Environmental Science and Pollution Research (2021) 28:11976–11987
https://doi.org/10.1007/s11356-020-08625-3

ENVIRONMENTAL AND ENERGY MANAGEMENT

Derivation of synthetic fuel from waste plastic: investigation of engine operating characteristics on DI diesel engine

Sakthivel Rajamohan[1] · Joseph John Marshal[2] · Sidharth Suresh[1]

Received: 24 September 2019 / Accepted: 26 March 2020 / Published online: 17 April 2020

Abstract

The utilization of plastic in day to day life is ever-increasing and has generated a large amount of plastic garbage that needs proper disposal to save the environment from harmful pollution. The plastic waste management becomes a pressing concern in the present scenario in developing countries like India. This research article evaluates the potential of synthetic fuel (SF) derived from waste plastics collected from the local shops. In this current investigation, the SF blends are tested in a direct injection diesel engine to analyze the performance and emission characteristics of the engine. Three different blends were made namely SF20, SF40, and SF60 on a volumetric basis and the tests were carried out. From the experimental results, it was found that brake thermal efficiency (BTE) of the fuel blends was reduced as compared with neat diesel operation regardless of loads whereas SF20 showed a similar trend as that of diesel operation. The analysis of the emission characteristics revealed that the SF20 blends reduced dangerous smoke and carbon monoxide emission as compared with other test fuels. From the overall results, SF20 showed superior performance and emission aspects as compared with other SF blends whereas the engine operated smoothly up to 60% of SF blending at all loading conditions.

Keywords Synthetic fuel · Waste plastic pyrolysis · Brake thermal efficiency · Emissions

Abbreviation

BMEP	brake mean effective pressure
NO_x	oxides of nitrogen
CV	calorific value
CO	carbon monoxide
BTE	brake thermal efficiency
HC	hydrocarbon
BSFC	brake specific fuel consumption
CO_2	carbon dioxide
TF	test fuel

Responsible editor: Philippe Garrigues

✉ Sakthivel Rajamohan
sakthivelmts@gmail.com

[1] Department of Mechanical Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, India

[2] Department of Mechanical Engineering, Karunya Institute of Technology and Sciences, Coimbatore, India

Introduction

The modern day has brought the need for alternative fuels an immediate necessity. The spiked rise in population, the industrial revolution, etc. have brought about the decline in fossil fuels. The growing population has also increased the amount of waste produced, of which food and paper being the most. The other major contributor to solid waste is plastics accounting for 9–12% by weight (Kalargaris et al. 2018). The need for safe disposal of this plastic has become an issue as the absence of apt methods can lead to pollution of the environment, especially in countries like India, who are in the developing framework. The use of pyrolysis to convert plastics into fuel, therefore, has a dual scope. The British Petroleum (BP) statistical review (2018) showed that oil demand grew by 1.7 Mb/d which was remarkably higher than the 10-year average. The growth in demand for these fossil fuels has also increased the refining runs, which increased by 1.6 Mb/d (2017), which was twice the 10-year average. The surge in natural gas consumption was led by China with an increase of over 15%, accounting for one-third in the surge of global gas consumption. The global power generation improved by 2.8%; this was near to its 10-year average. Carbon emissions have increased by 1.6%

globally. Also, the fact that the carbon cycle, when we tap fossil fuels, is open has led to climate change. The need to negate the CO_2 emissions to close the carbon cycle is exigent. The need for renewable sources of energy either derived from non-carbon sources (sunlight, oceans, etc.) or working on a closed carbon cycle is paramount. Bio-fuels work on the closed carbon cycle as they are used produced from bio-mass, which are CO_2-consuming.

Alternative fuel research has shown a promising future. The use of bio-fuels has shown promising abilities to replace fossil fuels. The bulk of the fossil fuels used in the transportation sector can be replaced by these fuels if they can show promising results. Plant bio-mass, apart from bio-diesel and bio-ethanol, is a potential source of renewable energy to meet demands which are currently using fossil fuels. The abundance of plastic wastes shows that pyrolysis can be a viable option for the production of bio-oils. The researches on the viability of bio-fuels as an adequate fuel for diesel engines are shooting up. Therefore, the use of pyrolysis to convert biomass into bio-fuels can be a viable source.

Pyrolysis is a promising waste recycling technology using chemical reactions for plastics. Pyrolysis involves the thermal degradation of complex molecules into short-chained molecules at an elevated temperature and in the partial presence or without oxygen. The phase of the pyrolysis product is generally liquid and the product quality depends on the plastic feedstock used and process parameters (Kalargaris et al. 2018). The gaseous products are made of CH_4, CO_2, H_2, and N_2 and traces of volatile compounds that can be used to power the pyrolysis reactors (Rajamohan and Kasimani 2018a). Bio-oils find its use in powering furnaces, boilers, etc. due to its high oxygenation and ester components.

Pyrolysis from plastics has an added advantage of not raising the food vs. fuel issue which arises when bio-fuels are made from bio-mass. The pyrolysis process always raises the question of quality, modification of the system using these, and also the production costs. The introduction of the ASTM standard D7544 has now made the introduction of pyrolysis in the fields of transportation, heating and cooling, and power generation a possible future. The ignition delay, high-water content, low thermal stability, etc. have posed the question of pyrolysis oil being a good fuel. The fact that these oils, when blended with diesel, can produce effective and efficient results is promising. The use of pyrolysis on a heterogeneous feed to produce viable fuels, therefore, can be a promising solution for the future. Furthermore, the absence of engine modification needs also helps in the application of these fuels into the transportation sector easily. Furthermore, it also has the added advantage of waste to energy conversion adding to waste management solutions. Therefore, plastic pyrolysis can prove to be a solution for waste management and alternative energy.

Diesel engines are the most suited machines for converting chemical energy to mechanical energy and hence are used predominantly. The use of pyrolysis-produced bio-oils to power this sector can yield good results for the environment. The bio-oil and diesel blends have high scope in this field. The bio-oils, even though they have well-oxygenated components, cannot be directly used in IC engines as the oils have a high-water content with corrosive elements present (Rajamohan and Kasimani 2018a). The research in the field of using a bio-fuel and diesel blend to power IC engines has been shooting up. These researches mainly investigate the performance and combustion characteristics of CI engines while decreasing the emissions produced, which is the need for these alternative fuels.

Kumaravel et al. have reviewed the importance of alternative fuels for diesel engines with importance given to tire pyrolysis (Kumaravel et al. 2016). The paper involves a study on the pyrolysis reactors, processes, mechanisms, yield, etc. The experiment was conducted in an inert environment. The study revealed that nitrous oxide, hydrocarbon, and carbon dioxide emissions were higher due to the aromatic content and the higher ignition delay at higher loads. Other engine characteristics were also analyzed. Quesada et al. have investigated the possibility of recycling municipal plastics using pyrolysis. The work aimed at obtaining liquid fuels from different operating conditions. The fuels were characterized both physically and chemically to ensure quality and results revealed that both the characteristics of the fuel resembled the properties of commercial fuels (Quesada et al. 2019). The results also revealed that pyrolysis oil blends of waste tires TF5, TF10, TF25, and TF35 can be utilized without any modification in diesel engines. With the reduction in aromatic compounds, this can become a viable source of fuel. Kalargaris et al. have studied the extraction of oils from plastic pyrolysis (Kalargaris et al. 2017a). Pyrolysis oils from polyethylene (LDPE700) and ethylene–vinyl acetate (EVA900) were produced at 700° and 900° respectively. The results showed that the operation of the engine, using both the oils, could be achieved without the inclusion of diesel. LDPE700 presented similar characteristics of diesel. The NO_x, CO_2, and CO emissions were lower but HC emissions proved to be higher for the same. The latter, EVA900, however, did not have better results than diesel and the addition of diesel to it did not have any prominent effects. Dobó et al. have verified the suitability of plastic pyrolysis fuels in a spark ignition engine. The work mainly dealt with the thermal pyrolysis of HDPE (high-density polyethylene), LDPE (low-density polyethylene), PP (polypropylene), PS (polystyrene), PET (polyethylene terephthalate), and PUR (polyurethane) plastic wastes. The oils produced from pyrolysis were upgraded by atmospheric distillation to separate the transportation fuels. The results showed that the oils showed elevated amounts of CO emissions compared with gasoline and reduced NO_x

emissions compared with the gasoline reference (Dobó et al. 2019). Kalargaris et al. have studied the characteristics of a diesel engine running on plastic pyrolysis oils produced by fast pyrolysis from a feed of different plastics (Kalargaris et al. 2017b). A four-stroke direct injection engine was run using pyrolysis oil–diesel blends from 0 to 100% which was used at different loads from 25 to 100% and this was studied. The engine parameters which were analyzed consisted of combustion, performance, and exhaust emissions. The results showed that BTE at full load was slightly reduced compared with diesel for plastic pyrolysis oils and emissions were increased. The study also showed that these blends have a prolonged ignition delay and a higher heat release rate. Sharma and Murugan have experimented with the use of TPO-JME blends in a single-cylinder, four-stroke, air-cooled, direct injection (DI) diesel engine to test its viability as an alternative fuel (Sharma and Murugan 2013). Five blend ratios namely 10%, 20%, 30%, 40%, and 50% was used. The 30%, 40%, and 50% showed a reduction in efficiency at 100% load. The combustion and emission characteristics deviated after 20%. JMETPO20 gives the optimum result, compared with the others. Yang et al. has studied the properties and characteristics of sewage sludge–derived intermediate pyrolysis oil (SSPO) and bio-diesel blends and evaluated its application. The investigation involved the study of the performance and emission analysis (Yang et al. 2013). The oils were found to have heating value comparable to that of the bio-diesel. The results showed that the 3% blend gave lesser NO_x emissions compared with the 50% even though the exhaust temperatures for both the blends were the same. The smoke emission, on the contrary, showed a dip for the 50% blend. The SSPO blends were found to have added carbon depositions and a lowered opening pressure and, therefore, can lead to deteriorated engine performance. Prasad and Murugavel have studied the pyrolysis of toato peels. The oil produced was then analyzed for engine purposes. The performance, emission and combustion characteristics was found out for a 5%, 10%, and 25% blend. The results revealed that the amount of HC and CO emissions was reduced and the NO_x emissions were increased. The combustion analysis revealed that the O_2 content in the tomato peel oils was more than that of diesel resulting in a higher heat release rate (Midhun Prasad and Murugavelh 2020). Ramanathan and Santhoshkumar have investigated the conversion of waste engine oil into diesel-like fuels using pyrolysis. The fuel showed a higher calorific value and lower NO and smoke emission when operated in a CRDI diesel engine. The thermal efficiency also improves on operation (Ramanathan and Santhoshkumar 2019). Yang et al. have studied the application of bio-oil obtained from the fast pyrolysis of coffee bean residue using a single-cylinder diesel engine (Yang et al. 2014). The coffee bean residue pyrolysis oil (CPO) has been mixed with diesel, through emulsifications, in varying proportions and its characteristics have been checked. The mixtures were at 0%, 5%, and 10%. The 5% and 10% blends showed higher fuel consumption and the emulsification increased certain aspects of combustion. The bio-oil mixture showed a promising reduction in NO_x emission reduction whereas the overall combustion efficiency and heating values were reduced. Kalargaris et al. have analyzed the outcome of pyrolysis temperature on polypropylene pyrolysis while using the oils PP700 and PP900 to run a four-cylinder diesel engine (Kalargaris et al. 2018). The engine parameters like combustion, emission, and performance were noted. The results revealed that PP700 and PP900 had longer combustion time and ignition delays with reduced thermal efficiencies. The HC and NO_x emissions were high whereas the CO_2 emissions were lower. The inclusion of a small amount of diesel increased the performance of the blends with PP900 producing similar results like that of diesel engines. Hudrogan et al. have analyzed the performance and emission characteristics of oil blends of diesel and waste tires produced by pyrolysis. The waste tire pyrolysis oil blends were compared with petroleum and diesel fuels and resemblance with diesel was noted. The 10% blend showed results comparable with that of diesel operation. The study concludes with the 10% waste tire pyrolysis oil being the closest to that of diesel operation (Hürdoğan et al. 2017). Wang et al. have studied the use of waste pyrolysis oil in a direct injection engine. The study focusses on monitoring the fuel consumption, engine power, and SO_2 emissions. The study showed that all blends of the waste tire pyrolysis oil worsened the engine performance. The paper also reveals that increasing the pyrolysis temperature can increase the performance (Wang et al. 2016). Vihar et al. have studied the operation of a 4-cylinder, turbocharged and intercooled, diesel engine run using a pure tire pyrolysis oil (Vihar et al. 2017). The use of this oil, with assistance from of pilot injection, is limited to medium-high load operations. The study had a primary operation of investigating the extension of the operating range to the lower side and the secondary objective being to study the emission characteristics. The results showed promising results while using strategized EGR to reduce and control emissions. Prakash et al. have described the use of bio-oil from waste wood pyrolysis in a single-cylinder, air-cooled, direct injection, diesel engine used in agricultural applications with an rpm of 1500 (Prakash et al. 2013). The emission, combustion, and performance of the engine were analyzed for three emulsions made from Jatropha methyl ester and wood pyrolysis oil. The results showed a shorter ignition delay accompanied by a significant reduction in NO emissions and smoke opacity reduction in comparison to diesel-fuelled engines. Umeki et al. have studied the properties of diesel-pyrolytic oil blends (Umeki et al. 2016). The pyrolytic oil was produced from the degradation of the tire, which had a black color and unpleasant odor. The TPO used in this study showed heat values lowered in comparison with diesel but the results revealed that the oil was miscible with diesel and promised potential viability as an alternative fuel. Krutolf and Hawboldt have reviewed the potential of pyrolysis oil blends in diesel engines. The paper shows that engines, mostly, require modifications in their systems (Krutof and Hawboldt 2016). The use of crude pyrolysis oil is limited and, therefore, processes like transesterification and hydro-processing are necessary to improve its fuel properties. The results also show that the oil is less miscible. The results also highlighted the challenges in blending bio-oils and also highlighted plausible solutions. Therefore, the work focuses on the promise of pyrolysis on waste plastics as an alternative fuel and a solution to solid waste management. The work shines its light on the experimental analysis of operating characteristics of a direct injection (DI) diesel engine powered by the plastic pyrolysis oil. The novelty of the work lies in extracting fuel from waste milk packet covers and using it in IC engines which is not much explored in previous research articles.

Materials and methods

Physico-chemical properties

The waste milk packets are collected from the local tea shops and hotels. Then, it is shredded and processed to carry out the pyrolysis trials. The properties of the plastic pyrolysis oil used for the investigation and engine testing are tabulated in Table 1. Kinematic viscosity is measured by Brookefield digital viscometer and a bomb calorimeter is utilized to determine the calorific value of the fuel. Flash and fire points were evaluated by Pensky Marten's closed cup apparatus. Density is measured by hydrometer. All measurements were taken as per the guidelines prescribed by ASTM. The details, range, and accuracy of the equipment used are tabulated in Table 3. It can be seen that the density of the plastic oil is high as compared with diesel whereas viscosity and flash points are of incomparable range within ASTM standards. On the other hand, the calorific value and cetane number are lower than diesel which may deteriorate the performance of the engine during operation. Higher viscosity and density negatively affects the spray characteristics of the fuel during engine operation and leads to poor atomization. Meanwhile, lower cetane rating increases the ignition delay which in turn augments specific emissions at the exhaust.

Table 1 Physico-chemical properties of plastic oil

Property	SF100	Diesel
Density (kg/m^3)	986	843
Kinematic viscosity (cSt)	4.97	2.6
Calorific value (MJ/kg)	37.25	44.7
Flash point (°C)	41	63
Fire point (°C)	49	72
Cetane number	42	51

Engine testing

A single-cylinder DI diesel engine was used for effectuating the engine testing. The performance and emission testing of bio-oil were enhanced by coupling the engine with an eddy current dynamometer. The detailed specification of the test engine is given below in Table 2.

All the experiments were carried out at standard compression ratio and injection timing. The exhaust gas emissions were analyzed using an AVL Modular Diagnostic System (MDS-250) exhaust gas analyzer and AVL smoke meter. The non-dispersive infrared testing principle was utilized to measure oxides of carbon in the exhaust. Within the gas analyzer setup, a flame ionization detector and a chemical luminescence detector were employed for determination of the magnitude of HC and NO.

Pyrolysis reactor setup

A fixed bed batch type reactor was used for the pyrolysis procedure (Fig. 1). The reactor is customized with heating arrangements and feeding arrangements. The feed is a top feed and the rate of heating was 30 °C/min. The cylinder reactor had a core with an inner diameter of 20 cm and a feed capacity of 2 kg and was heated with an electric heater with a rating of 240 V and 9.5 A rating. A PID controller integrated with a K-type thermocouple was used to control the heating and temperature. The gases evolved during the pyrolysis were cooled using a shell and tube heat water-cooled setup.

Experimental methodology

The reactor, initially, is cleansed of char and other dirt. The temperature is maintained using a PID controller and the

Table 2 Engine specification

Make	Kirloskar
No. of cylinder/stroke	1/4
Cylinder bore	87.5 mm
Cylinder stroke	110 mm
Compression ratio	17.5
Type of injection	Direct injection
Injection timing	23° bTDC
Engine speed	1500 rpm
Rated output	3.5 kW at 1500 rpm
Cooling system	Water cooling

Fig. 1 Pyrolysis setup

reactor is sealed with a PTFE gasket to ensure its isolation from the surroundings. Dimmerstat was utilized to regulate and set the voltage and PID is used to set a target temperature of 500 °C. On reaching the target temperature, the supply is cut off. The vapors evolved, on starting the reaction, are passed through the condenser arrangements. The condensed product i.e. plastic oil is collected and the other traces of non-condensable gases are left. The gaseous product is collected and GC analysis is conducted to find the composition. The residue of char formed is collected after the reactor is cooled in still air. The test fuel samples are prepared by blending plastic oil with diesel fuel in various proportions through emulsification by adding a minimum amount of surfactants (1% volume) for better blending. Span-80 and Tween-80 are used as surfactants in this present study.

The engine was run at rated speed under variable loading to assess the operating characteristics. The engine was operated with diesel before operating with plastic oil blends to ensure stability. Built-in Engine Soft software was used to evaluate the engine data. The readings were recorded for each test fuel run after the engine reaches a steady-state to maintain accuracy. The steady-state conditions were ensured by monitoring the engine data through Engine Soft software and stabilizing the speed, torque, temperatures, and pressures by allowing the engine to operate at the set load for a limited period. After the completion of each test fuel run, the engine was operated with neat diesel to eliminate the residual fuel in lines.

The gas analyzer was allowed to warm-up on starting. The leak test was done by purging the gas flow through the test lines. After passing the leak test, the HC residue test was carried out to ensure that there were no carbon particles in the testing lines due to previous test runs. After passing the preliminary test runs, the probe was placed in an exhaust tailpipe to gather the gas into the system for analysis. The results were analyzed by the automated AVL software.

Uncertainty analysis and instrument details

Uncertainty analysis is used to determine the validity of the results obtained from an instrument. The fitness value in a typical measurement is impossible to assess without the help of uncertainty analysis. As the present work involves the utilization of the fair number of the equipment for characterization and testing, it becomes inevitable to employ uncertainty analysis to validate the results (Paramasivam et al. 2019). Each experiment was replicated in triplicate and the average value is taken to ensure the reliability in results. The analysis was conducted at a confidence level of 95% and the results are given in Table 3.

Results and discussions

The results from the engine analysis are discussed in this section. Three different blends namely SF20, SF40, and SF 60 was tested and compared against dieseloperation. The analysis focused on comparing the performance and emission characteristics with varying BMEP. The tests were effectuated in standard compression ratio and ignition timing of the engine to analyze the effects of blended fuel at standard conditions and compare it with diesel operation.

Table 3 Accuracy, range, and uncertainties of the instruments used in the investigation

Instruments used	Range	Accuracy	Uncertainty
Engine testing			
BTE	NA	± 0.5%	± 0.05
BSFC	NA	± 0.05 kg/kW h	± 0.02
Density meter	0–3 g/cc	± 0.01 g/cc	± 0.28
Bomb calorimeter	0–50 MJ/kg	± 0.05%	± 1.23
Thermocouple (K-type)	− 150 to 1300 °C	± 1 °C	± 0.1
Pensky Martens apparatus	0 to 350 °C	± 2 °C	± 1.68
Emission testing			
CO_2	0–20% vol	± 0.03 vol%	± 0.5
NO_x	0–5000 ppm	± 1 ppm	± 2
HC	0–30,000 ppm	± 1 ppm	± 2
CO	0–15% vol	± 0.01 vol%	± 2
Smoke	0–100%	± 0.1%	± 1.25

The performance characteristics consist of the BTE and the BSFC. The emission characteristics included the analysis of CO, HC, NO_x, and smoke emissions.

Performance characteristics

The performance characteristics have dealt with the investigation of the BTE and BSFC with varying BMEP. The different blends were compared with each other as well as diesel fuels. Figure 2 shows the change in BTE with BMEP for the blends as well as diesel. Of the three blends, SF20 showed the best BTE and was close to that of diesel at 4.19 bar BMEP.

The results were obtained by averaging out the results from the data obtained from experimenting three times to ensure the reliability of the results. Table 1 shows the uncertainties associated with the components of the experimental setup.

The SF60 showed low BTE at 2.1 bar BMEP (namely, 24.9%) compared with the diesel fuel which showed a BTE of 27.14%. The BTE of the blends increased with BMEP and SF20 showed a maximum of 28.12% BTE which was sufficiently close to that of diesel (28.25%). The reduced performance of the other blends might be because the ignition delay period is not reduced, which is done by diesel in the lower ratio blends (Krutof and Hawboldt 2016). Longer ignition delays increase the energy loss which could have been converted into useful work. The lower calorific value and cetane rating, in higher ratio blends, also causes the reduction of BTE (Sakthivel et al. 2019).

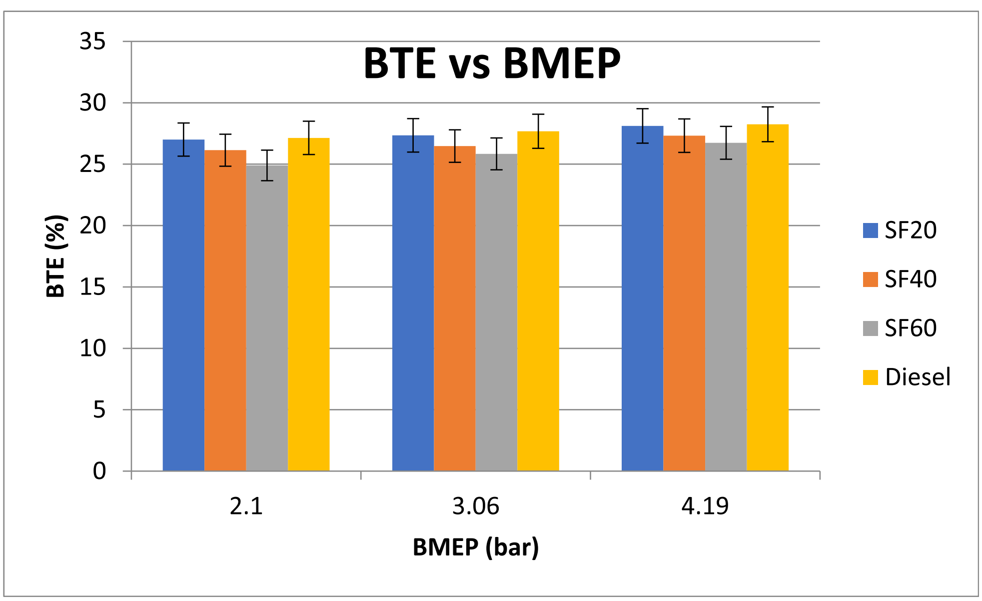

Fig. 2 Variation of BTE with BMEP

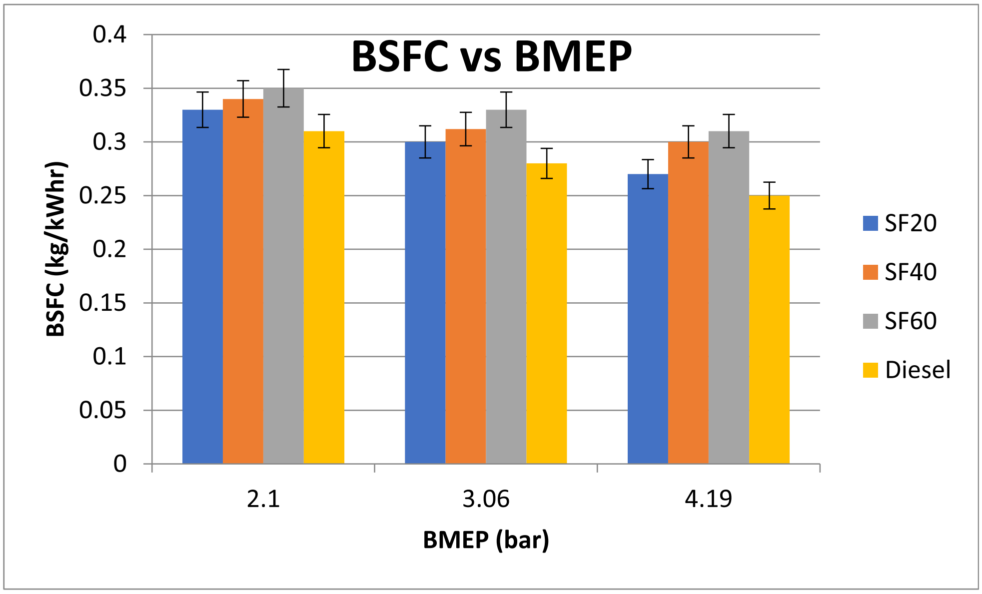

Fig. 3 Variation in BSFC Vs BMEP

Figure 3 shows the BSFC variation with BMEP. As the blend ratio increases, the BSFC increases. Diesel-fuelled engine showed the lowest BSFC out of all the fuels that were tested and SF20 showed the lowest of the blends. As the BMEP increases, the BSFC reduces. As the blend ratio increases, the BFSC grows higher as the calorific value decreases and heat loss in ignition delay is more due to the lower ratio of diesel. The increased viscosity of the fuel results in lower quality of atomization and, therefore, the BSFC increases (Baranitharan et al. 2019). The SP20 blend showed the best BSFC characteristics (0.27 kg/kWh) compared with SF40 (0.3 kg/kWh) and SF60 (0.31 kg/kWh) at 4.19 bar BMEP and was close to that of diesel fuel (0.25 kg/kWh). The BSFC was more at a BMEP of 2.1 bar because low pressure decreases the atomization efficiency and improper mixing (Kalargaris et al. 2018).

Emission characteristics

The emission characteristics involve the study of NO_x, CO, and HC emissions and its variation with BMEP. The emission characteristics of different blends at varying BMEPs are analyzed.

Figure 4 shows how the CO emissions are varying with the BMEP. CO emissions result in an effect of incomplete combustion of fuel. It may be due to either the richness of the air-fuel mixture or pure atomization of the fuel. Figure 3 shows that SP20 shows the lowest CO emissions (0.2% vol at 4.19 BMEP) compared with SF40 (0.25% vol at 4.19 BMEP) and SF60 (0.29% vol at 4.19 BMEP). At lower BMEP, rich mixtures are required to accelerate the engine and therefore the CO emissions become higher. As the blend ratio increases, the viscosity increases which causes the atomization quality and efficiency to decrease, causing an increase in CO emissions(Rajamohan and Kasimani 2018b). At 2.1 bar BMEP, the SF20, SF40, and SF60 have 0.28, 0.34, and 0.38 (%vol) respectively. The SF blends have elevated CO emission in comparison to diesel-fuelled combustion which had a CO emission of 0.25% vol at 2.1 bar BMEP and 0.15%vol at 4.19 BMEP. SF20 blend showed results close to that of diesel-fuelled engines due to its lesser viscosity and higher calorific value.

HC emissions are a result of unburnt fuel due to insufficient temperature. Generally, it is a phenomenon happening from areas near the cylinder walls where the temperatures are low. HC emissions are a result due to the use of rich fuel mixtures. If the temperature is sufficiently high enough, these HC can combine with oxygen to form non-polluting compounds. HCs are a polluting component and hurt human health as it causes severe respiratory and cardiac issues. Plastic oil blends show elevated HC emissions at the exhaust in comparison with that of diesel operation. Figure 5 shows that the SF20 blend has the lowest HC emission (52 ppm at 2.1 bar; 48 ppm at 3.06 bar; 43 ppm at 4.19 bar) compared with the other blends with SF60 having greatly higher emissions. As the BMEP increases, the HC emission decreases due to lower ignition delay and higher in-cylinder temperatures (Prakash et al. 2013). The viscosity decreases the atomization quality of the fuel which causes an increase in the HC emission characteristic. Diesel has the lowest HC emission (49 ppm at 2.1 bar; 42 ppm at 3.06 bar; 38 ppm at 4.19 bar) because of a lower ignition delay and lower viscosity in comparison with the fuel used. SF20 shows results close to that exhibited by diesel. The higher ignition delay tends to induce knocking characteristics in engines. This can cause an improper function of the engine.

The smoke formation is associated with the formation of particulate matter and incomplete combustion. This may be an effect of the high temperature and rich fuel mixture (Pradhan

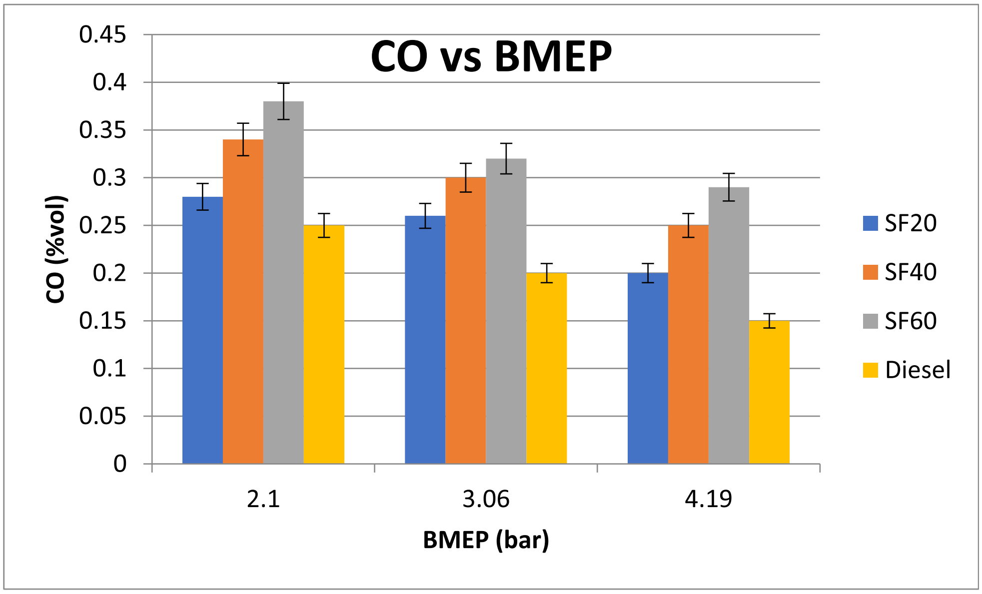

Fig. 4 The variation of CO emissions with BMEP

et al. 2017). Smoke being so visible and odorous is objected to the public and also reduces visibility and has daubing character, but is not harmful to health generally. In CI engines, the smoke formation occurs due to the inconsistencies in the air-fuel mixtures as well asan insufficient air supply. Figure 6 shows that the percentage volume of smoke emission grows with the blend ratio. SF20 has the lowest emission (36% vol at 2.1 bar; 33% vol at 3.06 bar; 29% vol at 4.19 bar) compared with SF40 (38% vol at 2.1 bar; 35% vol at 3.06 bar; 30% vol at 4.19 bar) and SF60 (40% vol at 2.1 bar; 36% vol at 3.06 bar; 32% vol at 4.19 bar). This is because of the increase in viscosity and lower calorific value of the oil. The atomization quality and effectiveness depend largely on the fuel's viscosity and is affected drastically by its increase. As viscosity increases, the quality of atomization decreases, thereby decreasing the combustion efficiency and increasing the smoke emission. Diesel fuel exhibited better smoke emission characteristics (35% vol at 2.1 bar; 31% vol at 3.06 bar; 27% vol at 4.19 bar). SF20 showed smoke emission characteristics similar to diesel. The use of higher blends, therefore, would require the use of extensive filtering systems to manage the exhaust emissions to be on par with the emission norms of current day.

NO_x emissions are a result of the reaction of nitrogen present in air and oxygen at very high (in-cylinder) temperatures. The amount of NO_x present is closely related to the in-cylinder temperatures of the engine as well as the quantity of available oxygen. NO_x emission generally consists of NO and NO_2 with NO emissions being the majority. NO is generally converted into NO_2 in

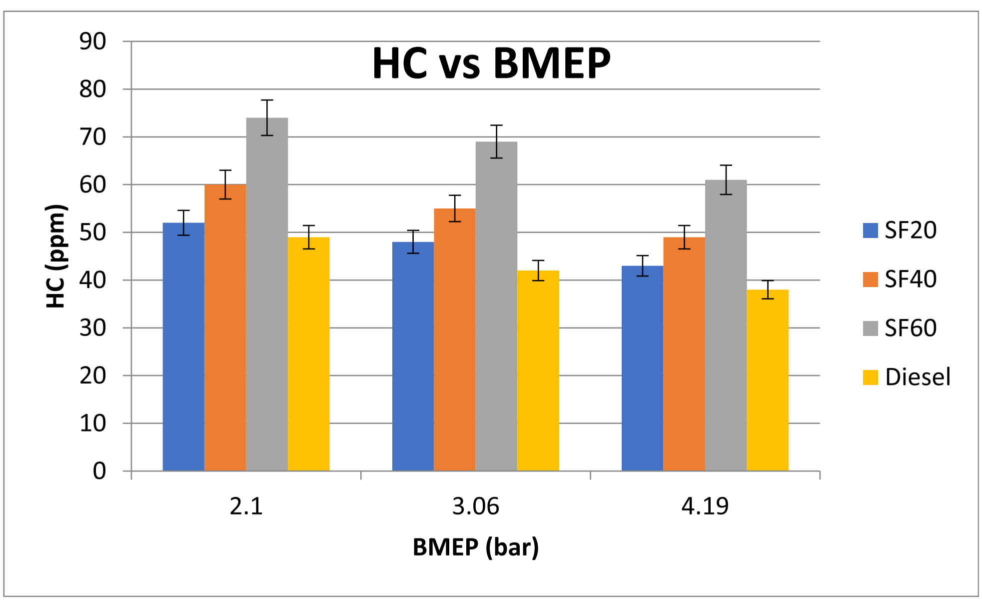

Fig. 5 Variation of HC emission with BMEP

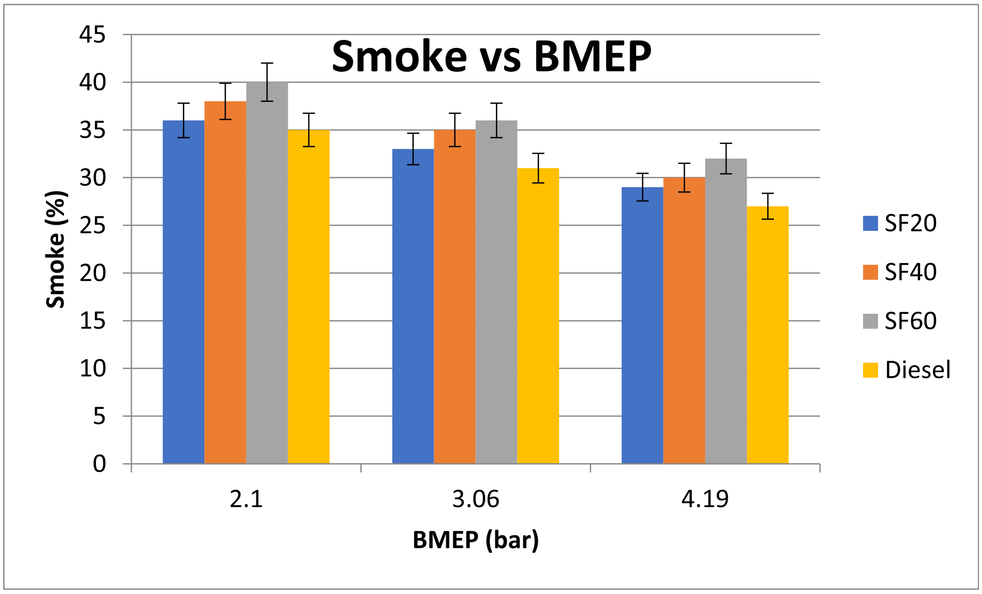

Fig. 6 Variation of smoke emission with BMEP

atmospheric conditions gradually. NO_x emissions are generally formed in the early stages of combustion. NO_x gases are hazardous and toxic for human life as they cause respiratory deceases as well as environmental hazards like acid rain. Except for SF20, all the plastic oil blends showed augmented NO_x magnitude at all loading conditions as compared with diesel fuel which can be seen from Fig. 7. As the pyrolysis oil blend ratio increased, the value of NO_x at exhaust increased at all loads. Specifically, SF60 showed a 13.47% increase in NO_x value at peak load compared with diesel fuel whereas the same augmentation was 16.21% as compared with that of SF20. The augmentation NO_x at the high blending of plastic pyrolysis oil can be attributed to a low cetane number of blended fuels which on the other hand augments fuel in the diffusion combustion phase thereby elevating the combustion temperature.

Combustion characteristics

The net heat release rate is the quantitative measure of effective combustion. Figure 8 shows that SF blends and diesel have a similar profile. The increase in the blend ratio also prolongs the ignition delay as well as lowers the combustion period. As the ignition delay increases, the fuel atomization is improved and, therefore, the heat release rate increases (Kalargaris et al. 2017b). This is seen as the SF60 blend has the highest heat release rate, slightly higher than that of diesel.

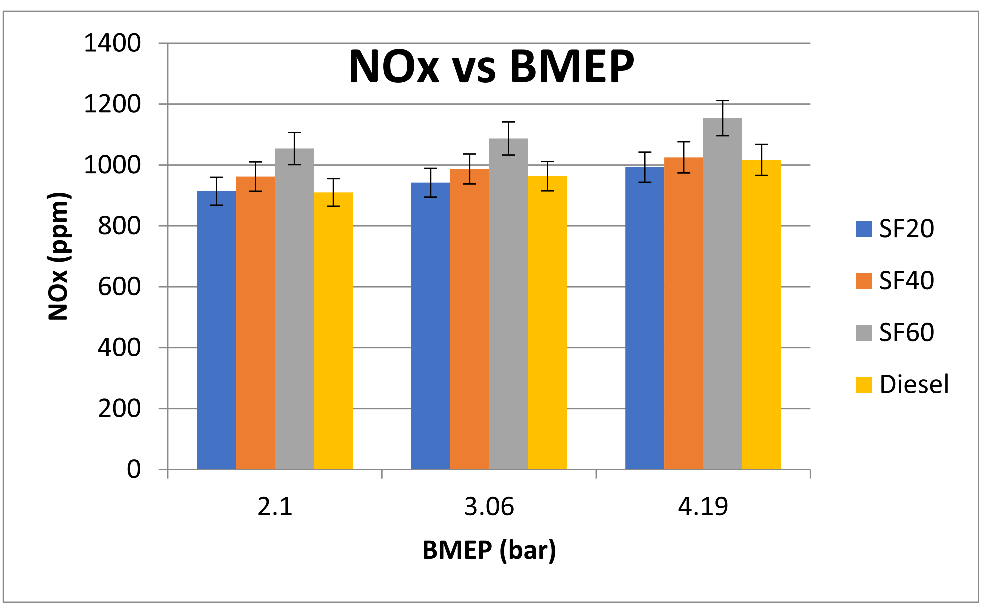

Fig. 7 Variation of NO_x emission with BMEP

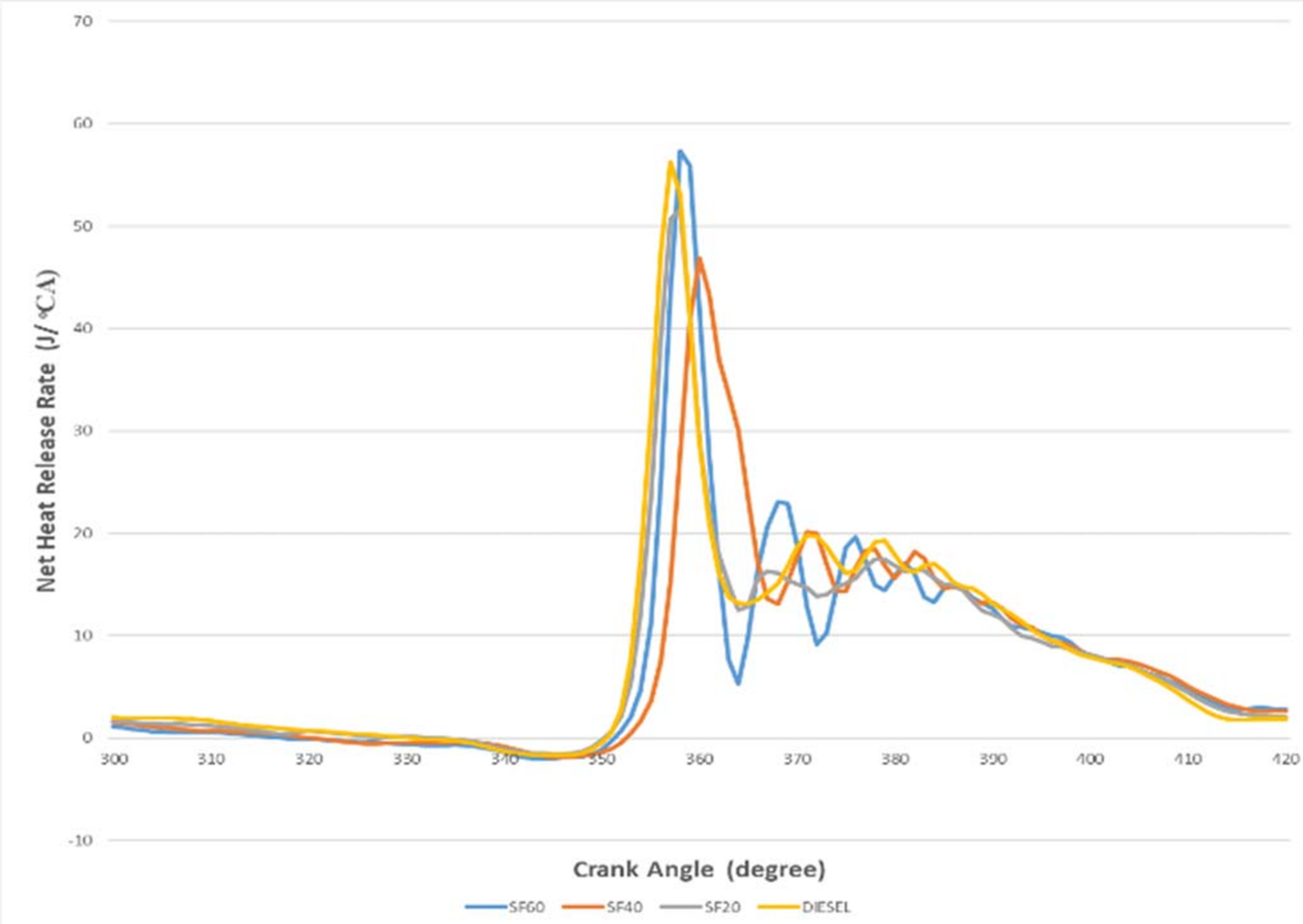

Fig. 8 Variation of net heat release rate with crank angle

The period of combustion, similarly, is prolonged for a lower blend ratio as the combustion is prolonged. Figure 8 also allows us to conclude that SF60 will not be an ideal fuel for long-term use as it has a high heat release rate and therefore can have harmful effects on the engine. The net heat release rate also increases the in-cylinder temperature thereby contributing to the NO_x emissions as seen in Fig. 7. SF20 has the lowest heat release rate which is explained by its lower ignition delay and lower viscosity.

The cylinder pressure profiles are similar to that of diesel which is illustrated in Fig. 9. Lower blending ratios have no significance on the cylinder pressure. The SF20 blend has a cylinder pressure close to that of diesel. This might be due to the decrease in viscosity of the fuel which increases atomization, in turn, increases the premixed combustion (Kalargaris et al. 2017b; Sakthivel et al. 2019). The ignition delay was longer as the blend ratio increased resulting in unstable combustion. This causes knocking in CI engines which is undesirable. Therefore, the viscosity must be kept in check and higher blends would require some modifications in the engine to overcome this ignition delay.

Conclusion

An experimental investigation of the characteristics of different plastic oil–diesel blends (SF20, SF40, and SF60) was conducted. The performance, emission and combustion characteristics of different blends were compared with that of diesel. The following results were observed from the analysis:

i. The BTE declined with the augmentation of plastic oil in the blend and increased with BMEP. The BSFC showed inverse trending as that of BTE at all test conditions. This phenomenon can be attributed to poor cetane rating and calorific value of the plastic oil. At all loading conditions, SF20 showed superior performance as compared with other plastic oil blends.

ii. The CO and HC emission increased with blend ratio due to unburnt species and increased viscosity. For all the blends, CO and HC inversely vary with respect to BMEP. The incomplete nature of the test fuels due to poor atomization is addressed as the root cause of the increased emission levels.

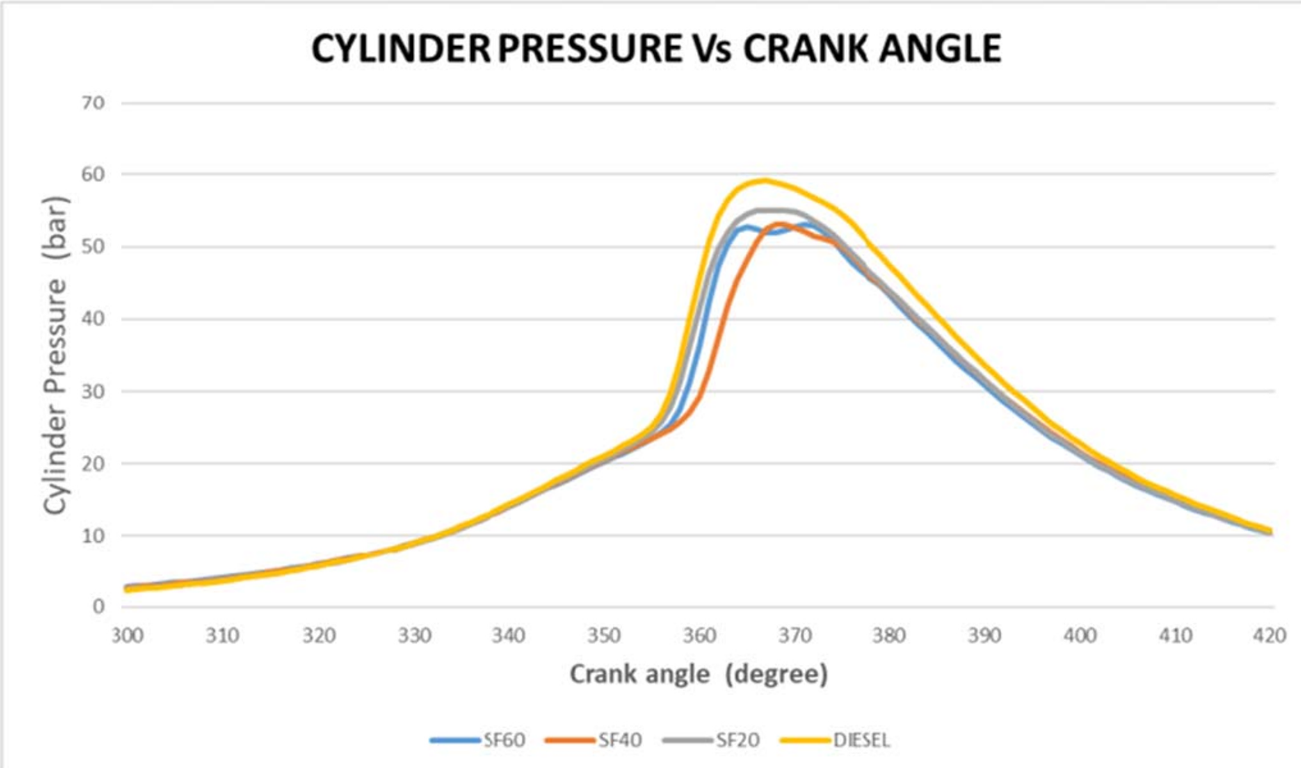

Fig. 9 Variation of cylinder pressure with crank angle

iii. On the contrary, NO_x emission increases with the increase in BMEP as reported in previous studies. Due to delayed cetane rating and increased ignition delay period of the plastic oil, more fuel is burned in the premixed combustion phase leading to augmented NO_x emission owing to the increased combustion temperature. The SF20 blends showed the best emission characteristics amongst all the blends.

iv. The heat release rate profile is similar for the blends as well as diesel. The SF60 blend showed a higher heat release rate (slightly higher than that of diesel). The ignition delay also increases with the blend ratio contributing to the same.

v. The cylinder pressure profile revealed that at a lower blend ratio, the cylinder pressure increases. The pressure profiles were similar. SF20 blend showed promising characteristics and was close to that of diesel.

The characteristics of the plastic oil at lower blending ratios (SF20) show promising results from the analysis. The use of technologies like EGR and engine preheating can increase the thermal efficiency of the engine which can be taken as future scope of this present study. The utilization of these technologies may turn waste plastic oil–diesel blends as a viable source of fuel which is a promising resource for the future. Therefore, the waste plastics can be recycled with proper waste to energy conversion and therefore serves a dual purpose.

References

Baranitharan P, Ramesh K, Sakthivel R (2019) Measurement of performance and emission distinctiveness of Aegle marmelos seed cake pyrolysis oil/diesel/TBHQ opus powered in a DI diesel engine using ANN and RSM. Measurement 144:366–380

Dobó Z, Jakab Z, Nagy G, Koós T, Szemmelveisz K, Muránszky G (2019) Transportation fuel from plastic wastes: production, purification and SI engine tests. Energy 189:116353

Hürdoğan E, Ozalp C, Kara O, Ozcanli M (2017) Experimental investigation on performance and emission characteristics of waste tire pyrolysis oil–diesel blends in a diesel engine. Int J Hydrog Energy 42:23373–23378

Kalargaris I, Tian G, Gu S (2017a) Experimental evaluation of a diesel engine fuelled by pyrolysis oils produced from low-density polyethylene and ethylene–vinyl acetate plastics. Fuel Process Technol 161: 125–131

Kalargaris I, Tian G, Gu S (2017b) Combustion, performance and emission analysis of a DI diesel engine using plastic pyrolysis oil. Fuel Process Technol 157:108–115

Kalargaris I, Tian G, Gu S (2018) Experimental characterisation of a diesel engine running on polypropylene oils produced at different pyrolysis temperatures. Fuel 211:797–803

Krutof A, Hawboldt K (2016) Blends of pyrolysis oil, petroleum, and other bio-based fuels: a review. Renew Sust Energ Rev 59:406–419

Kumaravel ST, Murugesan A, Kumaravel A (2016) Tyre pyrolysis oil as an alternative fuel for diesel engines – a review. Renew Sust Energ Rev 60:1678–1685

Midhun Prasad K, Murugavelh S (2020) Experimental investigation and kinetics of tomato peel pyrolysis: performance, combustion and emission characteristics of bio-oil blends in diesel engine. J Clean Prod 254:120115

Paramasivam B, Kasimani R, Rajamohan S (2019) Experimental assessment and multi-response optimization of diesel engine performance and emission characteristics fuelled with Aegle marmelos seed cake pyrolysis oil-diesel blends using Grey relational analysis coupled principal component analysis. Environ Sci Pollut Res 26:6980–7004

Pradhan D, Bendu H, Singh RK, Murugan S (2017) Mahua seed pyrolysis oil blends as an alternative fuel for light-duty diesel engines. Energy 118:600–612

Prakash R, Singh RK, Murugan S (2013) Experimental investigation on a diesel engine fueled with bio-oil derived from waste wood–biodiesel emulsions. Energy 55:610–618

Quesada L, Calero M, Martín-Lara MA, Pérez A, Blázquez G (2019) Characterization of fuel produced by pyrolysis of plastic film obtained of municipal solid waste. Energy 186:115874

Rajamohan S, Kasimani R (2018a) Analytical characterization of products obtained from slow pyrolysis of Calophyllum inophyllum seed cake: study on performance and emission characteristics of direct injection diesel engine fuelled with bio-oil blends. Environ Sci Pollut Res 25:9523–9538

Rajamohan S, Kasimani R (2018b) Studies on the effects of storage stability of bio-oil obtained from pyrolysis of Calophyllum inophyllum deoiled seed cake on the performance and emission characteristics of a direct-injection diesel engine. Environ Sci Pollut Res 25:17749–17767

Ramanathan A, Santhoshkumar A (2019) Feasibility analysis of pyrolysis waste engine oil in CRDI diesel engine. Energy Procedia 158:755–760

Sakthivel R, Ramesh K, Joseph John Marshal S, Sadasivuni KK (2019) Prediction of performance and emission characteristics of diesel engine fuelled with waste biomass pyrolysis oil using response surface methodology. Renew Energy 136:91–103

Sharma A, Murugan S (2013) Investigation on the behaviour of a DI diesel engine fueled with Jatropha methyl Ester (JME) and tyre pyrolysis oil (TPO) blends. Fuel 108:699–708

Umeki ER, de Oliveira CF, Torres RB, Santos RGD (2016) Physicochemistry properties of fuel blends composed of diesel and tire pyrolysis oil. Fuel 185:236–242

Vihar R, Žvar Baškovič U, Seljak T, Katrašnik T (2017) Combustion and emission formation phenomena of tire pyrolysis oil in a common rail diesel engine. Energy Convers Manag 149:706–721

Wang W-C, Bai C-J, Lin C-T, Prakash S (2016) Alternative fuel produced from thermal pyrolysis of waste tires and its use in a DI diesel engine. Appl Therm Eng 93:330–338

Yang Y, Brammer JG, Samanya J, Hossain AK, Hornung A (2013) Investigation into the performance and emissions of a stationary diesel engine fuelled by sewage sludge intermediate pyrolysis oil and biodiesel blends. Energy 62:269–276

Yang SI, Hsu TC, Wu CY, Chen KH, Hsu YL, Li YH (2014) Application of biomass fast pyrolysis part II: the effects that bio-pyrolysis oil has on the performance of diesel engines. Energy 66:172–180

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.