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PERFORMANCE, EMISSION AND CHARACTERISTICS OF A HCCI ENGINE RUNNING WASTE PLASTIC OIL

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ABSTRACT

Increase in energy demand, stringent emission norms and depletion of oil resources have led the researchers to find alternative fuels for internal combustion engines. On the other hand waste plastic pose a very serious environment challenge because of their disposal problems all over the world. Plastics have now become indispensable materials in the modern world and application in the industrial field is continually increasing. In this context, waste plastic solid is currently receiving renewed interest. The properties of the oil derived from waste plastics were analyzed and compared with the petroleum prod- ucts and found that it has properties similar to that of HCCI. In the present work, waste plastic oil was used as an alternate fuel in a HCCI engine with modification. The present investigation was to study the performance, emission and combustion characteristics of a single cylinder, four-stroke, and HCCI engine run with waste plastic oil. The experimental results have showed a stable perfor- mance with brake thermal efficiency similar to that of HCCI. Carbon dioxide and unburned hydrocarbon were marginally higher than that of the HCCI baseline. The toxic gas carbon monoxide emission of waste plastic oil was higher than HCCI. Smoke reduced by about 30% to 40% in waste plastic oil at all loads.

INTRODUCTION

Plastics have become an indispensable part in today's world. Due to their lightweight, durability, energy efficiency, coupled with a faster rate of production and design flexibility, these plastics are employed in entire gamut of industrial and domestic areas. Plastics are produced from petroleum derivates and are composed primar- ily of hydrocarbons but also contain additives such as antioxidants, colorants and other stabilizers (T. W. Ryan; P.T. Williams, 2000). Disposal of the waste plastics poses a great hazard to the environment and effective method has not yet been implemented.

Plastics are non-biodegradable polymers mostly containing car- bon, hydrogen, and few other elements like nitrogen. Due to its non-biodegradable nature, the plastic waste contributes signifi- cantly to the problem of waste management. According to a nationwide survey which was conducted in the year 2000, approx- imately 6000 tonnes of plastic waste were generated every day in India, and only 60% of it was recycled, the balance of 40% could not be disposed of. Today about 129 million tonnes of plastics are pro- duced annually all over the world, out of which 77 million tonnes are produced from petroleum (M. Richter, 2000). In India alone, the demand for plastics is about 8 million tonnes per year. More than 10,000 met- ric tonnes per day of plastics are produced in India and almost the same amount is imported by India from other countries. The per capita consumption of plastics in India is about 3 kg when com- pared to 30 kg to 40 kg in the developed countries. Most of these come from packaging and food industries. Most of the plastics are recycled and sometimes they are not done so due to lack of suf- ficient market value. Of the waste plastics not recycled about 43% is polyethylene, with most of them in containers and packaging.

Waste plastic oil in HCCI engines

HCCI engines are most preferred power plants due to their excellent driveability and higher thermal efficiency. Despite their advantages, they emit high levels of NOx and smoke which will have an effect on human health. Hence, stringent emission norms and the depletion of petroleum fuels have necessitated the search for alternate fuels for HCCI engines. On the other hand, due to the rapid growth of automotive vehicles in transportation sector, the consumption of oil keeps increasing. Most of the research work has been done by mixing oil developed from waste plastic disposal with heavy oil for marine application .The results showed that waste plastic disposal oil when mixed with heavy oils reduces the viscosity significantly and improves the engine performance. However, very little has been done to test their use in high-speed HCCI engines. A pilot level method of recycling waste plastic dis- posal in India produces waste plastic oil of 25,000 liter/day. The kind of plastic materials are Polyethylene, Polypropylene, Teflon Nylon and Dacron. For application, waste plastic oil is used in HCCI engine.

Nomenclature

LPG	liquid petroleum gas	X_1	uncertainty of total fuel consumption
TFC	total fuel consumption	X_2	uncertainty of brake power
NO_x	oxides of nitrogen.	X_3	uncertainty of brake thermal efficiency
UHC	unburned hydrocarbon.	X_4	uncertainty of CO
CO	carbon monoxide	X_5	uncertainty of unburned hydrocarbon
CO_2	carbon dioxide	X_6	uncertainty of NO_x
TDC	top dead centre	X_7	uncertainty of smoke number
CA BTDC	crank angle before top dead centre	X_8	uncertainty of exhaust gas temperature
Y	total percentages uncertainty	X_9	uncertainty of pressure pickup

Conversion process

The feed system consists of equipment for sizing hard, thick flexible and thin flexible materials, which normally constitutes the municipal waste stream. The system essentially consists of sorters and sizing equipment like crusher, cutter and shredder. The various sizes and shapes of the material are sorted into categories suitable for crushing, cutting and shredding. The sorted material was crushed or cut or shredded and graded into uniform size for ease of handling and melting in the melting/preheating process. This process of sizing and grading the waste was semi-automatic. The graded feed was stored in a hopper before feeding to the process by a conveyor feeder. The sorted feedstock of known composition was stored separately for proportionate feeding for processing nonstandard feed design or processing special feed designs. The dust and other fine wastes collected from the cyclone filter were disposed through a vent with particle size monitoring system. The assorted waste plastic was fed into a reactor along with 1% (by weight) catalyst and 10% (by weight) coal and maintained at a temperature of 300°C to 400°C at atmospheric pressure for about 3 hours to 4 hours. The pyrolysis process involves the breakdown of large molecules to smaller molecules. Produce hydrocarbons with small molecular (e.g. ethane) that can be separated by fractional distillation and used as fuels and chemicals. This process gives on weight basis 75% of liquid hydrocarbon, which is a mixture of petrol, HCCI and kerosene, 5% to 10% residual coke and the rest is LPG

Comparison of waste plastic oil and waste tyre pyrolysis oil

Waste tyre pyrolysis liquids are a complex mixture of C5 to C20 organic compounds, with a great proportion of aromatics (Isabel, 2001) whereas waste plastic oil is a mixture of C10 to C30 organic compounds. Waste plastic oil has high calorific value than the waste tyre pyrolysis oil. Sulphur and distillation temperature is lesser than waste tyre pyrolysis oil. The properties of waste plastic oil, waste tyre pyrolysis oil (S. Morimoto, 2001; Isabel, 2001) and HCCI are compared in Table 1. The gaseous products and chemical composition of waste plastic oil are given in Tables 2 and 3.

Experimental setup

The schematic of the experimental set up is shown in Fig. 1. The research engine specifications are given in Table 4. An electrical dynamometer was used to provide the engine load. An air box was fitted to the engine for air flow measurement. The fuel flow rate was measured on volumetric basis using a burette and a stopwatch. Chromel alumel thermocouple in conjunction with a digital temperature indicator was used to measure the exhaust gas temperature. A pressure transducer mounted on the cylinder head with a charge amplifier and a computer were used to measure and record the cylinder pressure. A TDC encoder was used to detect the engine crank angle. An exhaust gas analyzer was used to measure NOx/HC/CO emissions in the exhaust. Smoke was measured in Bosch Smoke Units (BSU) by an AVL smoke meter. All the experiments were conducted at the rated engine speed of 1500 rpm. All the tests were conducted by starting the engine with HCCI only and then switched over to run with waste plastic oil. At the end of the test, the engine was run for some time with HCCI to flush out the waste plastic oil from the fuel line and the injection system.

Error analysis

Errors and uncertainties in the experiments can arise from instrument selection, condition, calibration, environment, observa- tion, reading and test planning. Uncertainty analysis is needed to prove the accuracy of the experiments (G.Kontarakis, 2000). The percentage uncer- tainties of various parameters like brake power and brake thermal efficiency were calculated using the percentage uncertainties of various instruments given in Table 5. An uncertainly analysis was performed using Eq. (1).

$$Y = \sqrt{(X1)2 + (X2)2 + (X3)2 + (X4)2 + (X5)2 + (X6)2 + (X7)2 + (X8)2 + (X9)2}$$

$$Y = \sqrt{(1)2 + (0.2)2 + (1)2 + (0.2)2 + (0.2)2 + (0.2)2 + (1)2 + (0.15)2 + (1)2}$$

$$Y = \pm 2.28\%$$

RESULTS AND DISCUSSION

A series of performance, emission and combustion tests were carried out on a 4.4 kW constant speed engine using HCCI and waste plastic oil and the results are presented.

Combustion parameters

Delay period

From Fig. 2, it can be observed that the ignition delay of waste plastic oil is considerably longer than that of HCCI. The longer delay period of waste plastic oil, results in a rise in-cylinder peak pressure. It may also be seen that the ignition delay is longer by about 2 CA to 2.5 CA for waste plastic oil than that of HCCI and the peak pressure increases by 5 bar for waste plastic oil com- pared to HCCI because of longer ignition delay

Table 1
Comparison of waste plastic oil, waste tyre pyrolysis oil and diesel.

Property	Waste plastic oil	Waste tyre pyrolysis oil	Diesel
Density @ 30 °C in (g/cc)	0.8355	0.935	0.840
Ash content (%)	0.00023	0.31	0.045
Gross calorific value (kJ/kg)	44,340	42,830	46,500
Kinematic viscosity, cst @ 40 °C	2.52	3.2	2.0
Cetane number	51	–	55
Flash point (°C)	42	43	50
Fire point (°C)	45	50	56
Carbon residue (%)	82.49	2.14	26
Sulphur content (%)	0.030	0.95	0.045
Distillation temperature (°C) @ 85%	344	381	328
Distillation temperature (°C) @ 95%	362	388	340

Table 2
Gaseous product of the waste plastic oil.

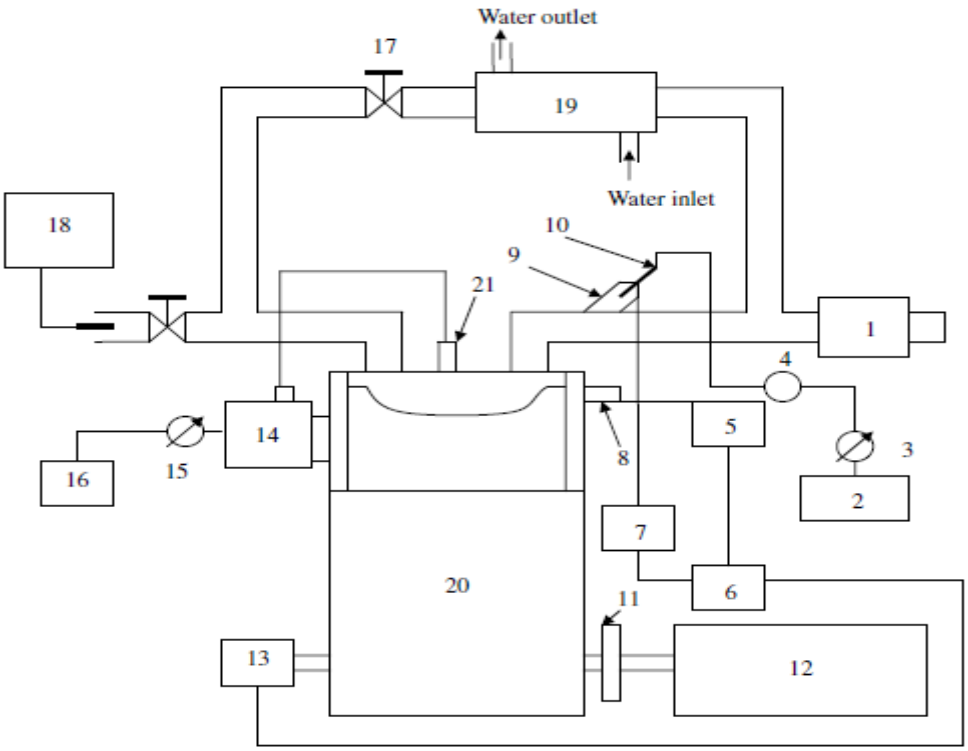
Component	Quantity (wt%)
Methane	6.6
Ethane ethylene	10.6
Propane	7.4
Propylene	29.1
Iso-butane	1.9
n-Butane	0.9
C_4 (unsaturated)	25.6
Iso C_5–*n*-C_5	0.1
C_5+higher	15.3
Hydrogen	2.5
CO/CO_2	<400 ppm

Table 3
Chemical composition of waste plastic oil.

Composition	Percentage
C_{10}	61
C_{10}–C_{13}	2.4
C_{13}–C_{16}	8.5
C_{16}–C_{20}	4.1
C_{20}–C_{23}	7.6
C_{23}–C_{30}	16.4

Engine specifications

S. no	Parameters	Specifications
1	General details	Single cylinder, four stroke, compression ignition, Constant speed, vertical, air cooled, direct injection
2	Bore	87.5 mm
3	Stroke	110 mm
4	Swept volume	662 cm^3
5	Injection timing	23 deg bTDC
6	Compression ratio	17.5:1
7	Rated output	4.4 kW at 1500 rpm
8	Rated speed	1500 rpm
9	Injection pressure	200 bar



1 Air surge tank
2 fuel tank
3 Flow meter
4 Fuel control valve
5 Charge amplifier
6 Data acquisition
7 Relay and temperature controller
8 Pressure sensor
9 Diesel fuel vaporizer
10 Fuel tube
11 Flywheel
12 Dynamometer
13Crank angle encoder
14 Fuel injection pump
15 Flow meter for Diesel HCCI mode
16 Diesel fuel tank
17 EGR control valve
18 Exhaust gas analyser
19 EGR Cooler
20 Engine
21 Diesel DI injector

Cylinder pressure crank angle diagram

Fig. 3 indicates the cylinder pressure with crank angle for both fuels at rated power. The cylinder peak pressure for HCCI is 67 bar at rated power and 71 bar in the case of waste plastic oil. Higher cylinder pressure in the case of waste plastic oil compared to HCCI is due to the evaporation of waste plastic oil inside the cylinder by

absorbing heat from the combustion chamber. Longer ignition de- lay at high load range increases the pressure of waste plastic oil than that of HCCI. In other words, this period depicts the abnormal combustion or premixed combustion. However, this is the usual behaviour of high-octane fuel in high compression ratio engines. This can be controlled by proper selection of compression ratio.

Cylinder peak pressure

The variation of cylinder peak pressure with brake power for waste plastic oil and HCCI operation at different loads is given in Fig. 4. It may be noticed that the cylinder peak pressure for the waste plastic oil is higher than the HCCI. The cylinder peak pressure for HCCI increases from 50 bar at no load to 60 bar at rated power and from 54 bar at no load to 71 bar at rated power in the case of waste plastic oil. In a CI engine, the peak pressure de- pends on the combustion rate in the initial stages, which is influ- enced by the amount of fuel taking part in the uncontrolled combustion phase that is governed by the delay period. It is also affected by the fuel mixture preparation during the delay period (J. Dec, 2002). Longer ignition delay is the reason for higher peak pressure in waste plastic oil operation at rated power.

Rate of heat release

The heat release rate of the waste plastic oil and HCCI opera- tion at rated power is given in Fig. 5. Rate of heat release can be cal- culated with this equation (J.B. Heywood, 1988).

$$\text{Rate of heat release} = (r/r-1)p(dv/do)+(1/r-1)v(dp/do)$$

The first stage is from the start of ignition to the point where the heat release rate drops and this is due to the ignition of fuel–air mixture prepared during the delay period. The second stage starts from the end of the first stage to the end of combustion. HCCI shows the lowest heat release rate at initial stage and longer combustion duration at rated power. The heat release rate is 130 J/ CA for HCCI and 85 J/ CA for waste plastic oil. The maximum heat released in waste plastic oil is high compared to HCCI. It can be noticed that in waste plastic oil, most of the heat release occurs only during the premixed combustion. Longer ignition delay results in higher heat release during the premixed combustion phase. From Fig. 5 the heat release rate is higher in the case of waste plastic oil due to the higher fuel–air ratio. The higher heat release rate leads to an increase in exhaust gas temperature

Table 5
List of instruments and its range, accuracy and percentage uncertainties.

S. no.	Instruments	Range	Accuracy	Percentage uncertainties
1.	Gas analyzer	CO 0–10%,	+0.02% to −0.02%	+0.2 to −0.2
		CO_2 0–20%	+0.03% to −0.03%	+0.15 to −0.15
		HC 0–10,000 ppm	+20 ppm to −20 ppm	+0.2 to −0.2
		NO_x 0–5000 ppm	+10 ppm to −10 ppm	+0.2 to −0.2
2.	Smoke level measuring instrument	BSU 0–10	+0.1 to −0.1	+1 to −1
3.	Exhaust gas temperature indicator	0–900 °C	+1 °C to −1 °C	+0.15 to −0.15
4.	Speed measuring unit	0–1000 rpm	+10 rpm to −10 rpm	+0.1 to −0.1
5.	Load indicator	0–100 kg	+0.1 kg to −0.1 kg	+0.2 to −0.2
6.	Burette for fuel measurement		+0.1 cc to −0.1 cc	+1 to −1
7.	Digital stop watch		+0.6 s to −0.6 s	+0.2 to −0.2
8.	Manometer		+1 mm to −1 mm	+1 to −1
9.	Pressure pickup	0–110 bar	+0.1 kg to −0.1 kg	+0.1 to −0.1
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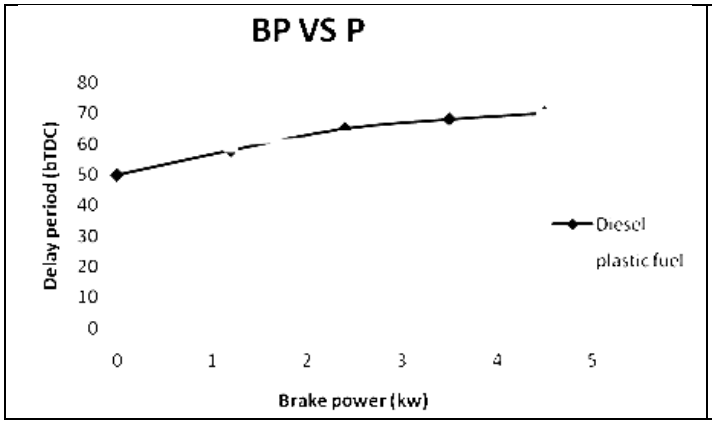
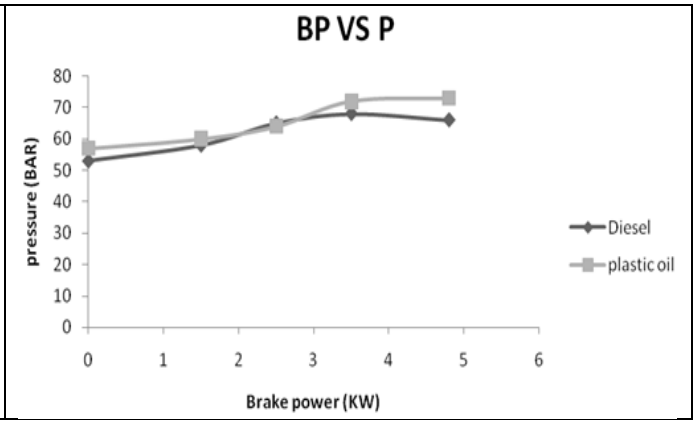
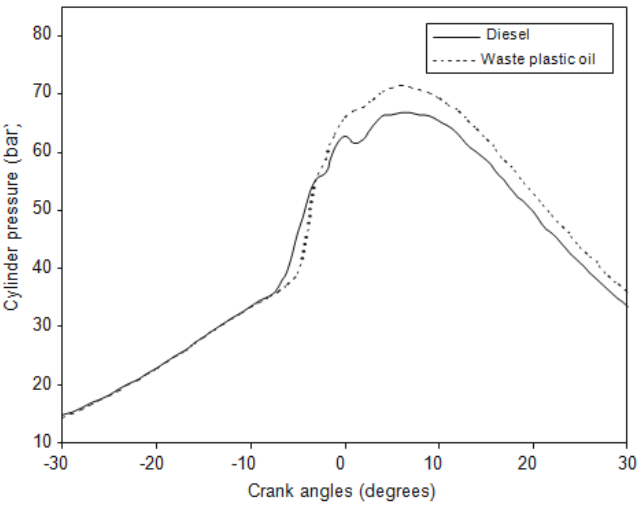
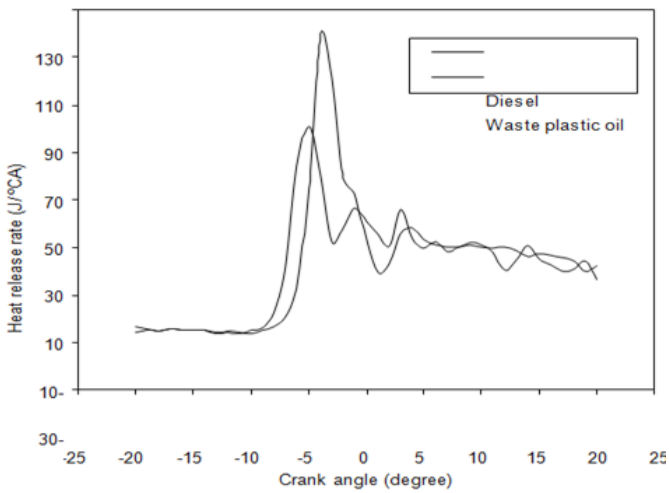








Emissions

Oxides of nitrogen

The oxides of nitrogen in the emissions contain nitric oxide (NO) and nitrogen dioxide (NO2). The formation of NOx is highly dependent on in-cylinder temperature, oxygen concentration and residence time for the reactions to take place. Fig. 6 shows the comparison of oxides of nitrogen with brake power. It can benoticed that the NOx emission increases in the waste plastic oil operation. NOx varies from 12.15 g/kWh at 25% of rated power to 7.91 g/kWh at rated power for HCCI and from 14.68 g/kWh at 25% of rated power to 8.93 g/kWh at rated power for waste plastic oil. The reason for the increased NOx is due to the higher heat release rate and higher combustion temperature. CI engines are always run lean and emit high amounts of NOx nonetheless. At high load, with higher peak pressures, and hence temperatures, and larger regions of close to stoichiometric burned gas, NO levels increase. Increased ignition delay of waste plastic oil promotes premixed combustion, by allowing more time for fuel to be injected prior to ignition, may also be another reason for increased NOx

Unburned hydrocarbon

The variation of unburned hydrocarbon with brake power for tested fuels is shown in Fig. 7. Unburned hydrocarbon is a useful measure of combustion inefficiency. Unburned hydrocarbon consists of fuel that is incompletely burned. The term hydrocarbon means organic compounds in the gaseous state and solid hydrocarbons are the particulate matter. At light load, large amounts of excess air and low exhaust temperature and lean fuel air mixture regions may survive to escape into the exhaust. Unburned hydrocarbon varies from 0.431 g/kWh at 25% of rated power to 0.1389 g/kWh at rated power for HCCI. In the case of waste plastic oil it varies from 0.4393 g/kWh at 25% of rated power to 0.147 g/kWh at rated power. From the results, it can be noticed that the concentration of the hydrocarbon of waste plastic oil is marginally higher than HCCI. The reason behind increased unburned hydrocarbon in waste plastic oil may be due to higher fumigation rate and non-availability of oxygen relative to HCCI. At lighter loads due to charge homogeneity and higher oxygen availability, the unburned hydrocarbon level is less in the case of waste plastic oil, whereas at higher load ranges due to higher quantity of fuel admission, unburned hydrocarbon increases.

Carbon monoxide

The variation of carbon monoxide with brake power is shown in Fig. 8. Generally, CI engine operates with lean mixtures and hence the CO emission would be low. CO emission is toxic and must be controlled. It is an intermediate product in the combustion of a hydrocarbon fuel, so its emission results from incomplete combustion. Emission of CO is therefore greatly dependent on the air fuel ratio relative to the stoichiometric proportions. Rich combustion invariably produces CO, and emissions increase nearly linearly with the deviation from the stoichiometry. The concentration of CO emission varies from 14.14 g/kWh at 25% of rated power to 5.75 g/kWh at rated power for HCCI, whereas it varies from18.51 g/kWh at 25% of rated power to 6.19 g/kWh at rated power for waste plastic oil. The results show that CO emission of waste plastic oil is higher than HCCI. The reason behind increased CO emission is incomplete combustion due to reduce in-cylinder temperatures. The drastic increase in CO emission at higher loads is due to higher fuel consumption

Carbon dioxide

Carbon dioxide occurs naturally in the atmosphere and is anor- mal product of combustion. Ideally, combustion of a HC fuel should produce only CO and water (H2O). The variation of carbon dioxide with brake power is shown in Fig. 9. CO2 varies from 1305.97 g/kWh at 25% of rated power to 789.36 g/kWh at rated power for HCCI. It can be observed that in waste plastic oil it var-ies from 1163.25 g/kWh at 25% of rated power

to 888.715 g/kWh at rated power. From the results, it is observed that the amount of CO2 produced while using waste plastic oil is lower than HCCI. This may be due to late burning of fuel leading to incomplete oxi- dation of CO.

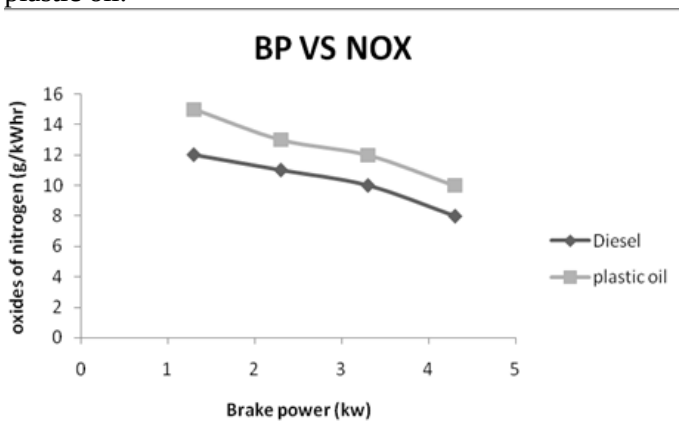
Smoke

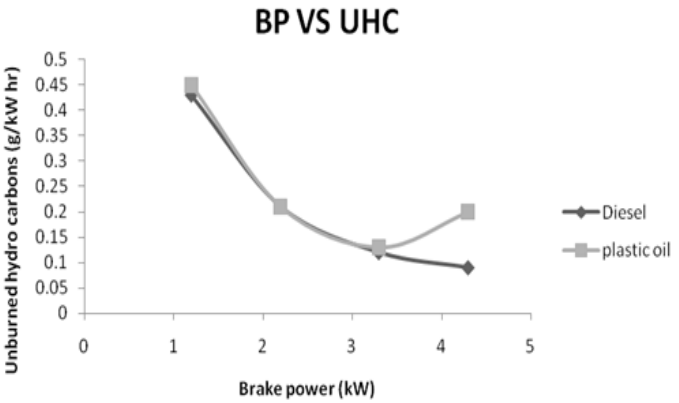
Smoke is nothing but solid soot particles suspended in exhaust gas. Fig. 10 shows the variation of smoke with brake power. Smoke varies from 0.66 BSU to 5.3 BSU for HCCI whereas in waste plastic oil it varies from 0.2 BSU to 3.48 BSU at rated power. It can be noticed that the smoke level for waste plastic oil is lower than HCCI. The reason for the reduced smoke is the availability of premixed and homogeneous charge inside the engine well before the commencement of combustion. Higher combustion temperature, extended duration of combustion and rapid flame propagation are the other reasons for reduced smoke. However, at higher load range due to non-availability of sufficient air and abnormal combustion there was a visible white smoke emission. Another reason for lower smoke may be better and complete combustion of fuel due to the oxygen present in the waste plastic oil.

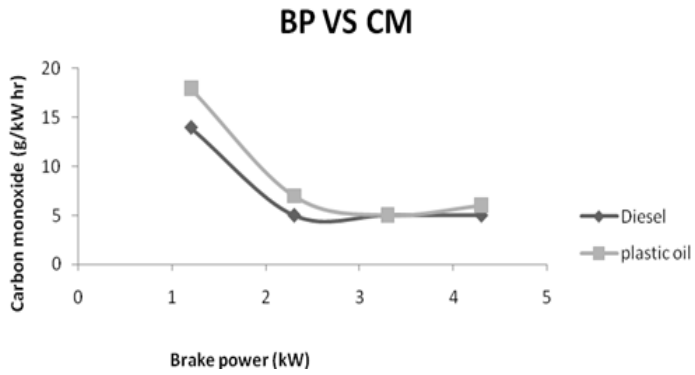
Performance

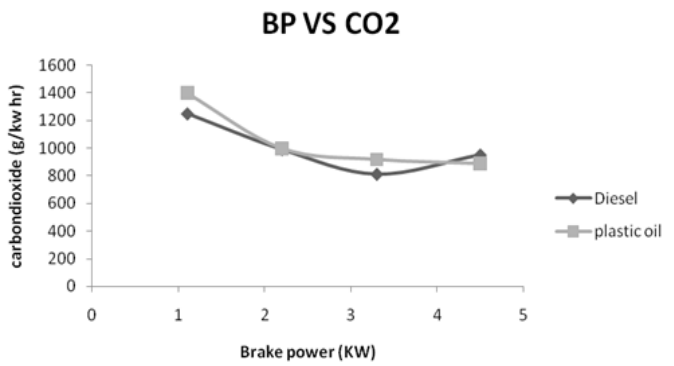
Brake thermal efficiency

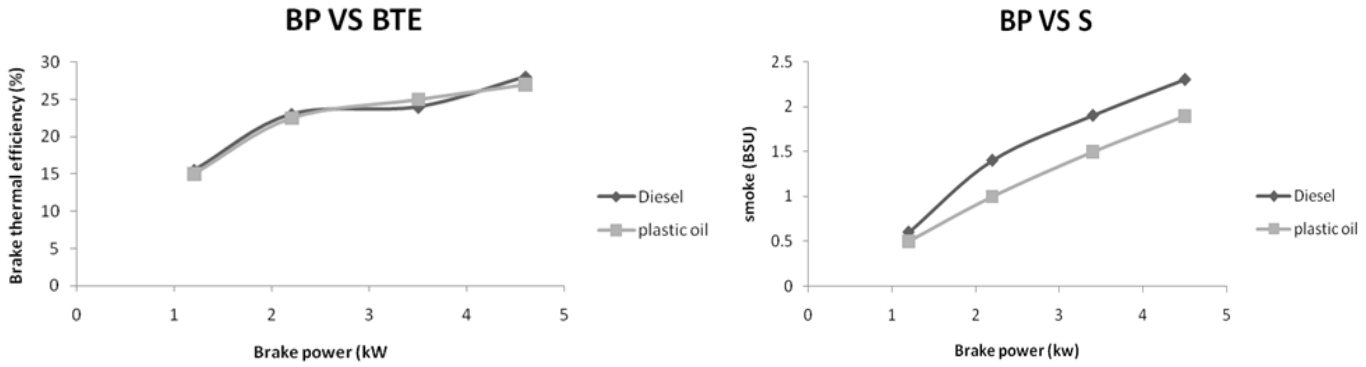
The variation of brake thermal efficiency with brake power is shown in Fig. 11 can be observed from the figure that the thermal efficiency is 28.2% at rated power for HCCI and for the waste plastic oil it is 27.4%. It is clear that the brake thermal efficiency of the waste plastic oil is closer to HCCI upto 75% of rated power, beyond which it starts decreasing. At full load, the efficiency is marginally higher for HCCI fuel. This may be due to the fact that at full load, the exhaust gas temperature and the heat release rate are marginally higher for waste plastic oil compared to HCCI. This may result in higher heat losses and lower brake thermal efficiency in the case of waste plastic oil.

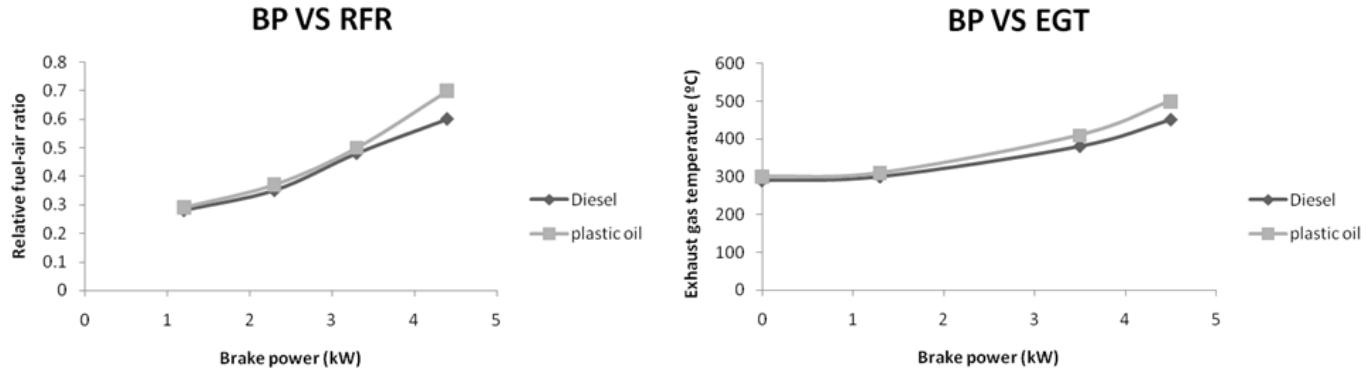












Exhaust gas temperature

Fig. 12 shows the variation of relative fuel air ratio with brake power. The variation of exhaust gas temperature with brake power is shown in Fig. 13. The exhaust gas temperature varies from 221 C at no load to 417 C at rated power for HCCI whereas in the case of waste plastic oil it varies from 240 C at no load to 450 C at rated power. The increase in exhaust gas temperature with engine load is clear from the simple fact that more amount of fuel was required by the engine to generate the extra power needed to take up the additional loading. It can be seen that the fuel air ratio increases with brake power for both fuels. Fuel air ratio is higher in the case of waste plastic oil compared to HCCI at all loads. This results in higher exhaust gas temperature in the case of waste plastic oil compared to HCCI. Another reason for the in- creased exhaust gas temperature at rated power is the higher heat release

CONCLUSION

From the tests conducted with waste plastic oil and HCCI on a HCCI engine, the following conclusions are arrived: Engine was able to run with 100% waste plastic oil. Ignition delay was longer by about 2.5 CA in the case of waste plastic oil compared to HCCI NOx is higher by about 25% for waste plastic oil operation than that of HCCI operation. CO emission increased by 5% in waste plastic oil compared to HCCI operation. Unburned hydrocarbon emission is higher by about 15%. Smoke reduced by 40% at rated power in waste plastic oil compared to HCCI operation. Engine fueled with waste plastic oil exhibits higher thermal efficiency upto 75% of the rated power

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