The utilisation of oils produced from plastic waste at different pyrolysis temperatures in a DI diesel engine

CrossMark

Ioannis Kalargaris, Guohong Tian, Sai Gu*

Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, GU2 7XH, United Kingdom

ABSTRACT

Chemical recycling is an attractive way to address the explosive growth of plastic waste and disposal problems. Pyrolysis is a chemical recycling process that can convert plastics into high quality oil, which can then be utilised in internal combustion engines for power and heat generation. The aim of the present work is to evaluate the potential of using oils that have been derived from the pyrolysis of plastics at different temperatures in diesel engines. The produced oils were analysed and found to have similar properties to diesel fuel. The plastic pyrolysis oils were then tested in a four-cylinder direct injection diesel engine, and their combustion, performance and emission characteristics analysed and compared to mineral diesel. The engine was found to perform better on the pyrolysis oils at higher loads. The pyrolysis temperature had a significant effect, as the oil produced at a lower temperature presented higher brake thermal efficiency and shorter ignition delay period at all loads. This oil also produced lower NO_X, UHC, CO and CO_2 emissions than the oil produced at a higher temperature, although diesel emissions were lower.

© 2017 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

The explosive growth in the production and everyday use of plastics over the past decades has made plastic waste disposal a serious environmental challenge. In 2015 global plastic production reached 322 million tonnes, a dramatic increase compared to the 279 million tonnes produces in 2011 [1]. The plastics demand in the European Union was 58 million tonnes, of which 29.7% was recycled, 39.5% was recovered in the form of energy (mainly incineration) and 30.8% was sent to landfill [1]. However, plastics contain a significant amount of energy due to the crude oil that is used in their production [2]. Moreover, most of the plastics are not biodegradable, therefore by sending them to landfill not only pollutes the environment, but also throws away a significant amount of energy that could be used to generate electricity and heat [3].

There are two main categories of recycling: mechanical and chemical. Mechanical recycling can be applied mainly to single polymer plastic waste, while chemical recycling can be performed on more complex and contaminated plastic waste [4]. Chemical recycling, or feedstock recycling, aims to chemically degrade plastic waste into its monomers or other chemicals (such as alternative fuels). Chemical recycling can be achieved by conventional refinery processes such as gasification, pyrolysis, hydrocracking and catalytic cracking. The pyrolysis process is one of the most promising technologies in the conversion of waste plastics into high quality oil [5—8]. During pyrolysis, plastic polymers are thermally degraded by heating them in the absence of oxygen. The main products of the pyrolysis process are liquid and gaseous, producing only a small amount of solid. The quantity and quality of the pyrolysis products depend on the waste plastics composition and the process parameters (temperature, residence time, catalyst, etc.) [9—12].

An important and extensively-studied process parameter is temperature, because it has a greater impact on the thermal cracking of plastic polymers than the other process parameters [13—15]. It has been shown that the pyrolysis temperature influences the characteristics of the liquid products to a much greater extent than the gaseous and solid products [5]. More specifically, the liquid product (or plastic pyrolysis oil) produced at lower pyrolysis temperatures has a higher viscosity due to the high content of long hydrocarbon chains [5], while higher pyrolysis temperatures increase the cracking of the C—C bonds, resulting in the formation of lighter hydrocarbons (shorter chains) [16,17]. The pyrolysis temperature also affects the amount of aromatic hydrocarbons in the plastic pyrolysis oil (PPO). The aromatic content of

---

* Corresponding author.
  E-mail address: sai.gu@surrey.ac.uk (S. Gu).

Nomenclature

PPO700	plastic pyrolysis oil produced at 700 °C
PPO700 75	75% PPO700+ 25% diesel fuel
PPO900	plastic pyrolysis oil produced at 900 °C
PPO900 75	75% PPO900+ 25% diesel fuel
NO_X	nitrogen oxides
CO	carbon monoxide
CO_2	carbon dioxide
UHC	unburned hydrocarbons
LHV	lower heating value
BMEP	brake mean effective pressure
HRR	heat release rate
MFB	mass fraction burned
°CA	crank angle degrees
ϕ	equivalence ratio
BTE	brake thermal efficiency

the PPO rises when the pyrolysis temperature increases due to the secondary reactions that take place [4,13,15]. Although the exact mechanisms underpinning the aromatics formation are disputed in the literature, it is generally hypothesised that there are two main routes; unimolecular cyclation reactions followed by dehydrogenation (pyrosynthesis) [15], and Dies-Alder reactions followed by dehydrogenation [18].

The properties of the PPO are similar to the petroleum products, therefore it is likely to be used in internal combustion engines. Diesel engines are experiencing a large growth since the beginning of the 20th century due to their excellent drivability and high efficiency over a large range of loads. Moreover, diesel engines are robust and desirable for testing alternative fuels with the potential to replace petroleum diesel. Nonetheless, studies investigating the use of PPO in diesel engines are currently limited, and have largely focused on the use of PPO-diesel blends in single cylinder diesel engines [19–24]. The use of medium blends of PPO with diesel in larger, multiple-cylinder diesel engines has been investigated by J. Pratoomyod et al. [25] and C. Gungor et al. [26]. These investigations revealed that diesel engines can produce acceptable performance on medium blends with diesel. However, comparing the engine performance results of the investigations is challenging

due to their different pyrolysis process parameters and feedstock, which are known to affect the quality of the PPO.

What has not yet been investigated in diesel engines is the use of PPO produced at different pyrolysis temperatures from the same feedstock. The aim of this study is to compare the performance of a larger diesel engine when running on plastic pyrolysis oils (at high blend rate and without diesel) produced from the same plastics feedstock but at different pyrolysis temperatures, and to estimate the best operational conditions for each one. To accomplish this purpose, the oils properties were characterised, and the engine combustion, performance and emission characteristics were analysed.

2. Materials and methods

2.1. Conversion process and fuel properties

The oils used for the experiments were produced in a pyrolysis plant consisting of three chambers; the primary chamber, the secondary chamber and the conversion chamber. The waste plastics were cut into small pieces (1–2 cm²) and transferred into the primary chamber. Carbon dioxide was injected into the first two chambers, thereby pushing the air to the top while the feedstock was transferred from the bottom to the next chamber. This ensured that no oxygen was transferred into the fixed bed reactor (conversion chamber), where the fast pyrolysis of the plastics occurred. The conversion chamber was maintained at an elevated temperature (700 °C or 900 °C) to convert the plastics into gas and char. The conversion chamber had two exits: one for the gas and one for the char. The char (approximately 10% of the feed) was collected for disposal. The gas was passed into a condenser where it was cooled down to 20 °C and the pyrolysis oil separated out. The schematic layout of the pyrolysis plant can be seen in Fig. 1. The pyrolysis oil was filtered to 1 μm to remove the deposits that might be able to pass to the fuel lines and deteriorate the injection system condition. The composition of the plastics used as a feedstock can be seen in Table 1. It should be noted that the main components are the styrene butadiene and polyester type of plastics.

The plastics were pyrolysed in the conversion chamber at two different temperatures, 700 °C and 900 °C, at the same feeding rate. The oil products were dark brown (almost black) in colour with a strong acrid smell. The basic properties of the plastic pyrolysis oils produced at 700 °C (PPO700) and 900 °C (PPO900) are
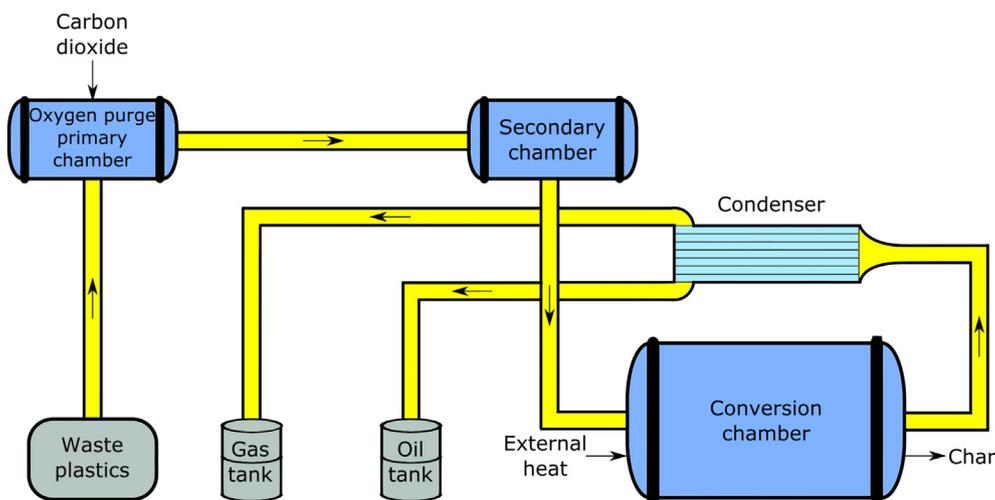

Fig. 1. Schematic layout of the pyrolysis process.

Table 1
Plastic mixture composition.

Material	Quantity (wt.%)
Styrene butadiene	47
Polyester	26
Clay	12
Ethylene-vinyl acetate	7
Rosin	6
Polyethylene	1
Polypropylene	1

Table 2
PPO700, PPO900 and diesel properties.

Property	PPO700	PPO900	Diesel
Density@15 °C (kg/l)	0.927	0.9813	0.8398
Kinematic viscosity@40 °C (cSt)	2.9	1.918	2.62
Aromatic content (%)	53	65.5	29.5
Acid number (mg KOH/g)	47.3	41	0
LHV (MJ/kg)	38.2	38.3	42.9
Ash content (wt.%)	<0.001	0.166	<0.001
Hydrogen content (wt.%)	9.8	8.5	13.38
Carbon content (wt.%)	84.6	87.9	86.57
Oxygen content (wt.%)	5.3	3.3	0.05

Table 3
Test engine specifications.

Brand	AKSA
Model	A4CRX46TI
Compression ratio	17:1
Displacement	4.58 lt
Rated power	68 kW
Rated speed	1500 rpm
Bore	110 mm
Stroke	125 mm

benchmarked with diesel, as shown in Table 2. Density, acidity, oxygen, ash content, total aromatic hydrocarbons and carbon to hydrogen ratio are higher than diesel for both PPO700 and PPO900, while the flash point, hydrogen and lower heating value (LHV) are lower. Furthermore, PPO700 has lower aromatic content and higher viscosity and hydrogen content than PPO900, which is in line with the literature [4,5,13,15]. The LHV of PPO700 and PPO900 is higher than most biofuels and slightly lower than diesel, indicating that these oils have good potential for use in diesel engines.

It was not possible to perform the distillation tests on PPO700 and PPO900, as the vapours produced from the sample during the tests interfered with the level follower. In addition, the heating rates were also affected causing the sample to 'bump', resulting in more false readings. Therefore, it was decided that the tests could not be performed safely. The cetane index, which is used as a substitute for the cetane number and indicates the compression needed for the fuel to ignite (i.e. the ignition delay period), could not be calculated because this requires the fuels distillation values and density. However, both PPO700 and PPO900 have significantly higher densities and aromatic contents than diesel, which suggest that the cetane index is lower. More specifically, PPO900 has higher density and aromatic content than PPO700, revealing that PPO700 has a higher cetane index value and consequently shorter ignition delay period. Finally, a review of the literature revealed that the cetane number of plastic pyrolysis oils is lower than diesel [21,26,27].

According to the fuel properties, both oils seem suitable for use in power generation and marine applications without any substantial upgrading. However, the quality of PPO700 appears superior and able to provide better diesel engine performance than PPO900. On this basis, the present work focused on evaluating the usage of the oils on a stationary diesel engine generator.

2.2. Experimental setup

Table 3 shows the main specifications of the four-cylinder, direct injection, turbocharged, water-cooled diesel engine that was used to conduct the experiments. The schematic layout of the experimental setup is shown in Fig. 2. The engine was mated to an alternator that was connected to a load bank to control the engines load. The load bank was a resistive type with a cooling fan, 72 kW maximum load and operational conditions of 400 V 50 Hz.

The cylinder pressure measurements were acquired by a KISTLER 6125C piezo-electric pressure transducer which was installed in the head of cylinder no.1. A KISTLER 2614C crank angle encoder was placed on the crankshaft on the side of cylinder no.1 to detect the crank-angle position. Two volumetric flow-meters were installed to measure the engine's fuel consumption; one in the supply line and one in the return line. Due to the fuels temperature difference between the supply and the return line, which results in considerable difference in the fuels density, two thermocouples were positioned to measure the temperature and calculate the density from the density-temperature curves. In addition, the engines exhaust emissions (NO_X, CO, CO_2 and UHC) were measured by the Testo 350 gas analyser. Finally, several more sensors were used to monitor the engine's performance, as shown in Fig. 2. The measurement ranges, accuracies and uncertainties of the instruments that were used are summarised in Table 4.

The experimental investigation was conducted at a rated speed of 1500 rpm and at three different engine loads. The loads were 75%, 85% and 100% of rated power, which represent 9.47 bar, 10.74 bar and 12.63 bar of brake mean effective pressure (BMEP), respectively. The engine was started on diesel, then set on the desired load and run for 30 min to ensure that the engine's conditions (e.g. oil and coolant temperature) were stable before switching to the desired PPO blend. After five minutes on fuel blend the data collection was started. More specifically, 100 consecutive cycles were collected from the in-cylinder pressure sensor, while for the rest of the sensors (flow-meters, thermocouples and gas analyser) the data was taken for a period of five minutes with one reading per second and the average was calculated. At the end of each test the engine was switched back to diesel and run for 30 min to flush the fuel blends out of the fuel lines and the injection system.

3. Results and discussion

This section presents and discusses the experimental results obtained from the engine by running on PPO700, PPO700 75 (75% PPO700 + 25% diesel), PPO900 and PPO900 75 (75% PPO900 + 25% diesel). The pyrolysis oils results are compared with the diesel fuel operation. The investigation is focused on the combustion characteristics, engine performance and exhaust emission analysis.

3.1. Combustion and performance characteristics

Fig. 3 shows the cylinder pressure for diesel and fuel blends at (a) 100% and (b) 75% load. According to Fig. 3a, at full load, PPO700 and PPO700 75 present similar pressure profiles with diesel. PPO900 75 has a slightly longer ignition delay period, while PPO900 has significantly longer ignition delay and higher peak cylinder pressure. The same trend can be observed at 75% load, but with even longer ignition delay periods for the fuel blends (Fig. 3b).
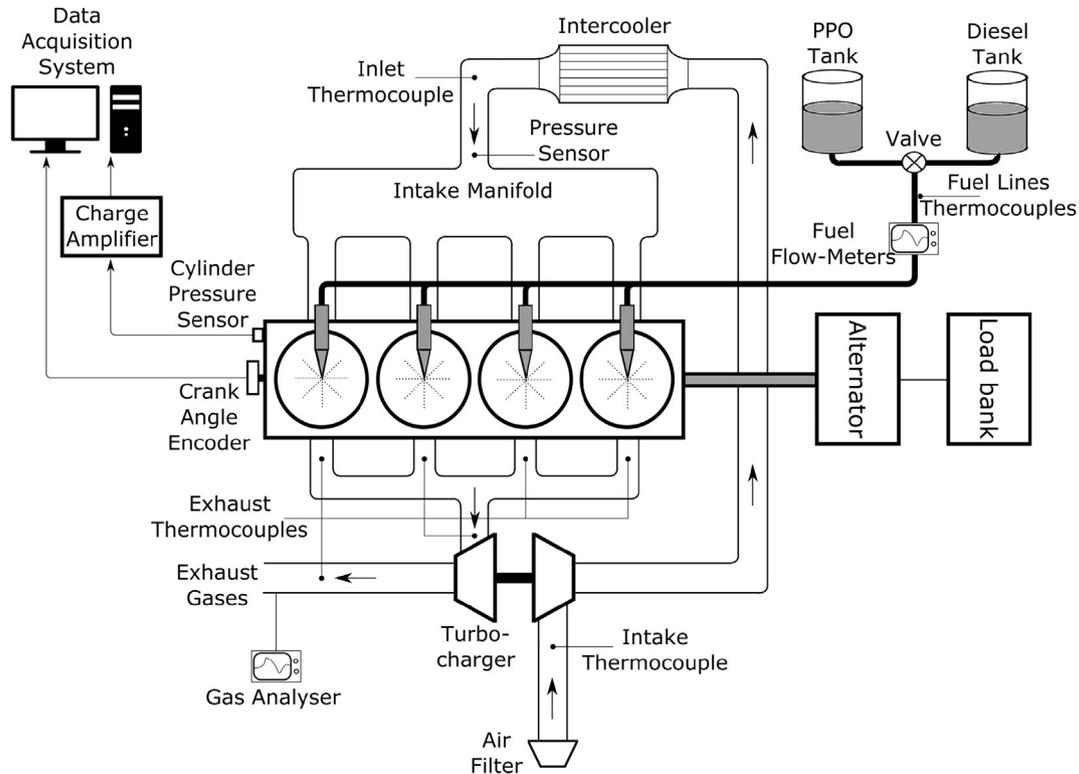
Fig. 2. Schematic layout of the experimental setup.

Table 4
Measuring ranges and accuracies of the instruments.

Instrument	Range	Accuracy
Gas analyser		
CO	0—10,000 ppm	$\pm 10 < 200$ ppm
CO_2	0—50 vol%	$\pm 0.3 < 25$ vol%
NO	0—3000 ppm	$\pm 5\%$ reading
NO_2	0—500 ppm	$\pm 5 < 100$ ppm
HC	0—40,000 ppm	$\pm 400 < 4000$ ppm
Fuel flow-meters	2-100 lt	$\pm 0.2\%$
Thermocouple Type K	0-1100 °C	± 1 °C
Loadbank	0—72 kW	± 0.5
Pressure transducer	0—250 bar	$< \pm 0.02$ FSO
Crank angle encoder	720×0.5 °CA	0.5 °CA

The ignition delay period of PPO900 is 7 °CA longer than diesel operation, but this difference is more observable in the heat release rate and mass fraction burned graphs below (Figs. 4 and 5). The longer ignition delay is predominantly due to the lower cetane number of PPO700 and PPO900. This can be attributed to the significantly elevated aromatic content of the oils, as aromatic bonds require more energy to break in comparison to long paraffin chains [28].

The heat release rate (HRR) for diesel, PPO700 and PPO900 blends at (a) 100% and (b) 75% load is shown in Fig. 4. It can be observed that the ignition delay period of PPO900 is significantly longer at both engine loads, resulting in extremely high peak heat release rates. The longer ignition delay enhances the fuel vaporation and fuel-air mixing by allowing longer air-fuel mixing time, resulting in lower local rich-fuel zones. More specifically, the peak HRR of PPO900 is 45% higher in comparison to diesel at 100% load, and 160% higher at 75% load. An interesting observation is that the peak HRR for PPO900 at 75% load is 20% higher than at 100% load. These values are extremely high and can be catastrophic to the
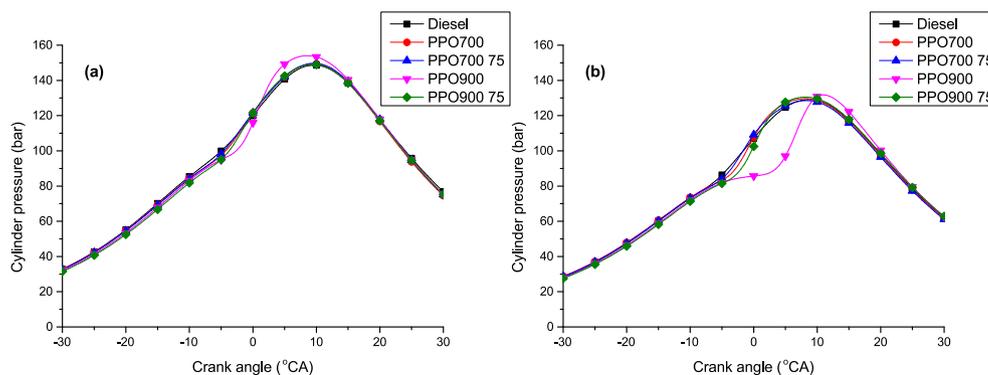

Fig. 3. Variation of cylinder pressure for 100% (a) and 75% (b) load.
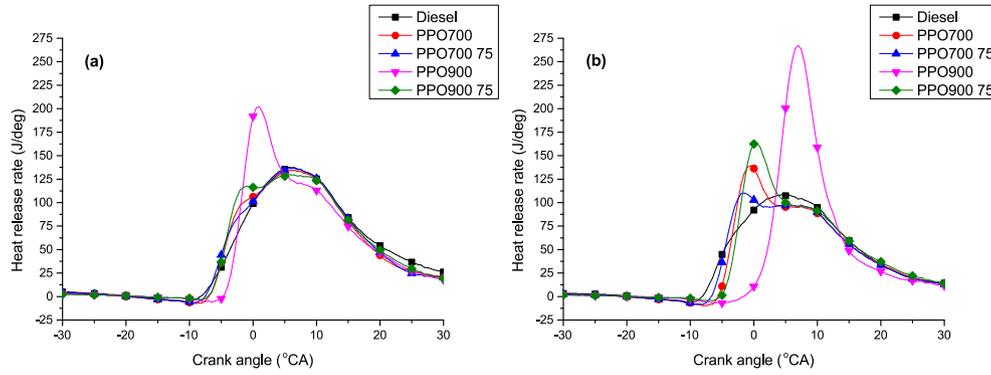
Fig. 4. Variation of heat release rate for 100% (a) and 75% (b) load.

engine in long term use due to the violent combustion (knock effect). Furthermore, a two-phase combustion is observable for all the fuel blends, except PPO900 at 75% load. The first phase is attributable to the longer ignition delay period, which enhances the premixed combustion portion. The extensive ignition delay period of PPO900 at 75% load allows most of the fuel to be mixed with the air, resulting in a violent combustion. It should be mentioned that the addition of diesel to PPO900 improves the ignition delay period, but not enough to match the combustion performance of PPO700. This result illustrates the superior oil quality of PPO700.

Fig. 5 depicts the combustion characteristic angles, i.e. the 10%, 50% and 90% of mass fraction burned (MFB) at 75%, 85% and 100% load. It is evident that PPO700 has similar MFB °CA degrees to diesel at 75% and 85% load, while at 100% load there is a shorter combustion period (the period from 10% until 90% MFB). In contrast, PPO900 shows a delay of 7 °CA degrees for the 10% MFB at 75% load in comparison to diesel, and an advanced 2 °CA degrees for the 90% MFB. Thus, the resulting combustion period of PPO900 is shorter by 9 °CA degrees. The same trend is observed at 100% load, although the differences are less pronounced. The faster combustion evolution/expansion can be explained by the increased air-fuel mixing due to the lower viscosity, longer ignition delay period (larger premixed portion) and higher oxygen content.

The variation of brake thermal efficiency (BTE) of diesel and fuel blends with brake power is presented in Fig. 6. The results show that the BTEs of the fuel blends are significantly lower than diesel, and that the difference between the PPO700 and PPO900 is
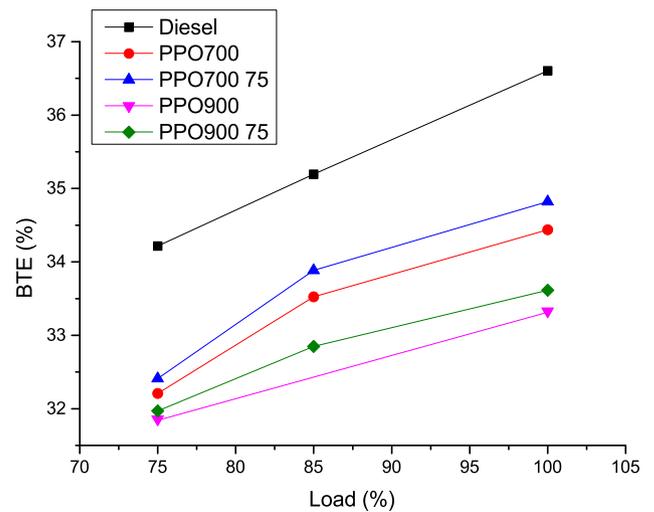

Fig. 6. Variation of brake thermal efficiency with load.

approximately 1%. Furthermore, the addition of diesel appears to only slightly improve the efficiency of the oils. The oils lower BTEs are largely attributable to their higher aromatic content, as aromatic bonds require more energy to break. Other contributing factors could be the higher combustion temperature and the longer ignition delay period of the oils, which result in higher heat transfer losses and less heat energy conversion to kinetic on the pistons. The results suggest that pure PPO900 is not preferable for long-term use due to the extremely high HRR that can prove catastrophic for the engine. PPO700 would be acceptable at loads higher than 85%, where the peak HRR is lower and more comparable to diesel operation.

3.2. Exhaust emissions

Fig. 7 shows the variation of nitrogen oxides emissions (NO_X) with load for diesel, PPO700 and PPO900 blends. According to the combustion theory, there are three NO_X production mechanisms: the thermal mechanism, the prompt mechanism and the fuel mechanism [29,30]. The main mechanism for the production of NO_X emissions in diesel engines is the thermal mechanism, due to the high oxygen availability and elevated in-cylinder temperatures. It can be observed that the NO_X emissions of the PPO900 are much higher than those of diesel and PPO700. More specifically, the NO_X emissions of PPO900 are 45% higher than diesel at 100% load, and 65% higher at 75% load. PPO700 NO_X emissions were found to be
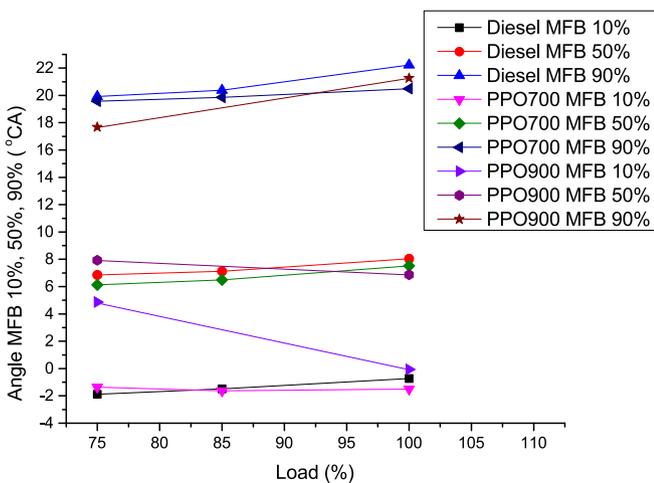

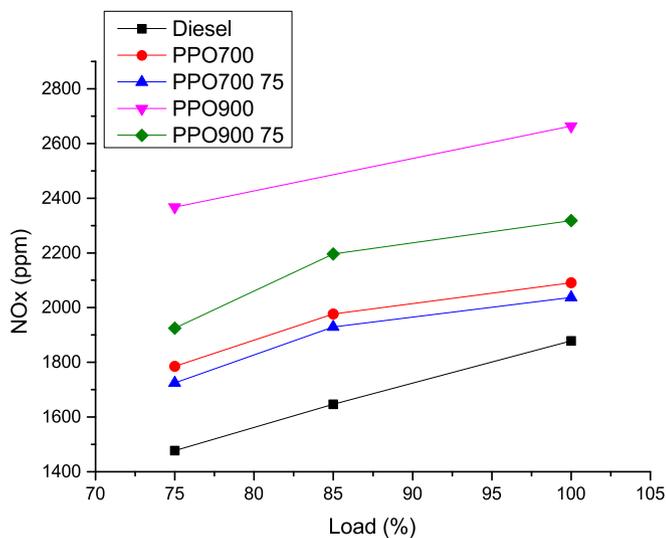**Fig. 5.** Variation of angle mass fraction burned with load.

Fig. 7. Variation of oxides of nitrogen emission with load.

12% higher at 100% load and 25% higher at 75% load. This is due to the longer ignition delay period which results in higher premixed combustion portion, heat release rate and in-cylinder local temperatures.

Fig. 8 depicts the variation of unburned hydrocarbon (UHC) emissions with brake power for diesel and oil blends. The main factors affecting the UHC emissions in the exhaust are the under-mixing or over-leaning zones and the wall flame-quenching [29,31,32]. PPO900 produces almost double the UHC emissions compared to diesel, while PPO700 has 50% higher UHC emissions. The addition of diesel significantly reduces the UHC emissions, which could be explained by the increased combustion perfor-mance associated with the lower aromatic content of diesel. The high UHC emissions of the oils can be attributed to their increased aromatic content and longer ignition delay period, which results in shorter combustion duration.

Fig. 9 presents the variation of carbon monoxide (CO) emissions against load. The low equivalence ratio (ϕ) and the high in-cylinder temperatures of the diesel engines result in very low CO emissions. High CO exhaust emissions from diesel engines are a sign of incomplete combustion. The experimental results reveal that the
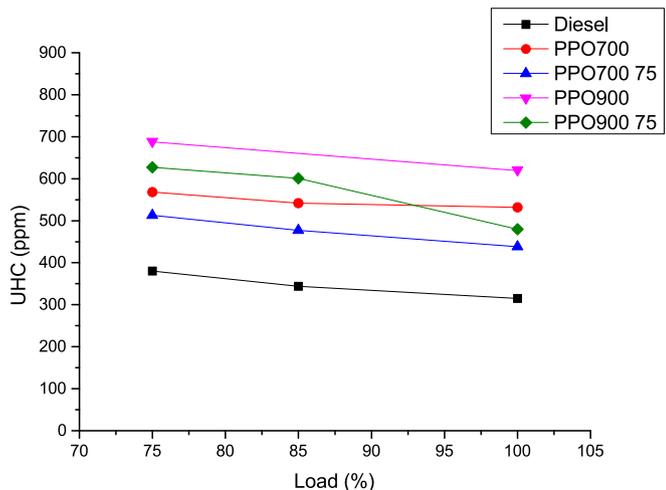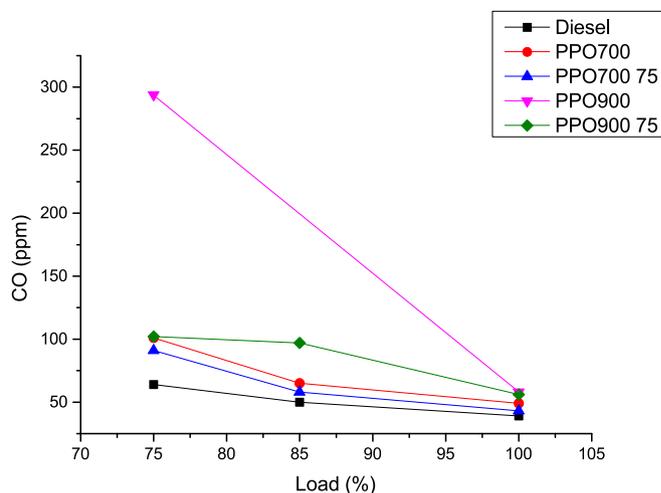

Fig. 9. Variation of carbon monoxide emission with load.

CO emissions decrease as the load increases for all fuel blends. Diesel operation produces the lowest CO emissions, while the highest are emitted by PPO900. The CO emissions of PPO700 are slightly higher than diesel. These results indicate deterioration of the combustion process, which is severe in the case of PPO900 at 75% load. This behaviour can be explained by the lower cetane number and the higher aromatic content of the fuel blends, which cause longer ignition delay and shorter combustion periods, as shown in combustion characteristic angles graph (Fig. 5).

Fig. 10 presents the variation of carbon dioxide (CO_2) emissions with load for diesel, PPO700, PPO700 75, PPO900 and PPO900 75. CO_2 is formed by the complete oxidation (complete combustion) of the carbon atoms contained in the fuel. From an environmental perspective, there is a strong requirement for CO_2 to be reduced, as it is a major contributor to the greenhouse effect. According to Fig. 10, the CO_2 emissions of PPO900 are much higher at all three loads in comparison to PPO700 and diesel operation, which can be explained by the lower BTE which means that, at constant power, more fuel has to be burned and consequently more CO_2 is pro-duced. In addition, the increased CO_2 can also be attributed to the higher carbon:hydrogen ratio of PPO900 (C:H = 10.34) than that of PPO700 (C:H = 8.63) and diesel (C:H = 6.46). Therefore, for the same amount of energy released from the combustion of the oils, more carbon atoms have to be oxidized and form CO_2.

4. Conclusions

An experimental investigation was carried out to analyse and understand the combustion performance and emission character-istics of a diesel engine gen-set running on oils derived from the pyrolysis of plastics at 700 °C and 900 °C. The following conclusions are drawn based on the results of the investigation:

- The engine was able to operate stably on PPO700 and PPO900 blends at 75%, 85% and 100% load.
- PPO900 had a significantly longer ignition delay period, higher peak heat release rate and shorter combustion period compared to PPO700.
- The engine brake thermal efficiency was 3—4% lower for PPO900 and 2—3% lower for PPO700 in comparison to diesel.
- All measured emissions (NO$_X$, UHC, CO and CO_2) were higher for PPO700 and PPO900 compared to diesel, however the highest emissions were produced by PPO900.

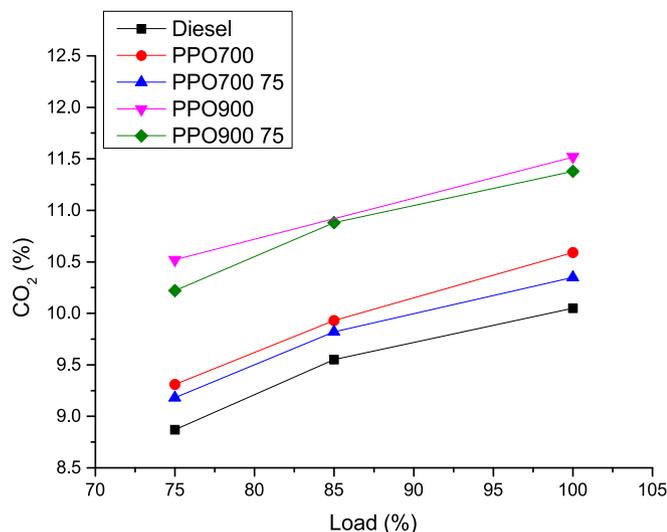**Fig. 8.** Variation of unburned hydrocarbon emission with load.

Fig. 10. Variation of carbon dioxide emission with load.

The results suggest that PPO700 is a superior fuel to PPO900, but neither non-blended oil would be suitable for long-term running due to the longer ignition delay period. The only way to utilise the PPO900 would be to increase the blending ratio with diesel (30–40%) and run at engine loads higher than 85%. The engine performance on PPO700 would be acceptable for long-term use at a blend rate of 25% with diesel and at loads higher than 85%. Nevertheless, more parameters (e.g. cetane number improvers, injection pressure and injection timing) need to be investigated to achieve optimum engine performance.

Acknowledgements

References

[1] Association of Plastic Manufacturers Europe, Plastics – the Facts 2016. An analysis of the European plastics production, demand and waste data. European Association of Plastics Recycling and Recovery Organisations; 2016. p. 1–38.

[2] Kumar R, Mishra MK, Singh SK, Kumar A. Experimental evaluation of waste plastic oil and its blends on a single cylinder diesel engine. J Mech Sci Technol 2016;30(10):4781–9.

[3] Aguaro J, Serrano DP, San Miguel G. European trends in the feedstock recycling of plastic wastes. Glob NEST J 2007;1(9):12–9.

[4] Kaminsky W, Kim J. Pyrolysis of mixed plastics into aromatics. J Anal Appl Pyrolysis 1999;51. 137–134.

[5] Lpez A, de Marco I, Caballero B, Laresgoiti M, Adrados A. Influence of time and temperature on pyrolysis of plastic wastes in a semi-batch reactor. Chem Eng J 2011;173:62–71.

[6] Kaminsky W, Schlesselmann B, Simon C. Olefins from polyolefins and mixed plastics by pyrolysis. J Anal Appl Pyrolysis 1995;32:19–27.

[7] Kumar S, Singh RK. Recovery of hydrocarbon liquid from waste high density polyethylene by thermal pyrolysis. Braz J Chem Eng 2011;28(04):659–67.

[8] Kumar S, Prakash R, Murugan S, Singh R. 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 2013;74:323–31.

[9] Conesa JA, Font R, Marcilla A, Garcia AN. Pyrolysis of polyethylene in a fluidized bedreactor. Energy Fuel 1994;8:1238–46.

[10] Wallis MD, Bhatia SK. Thermal degradation of high density polyethylene in a reactive extruder. Polym Degrad Stab 2007;92(9):1721–9.

[11] Panda AK, Singh RK. Catalytic performances of kaoline and silica alumina in the thermal degradation of polypropylene. J Fuel Chem Technol 2011;39(3): 198–202.

[12] Park JW, Kim JH, Seo G. The effect of pore shape on the catalytic performance of zeolites in the liquid-phase degradation of HDPE. Polym Degrad Stab 2002;76(3):495–501.

[13] Li A, Li X, Li S, Ren Y, Chi Y, Yan J, et al. Pyrolysis of solid waste in a rotary kiln: influence of final pyrolysis temperature on the pyrolysis products. J Anal Appl Pyrolysis 1999;50:149–62.

[14] Yoshioka T, Grause G, Eger C, Kaminsky W, Okuwaki A. Pyrolysis of poly(-ethylene terephthalate) in a fluidised bed plant. Polym Degrad Stab 2004;86: 499–504.

[15] Ji AHL, Sablier M. Study on the pyrolysis of polyethylene in the presence of iron and copper chlorides. Chemosphere 2006;65:1120–30.

[16] Aguado J, Serrano D. Feedstock recycling of plastic wastes. The Royal Society of Chemistry; 1999. p. 73–127. Chapter 4.

[17] Hernndez M, Gmez A, Garca A, Agull J, Marcilla A. Effect of the temperature in the nature and extension of the primary and secondary reactions in the thermal and HZSM-5 catalytic pyrolysis of HDPE. Appl Catal A Gen. 2007;317(2):183–94.

[18] Bockhorn H, Hornung A, Hornung U. Mechanism and kinetics of thermal decomposition of plastics from isothermal and dynamic measurements. J Anal Appl Pyrolysis 1999;50:77–101.

[19] Mani M, Subash C, Nagarajan G. Performance, emission and combustion characteristics of a DI diesel engine using waste plastic oil. Appl Therm Eng 2009;29:2738–44.

[20] Wongkhorsub C, Chindaprasert N. A comparison of the use of pyrolysis oils in diesel engine. Energy Power Eng 2013;5:350–5.

[21] Mani M, Nagarajan G. Influence of injection timing on performance, emission and combustion characteristics of a DI diesel engine running on waste plastic oil. Energy 2009;43:1617–23.

[22] Guntur R, Kumar D, Reddy V. Experimental evaluation of a diesel engine with blends of diesel-plastic pyrolysis oil. Int J Eng Sci Technol 2011;6:5033–40.

[23] Mani M, Nagarajan G, Sampath S. Characterisation and effect of using waste plastic oil and diesel fuel blends in compression ignition engine. Energy 2011;36:212–9.

[24] Hariram V, Seralathan S, Vagesh RS, Yoga KN. Combustion characteristics of waste pyrolytic plastic oil at full load operation in a direct injection compression ignition engine. J Chem Pharm Res 2015;7(5):673–6.

[25] Pratoomyod J, Laohalidanond K. Performance and emission evaluation of blends of diesel fuel with waste plastic oil in a diesel engine. Int J Eng Sci Technol 2013;2:57–63.

[26] Gungor C, Serin H, Ozcanli M, Serin S, Aydin K. Engine performance and emission characteristics of plastic oil produced from waste polyethylene and its blends with diesel fuel. Int J Green Energy 2015;12:98–105.

[27] Frigo S, Seggiani M, Puccini M, Vitolo S. Liquid fuel production from waste tyre pyrolysis and its utilisation in a diesel engine. Fuel 2014;116:399–408.

[28] Kaimal VK, Vijayabalan P. A detailed study of combustion characteristics of a DI diesel engine using waste plastic oil and its blends. Energy Convers Manag 2015;105:951–6.

[29] Heywood JB. Internal combustion engine fundamentals. McGraw-Hill Inc; 1988.

[30] Semerjian H, Vranos A. NOx formation in premixed turbulent flames. Symp. Int Combust 1977;16(1):166–79.

[31] Greeves G, Khan IM, Wang CHT, Fenne I. Origins of hydrocarbons emissions from diesel engines, SAE Technical Paper (770259).

[32] Mendez S, Kashdan JT, Bruneaux G, Thirouard B, Vangraefschepe F. Formation of unburned hydrocarbons in low temperature diesel combustion, SAE Technical Paper (2009-01-2729).