, vol. 161, p. 49. https://doi.org/10.1016/j.fuel.2015.08.037
14. Zaher, F.A., El-Noamany, H.M., Megahed, O.A., and Abdallah, R.I., *Egypt. J. Pet.,* 2016, vol. 25, p. 247. https://doi.org/10.1016/j.ejpe.2015.05.016
15. Kaimal, V.K., and Vijayabalan, P., *J. Energy Inst*., 2017, vol. 90, p. 324. https://doi.org/10.1016/j.joei.2015.11.005
16. Pradhan, D., Bendu, H., Singh, R.K., and Murugan, S., *Energy*., 2017, vol. 118, p. 600. https://doi.org/10.1016/j.energy.2016.10.091
17. Mani, M. and Nagarajan, G., *Energy*, 2009, vol. 34, p. 1617. https://doi.org/10.1016/j.energy.2009.07.010
18. Periyasamy, P. and Geetha, N.K., *J. Taiwan Inst. Chem. Eng*., 2020, vol. 111, p. 346. https://doi.org/10.1016/j.jtice.2020.06.006
19. Das, A.K., Hansdah, D., Mohapatra, A.K., and Panda, A.K., *J. Energy Inst*., 2020, vol. 93, p. 1624. https://doi.org/10.1016/j.joei.2020.01.024
20. Damodharan, D., Sathiyagnanam, A.P., Rana, D., Saravanan, S., Rajesh Kumar, B., and Sethuramasamyraja, B., *Energy Convers. Manag*., 2018, vol. 166, p. 81. https://doi.org/10.1016/j.enconman.2018.04.006
21. Kumar, S., Radjarejesri, S., and Raj, Jawahar., *Mater. Today Proc*., 2020, vol. 33, p. 833. https://doi.org/10.1016/j.matpr.2020.06.272
22. Mangesh, V.L., Padmanabhan, S., Tamizhdurai, P., and Ramesh, A., *J. Clean. Prod*., 2019, p. 119066. https://doi.org/10.1016/j.jclepro.2019.119066
23. Chintala, V., Godkhe, P., Phadtare, S., Tadpatrikar, M., Pandey, J.K., and Kumar, S., *Energy Convers. Manag*., 2018, vol. 166, p. 579. https://doi.org/10.1016/j.enconman.2018.04.068
24. Kaimal, V.K. and Vijayabalan, P., *Fuel*., 2016, vol. 180, p. 90. https://doi.org/10.1016/j.fuel.2016.04.030
25. Kalargaris, I., Tian, G., and Gu, S., *Fuel Process. Technol*., 2017, vol. 157, p. 108. https://doi.org/10.1016/j.fuproc.2016.11.016
26. Venkatesan, H., Sivamani, S., Bhutoria, K., and Vora, H.H., *Alexandria Eng*., 2018, vol. 57, p. 2257. https://doi.org/10.1016/j.aej.2017.09.001
27. Damodharan, D., Sathiyagnanam, A.P., Rana, D., Kumar, B.R., and Saravanan, S., *Energy Convers. Manag*., 2018, vol. 161, p. 294. https://doi.org/10.1016/j.enconman.2018.01.045
28. Kumar, S., Prakash, R., Murugan, S., and Singh, R.K., *Energy Convers. Manag*., 2013, vol. 74, p. 323. https://doi.org/10.1016/j.enconman.2013.05.028