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Characterization of waste plastic oil derived from pyrolytic batch reactor and analysis of performance and emission parameters in a direct injection compression ignition engine

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ABSTRACT

The depletion in fossil fuel and an immediate need for its replacement led to the search of various sources of fuel like gaseous fuel, biofuels, ethanol, and many more. Environmental pollution through solid waste is also one of the major crisis in developed and developing countries. In order to bridge this gap, a pyrolytic batch reactor has been designed and developed to produce waste plastic oil from different combinations of used plastics. The PBR was designed with a cycle efficiency of 10 kgs used plastic which yielded 450 ml of WPO. The GC/MS analysis also revealed the presence of alkenes and alkanes with carbon number of C_8 *to* C_{19} *which was favorable to be used as fuel in CI engine. The experimental investigation was carried out in a single cylinder compression ignition engine to analyze its performance and emission characteristics. The BSEC of WPO blends was found increase marginally on comparison with straight diesel whereas BTE showed a decrease of 6% to 8%. The mechanical efficiency of WPO blends and straight diesel were almost similar at all loads. The UBHC, CO,* NO_x *and smoke emissions showed an increasing trend with a marginal decrease in* CO_2 *emission for WPO blends.*

Keywords: Pyrolysis, Performance, Emission, BSEC and WPO

INTRODUCTION

A large exponential growth has been witnessed in the plastic industrial sector for the past 30 to 40 years which finds application in home appliances, automobile products, medical field, aerospace application, electrical and electronic applications. The plastics like polypropylene, polystyrene, polyvinyl chloride, polyethylene broadly classified as polyolefin gained mush importance due to their lesser weight, corrosion resistance, ease to fabricate and mold, less cost, reusability and higher durability. Generally plastics are composed of long chain hydrocarbons in addition to fillers, monomers, peroxide catalyst, release agents, pigments and thickening agents. India was estimated to produce larger quantity of high density poly ethylene in addition to PVC and PP for its wide range of applications. As the productivity was increased and at the same time, due to restricted usage period, problem of waste plastic disposal emerges at a greater scenario than production. The government stringent norms and rules have been helping to a certain extent to save the environment but solid waste plastic management still to be overviewed with a suitable technique like thermal degradation, thermal cracking, recycling, decomposition and many more [1,10]. One such technique is called pyrolysis (i.e.) thermal degradation of solid waste plastic in liquid and gas in the absence of oxygen. This process can be improved to a greater extent with the use of catalyst like ZSM, red mud, alumina, zeolite, silica, and feedstock's of soyabean, neem and others. Many researchers have developed promising ways of pyrolysis with higher success rate. CI engine exhibited better performance and drivability characteristics with the use of WPO which showed a promising way of solid waste plastic recycling[11,12].

The gaseous oil of low density polyethylene was studied using thermogravimetric analysis in the presence of catalyst like HZSM, HUSY, HBeta zeolite, FCC catalyst and Al-MCM-41. The results showed catalyst like HBeta and zeolite was more active in decomposing the mixture and ZSM-5 zeolite produced coke at a lower quantity. The vacuum gas oil – polyethylene blend was produced through thermal and catalytic pyrolysis relating to vaporization and degradation technique [15].A tertiary recycling process of waste polymers in standard FCC LDPE was studied to produce vacuum gas oil in a Riser simulator laboratory reactor. The reaction temperature were between 500^{o}C to 550^{o}C which yielded deoxidized gas, liquefied petroleum gas, LCO and coke at various percentages. Two types of catalyst were used namely conventional and resid type in which resid type catalyst showed best performance on comparison with others[8,9]. Hydro pyrolysis and conventional pyrolysis of mixed plastics was carried out between 150^{o}C to 350^{o}C under nitrogen gas atmosphere which underwent thermal and catalytic decomposition in single and two stage reactions. The results revealed that the conversion to liquid and gaseous products as more than 90% for PDPE and less than 50% for HDPE, PP and PVC exhibited the production of VGO more than 85% proved to be a promising way to substitute petroleum derivatives [21].High-density poly ethylene was used to produce WPO in the presence of kaolin catalyst. The catalyst was primarily acid treated with HNO_3 followed by acid digestion. The HDPE and kaolin at 4% ratio was treated in a reactor furnace at 450^{o}C and the outlet gas was condensed and collected in a jar outside the setup. The derived oil was subjected to GC/MS and FTIR test for its characterization used in CI engine to analyze its performance. It was noticed that, the BTE was lower than diesel at all blends and load were as exhaust gas temperature and mechanical efficiency was found to be increased with load. The emissions like NO_x and CO was also found to increase with increase in blend of WPO were as CO_2 was found to be lower than diesel across all blends and load [22-23].

In the present investigation, a pyrolytic batch reactor was designed and developed with the overall dimension of 458 X400 X 200 cm. A combination of HDPE, LDPE, PVC and PP was mixed and fed into the reaction chamber for the pyrolytic gas yield in the absence of catalyst. The thermal degradation behavior of waste plastics was studied and analyzed using GC/MS technique. The resultant WPO was blended with straight diesel and subjected to CI engine to estimate its performance and emission parameters.

EXPERIMENTAL SECTION

2.1 Design of Pyrolytic Batch Reactor

The PBR was designed and fabricated using SS316L-Stainless steel by forging and rolling techniques. The overall dimension of PBR was 458 X 400 X 200 cm as shown in Figure (1). The PBR consist of conical lid on the top with an exhaust chute. The reactor cylinder is composed of two compartments, inner cylinder at a radius of 65 cm and outer cylinder at 76 cm as shown. The intermediate compartment between the two cylinders was compactly filled with glass wool with 2X2 m dimension to reduce the heat loss to atmosphere and to enhance thermal recycling process. The capacity of PBR was designed to be 10 to 12 Kgs of waste plastic for a single cycle. The exhaust chute was equipped with a temperature sensor which is connected to a cutout relay to maintain the working temperature between 250^{o}C to 450^{o}C.The heating of PBR was accomplished with three koyos flexible induction coil upto a heating limit of 650^{o}C to 700^{o}C. The temperature controller with a sensor was equipped in the PBR setup interlinked with heating coil to avoid over heating issues.The exhaust chute was directed towards a condensation chamber made of fiber glass through 350 cm SS pipe to admit the smoke into the condensation chamber filled with cooling water. The condensed smoke in the form of WPO occupies the top layer of the chamber is carefully separated through an outlet arrangement as shown in Figure (1).

2.2 Conversion of waste plastic into WPO and its properties

25 kgs of waste plastic consisting of HDPE, LDPE, PVC and PP was collected from a local yard in Padur, Chennai, Tamil Nadu.The plastics were made into pieces of 1cm X 1cm size using crushing/grinding machine and washed with flowing water to remove impurities and then dried. 10 kgs of processed waste plastic was placed in the inner cylinder of PBR reactor and the temperature was increased gradually in four step ratios (i.e.) 250^{o}C, 280^{o}C, 330^{o}C and 370^{o}C. The effect of reactor temperature on yield of solid char, liquid and gases are shown in Table (1). The crude WPO was collected through the exhaust chute in the condensation chamber fitted with fiber glass as shown in Figure (1) and subjected to fractional distillation process to remove moisture. The Table (2) reveals elemental analysis of WPO which exhibits 81.58% C, 12.31% H2, 5.43% O2, 0.17% N2, 0.41% S and 0.1% Ash [3-6].

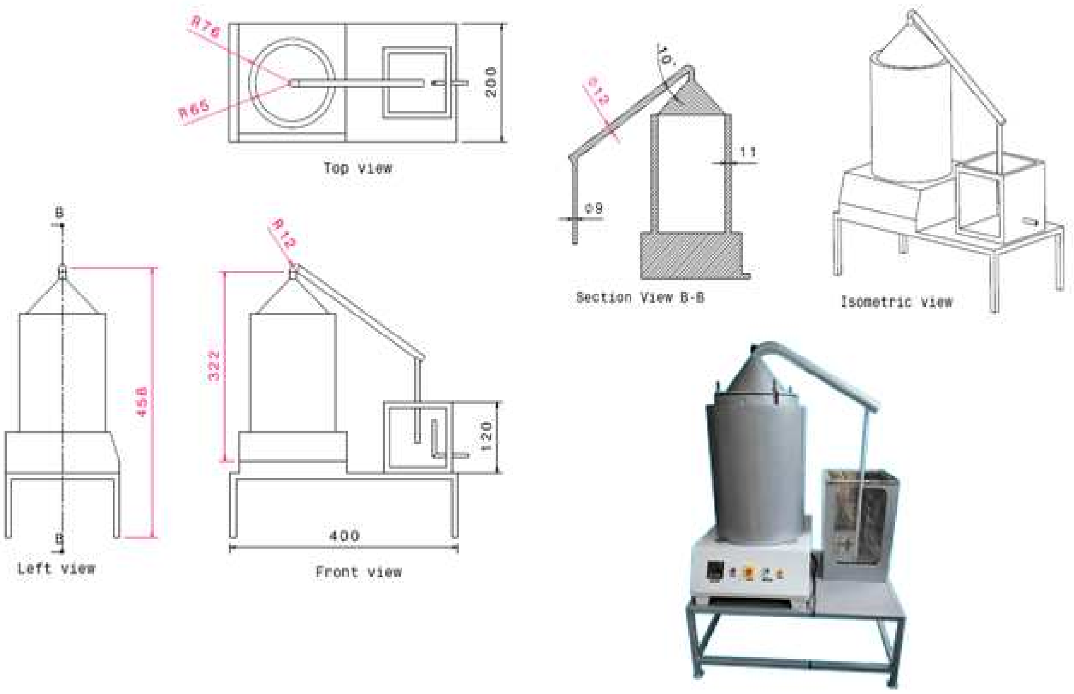

Figure 1. Detailed and Pictorial view of PBR

Table 1. Effect of Reactor Temperature on the Products Yield

Types of Products	**Products yield at different reactor temperature in (wt %)**			
	250°C	**280°C**	**330°C**	**370°C**
Solid char	40	33	26.5	23
Liquids	50	56.5	62.5	65
Gases	10	10.5	11	12

Table 2. Elemental Analysis of Waste plastic oil

Elements	**Ratio proportions (wt. %)**
Carbon	81.58
Hydrogen	12.31
Oxygen	5.43
Nitrogen	0.17
Sulphur	0.41
Ash	0.1

Table (4) shows the comparison of physio-chemical properties of waste plastic oil, tyre pyrolysis oil with straight diesel. The density of WPO was found to be 835.5 kg/m^3 whereas straight diesel and TPO showed 840 kg/m^3 and 937 kg/m^3 respectively. The kinematic viscosity at 40°C for WPO lies intermediate between diesel and TPO. The flash and fire point was also found to be comparable with diesel fuel for its use in CI engine. The sulphur content of WPO was found to be lowest as 0.030% on comparison with diesel and TPO which removes the desulphurization process. The cetane number of WPO was found to low on comparison with diesel and TPO.The Table (3) shows the comparison of WPO blends at WPO 15%, 25% and 35% ratios. It is also evident from the literature survey that WPO blends with completely with diesel and can be used in CI engine without any modification. IS1448 testing methods was adopted to estimate the physio-chemical properties of diesel-WPO blends like density, kinematic viscosity, flash & fire point, calorific value, sulphur content and cetane number decreases with increase in WPO concentration whereas kinematic viscosity and carbon residue increases to a marginal level. The initial and final boiling point of distillation temperature lies between 120°C and 368°C for WPO blends [13, 14, and 19].

Table 3. Comparison of Properties of WPO Blends

Properties	Units	Testing Methods	WPO 15	WPO 25	WPO 35
Density @ 30°c	kg/m^3	IS:1448 P:16	834	849	858
Kinematic viscosity, @ 40°c	Cst	IS:1448 P:25	2.47	2.60	2.65
Flash point	°c	IS:1448 P:20	48	42	38
Fire point	°c	IS:1448 P:20	60	56	58
Gross Calorific value	kJ/kg	IS:1448 P:6	43,216	42,667	40,477
Sulphur content	%	IS:1448 P:33	0.02	0.01	-
Carbon residue	%	IS:1448 P:122	0.03	0.06	0.07
Ash content	%	IS:1448 P:126	0.01	0.01	0.01
Cetane Index	-	IS:1448 P:9	51	49	43
Distillation Range	°c	IS:1448 P:18			
Initial Boiling Point	°c		120	128	136
Final Boiling Point	°c		365	370	368

Table 4. Comparison of Diesel, WPO and TPO

Properties	Units	Diesel	Waste Plastic Oil	Tyre Pyrolysis Oil
Density @ 30°c	kg/m^3	840	835.5	937
Kinematic viscosity, @ 40°c	Cst	2	2.52	3.22
Flash point	°c	50	42	44
Fire point	°c	56	45	52
Gross Calorific value	kJ/kg	46,500	44,340	42,855
Sulphur content	%	0.045	0.030	0.41
Carbon residue	%	0.35	82.49	2.14
Ash content	%	0.01	0.00023	0.1
Cetane Index		55	51	53

Experimental Procedure

The schematic layout and pictorial view of the test engine is shown in Figure (2). The engine is equipped with performance measurement, combustion and emission analyzer. Kirloskar DM10 single cylinder, direct injection, naturally aspirated compression ignition engine with bore and stroke of 102mm X118mm was used in this study. The cubic capacity of the engine is 948cc with compression ratio of 17.5:1. The detailed engine specification is give in Table (5). U-Tube manometer and burette setup is equipped on the engine test panel to analyze the intake of air and fuel.

Initially the engine was started with diesel and WPO blends was admitted through a three way cock setup in the fuel tank and fuel consumption for 10cc was measured using a stop watch. The loading of the engine was accomplished by electrical dynamometer coupled to the engine as shown and the indications was taken from ammeter and voltmeter arrangements. The engine was also equipped with Crypton 5 gas analyzer and Bosch smoke meter to measure emission outlets through the exhaust probe. The engine was warmed up with diesel initially for 45 min before the admittance of WPO blends at 1500 rpm. The experiments were conducted with WPO15%, WPO25% and WPO35% blends at no load, part load and full load of the engine.

Table 5. Test Engine Specification

Name	Description
Make	Kirloskar
Model	DM 10
Bore	102 mm
Stroke	118 mm
Cubic capacity	948 cc
Compression ratio	17.5:1
Engine speed	1500 Rpm
Injection timing	26^o BTDC
IVO (BTDC)	4.5^o
IVC (ABDC)	35.5^o
EVO (BBDC)	35.5^o
EVC (ATDC)	4.5^o

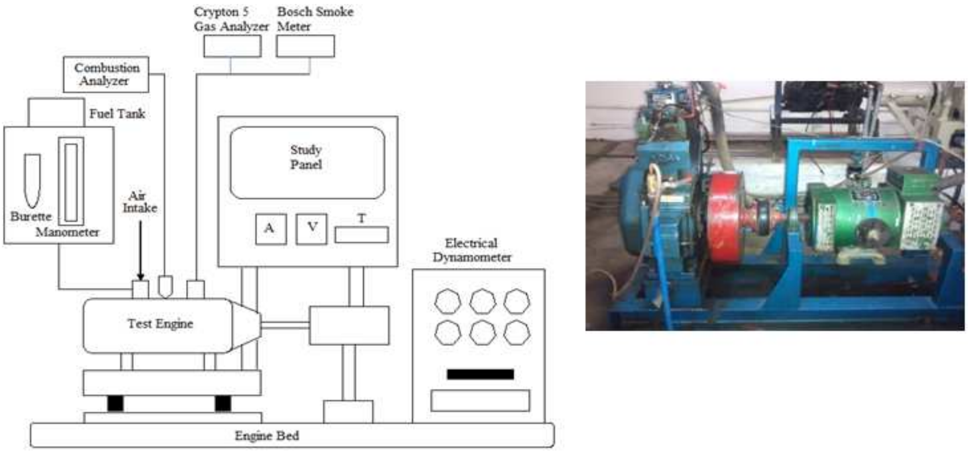

Figure 2. Schematic Diagram and Pictorial view of Experimental Setup

RESULTS AND DISCUSSION

4.1 Gas chromatography Mass spectrometry analysis of WPO

The GC/MS analysis was carried out to characterize the WPO obtained the PBR. JEOL GCMateII data system with high resolution, double focusing instrument maximum resolution and calibrated mass of 6000 and 1500 Daltons respectively and chemical ionization technique was used on WPO. It was noticed that WPO contained 14 compounds mainly composed of n-styrene, n-hexane and phenolic hydrocarbons as detailed in Table (6). The characteristics mass spectrum of WPO is shown in Figure (3) with retention time between 2.97 min and 21.65 min. The compounds identified in the chromatogram were alkenes and alkanes with carbon number between C_8 to C_{19}[24-25].

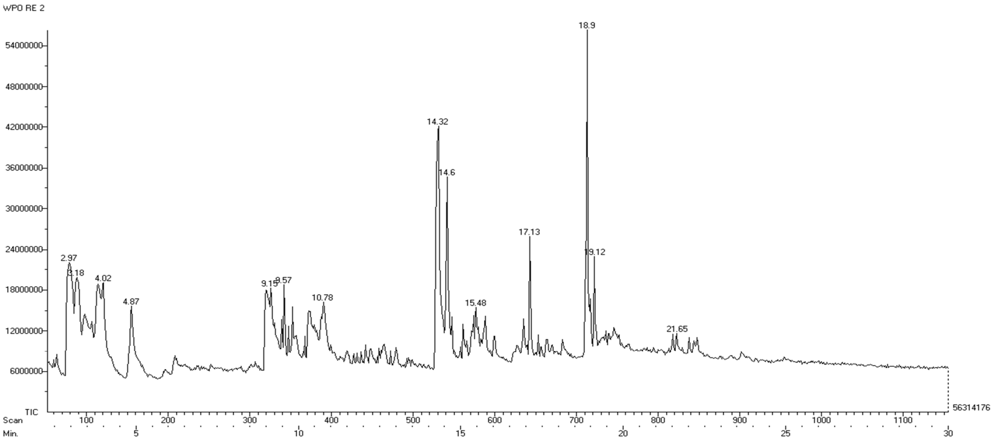

Figure 3. GC/MS Mass Spectrum of Waste Plastic Pyrolysis Oil

Table 6. GC/MS Analysis of Waste Plastic Oil

RT (min)	Name of Compounds	Molecular Formula	Scan	Ions
2.97	Spiro[2.4]heptane,1-ethenyl-5-(1-propenylidene)	$C_{12}H_{16}$	79	1809
3.27	1.6-heptadien-3-yne,5-methyl	$C_{12}H_{17}$	91	1768
4.07	2-nitro-1-phenyl-ethanol	$C_8H_9NO_3$	123	1583
4.95	Methyl styrene	C_9H_{10}	158	1520
9.15	1,5,5-trimethyl-6-methylene-cyclohexene	$C_{10}H_{16}$	325	1666
9.57	5-Caranol, (1S,3R,5S,6R)-(-)-	$C_{10}H_{18}O$	342	1626
10.28	1-propene-1-amine,N-benzylidene-2-methyl	$C_{11}H_{13}N$	390	1643
14.35	Methanone, (3-methylphenyl)phenyl-	$C_{14}H_{12}O$	532	2771
14.62	1h-inden-1-one 2 3-dihydro-3-phenyl	$C_{18}H_{14}O$	543	1990
15.48	2h-1-benzopyran,3,4-dihydro-2-phenyl	$C_{15}H_{14}O$	577	1750
17.13	pentadecanoic acid 13-methyl- methyl ester	$C_{17}H_{34}O_2$	643	1912
18.92	2-hexadecanoic acid ,2,3-dimethyl,methyl ester	$C_{19}H_{36}O_2$	714	2139
19.12	heptadecanoic acid 14-methyl- methyl ester	$C_{19}H_{38}O_2$	722	2004
21.65	methanone,(4-(2-hydroxy-5-methyl benzylidene) phenyl) (phenyl)	$C_{15}H_{14}O_5$	823	1998

4.2 Variation in Performance parameters

The variation in brake specific energy consumption of straight diesel, WPO 15%, 25% and 35% blends at all loads are shown in Figure (4). The BSEC of straight diesel at low load, part load and full load was found to be 22.5 MJ/kWh, 16 MJ/kWh and 16.8 MJ/kWh respectively. WPO blends showed increased BSEC than straight diesel at all loads with similar trend as shown.

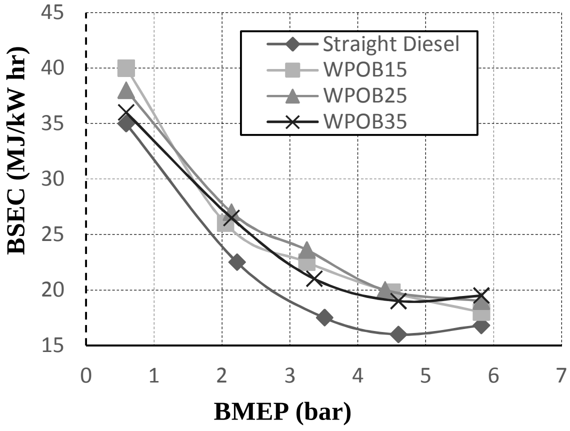

Figure 4. Comparison of Brake Mean Effective Pressure with Brake Specific Energy Consumption

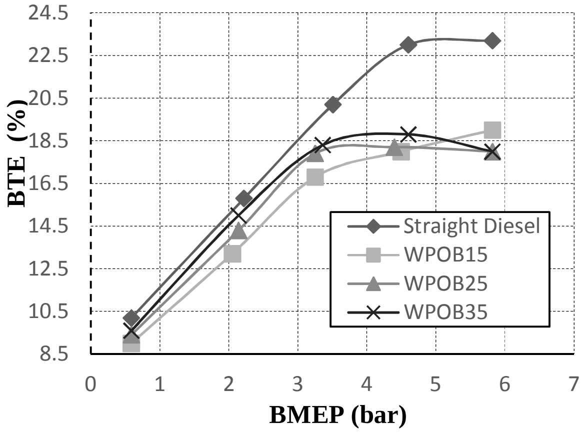

Figure 5. Comparison of Brake Mean Effective Pressure with Brake Thermal Efficiency

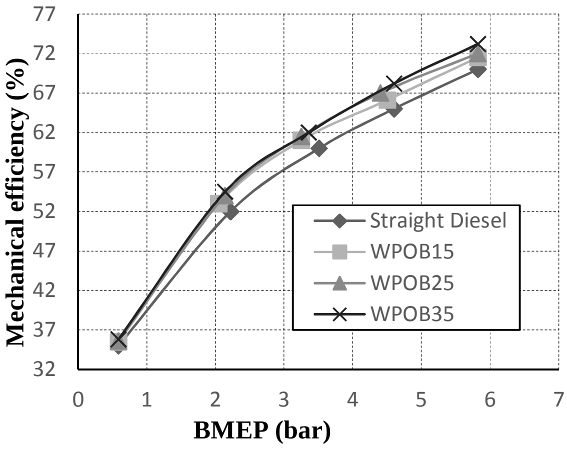

Figure 6. Comparison of Brake Mean Effective Pressure with Mechanical Efficiency

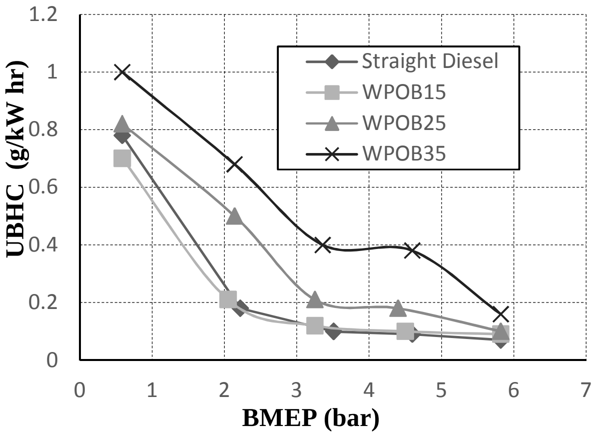

Figure 7. Comparison of Brake Mean Effective Pressure with UBHC

The BSEC of WPO 15%, 25% and 35% blends at part load was noticed to be 26 MJ/kWh, 27.2 MJ/kWh and 26.5 MJ/kWh whereas full load showed 18.1 MJ/kWh, 19.3 MJ/kWh and 19.5 MJ/kWh respectively, which may be due to decrease in calorific value with the increase in WPO blends between 43216 kJ/kg to 40477 kJ/kg. It is evident from the graph that with increase in BMEP, the consumption of WPO blends continuously increases across all the blends and it can also be seen that BSEC decreases gradually with an increase in load for all WPO blends [16,17].

The variation in brake thermal efficiency for straight diesel, WPO 15%, 25% and 35% blend for all load are shown in Figure (5). The BTE for straight diesel varies between 10.2% to 23.2% for no load, part load and full load operations whereas WPO blends show variation between 9.2% and 18.6% for all loads. Generally, BTE shows an increasing trend irrespective for fuel across all blends and straight diesel. The BTE for straight diesel at full load was noticed to be 23.2% but WPO blends lied between 17.5% to 18.6% as shown in Figure (5). The BTE for WPO 15% blend at part load was found to be 16.8% whereas WPO25% and WPO35% exhibited 17.9% and 18.3% respectively. This huge variation between straight diesel and WPO may be due to poor atomization and reduced pre-mixed combustion which is in turn due to reduction in cetane number with an increase in WPO blends. As the BTE for WPO blends shows a decreasing trend, the heat energy is lost to the surrounding to a greater extent without converting into useful work.

The effect of mechanical efficiency on straight diesel and WPO blends at low load, part load and full load is shown in Figure (6). Generally, the mechanical efficiency shows an increasing trend with straight diesel and blends of WPO for all loads. At low load condition, the mechanical efficiency of straight diesel was found to 52% whereas WPO 15%, 25% and 35% blends showed 53%, 54% and 54.5% respectively. As the load increases, the variation in mechanical efficiency marginally increased between 53% and 63% for all blends. At full load operations, the mechanical efficiency showed minimal variation between 70% and 73% for all blends which proved that WPO blend more suitable to be used in CI engine as a substitute for straight diesel. A similar and marginal variation in mechanical efficiency between diesel and WPO blends signifies that the frictional loss occurred due to moving parts in the engine is almost similar when the operating fuel is straight diesel and WPO blends[18].

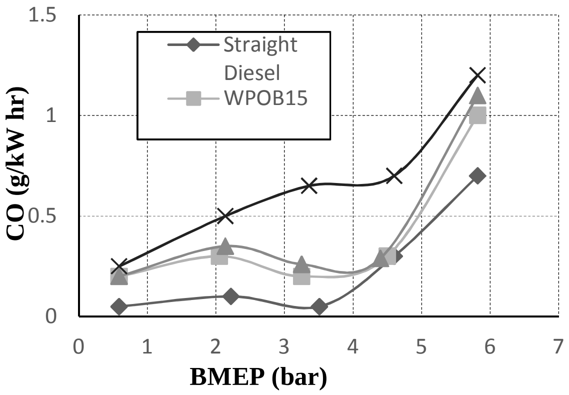

Figure 8. Comparison of Brake Mean Effective Pressure with CO

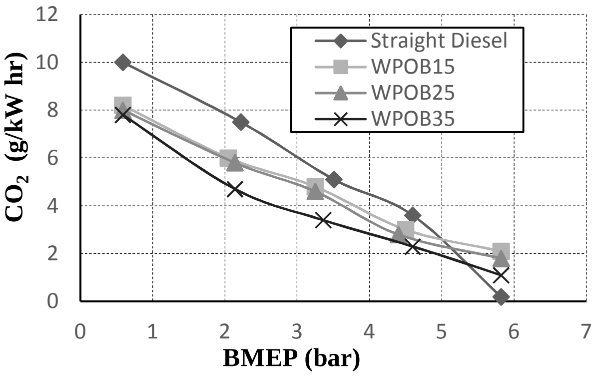

Figure 9. Comparison of Brake Mean Effective Pressure with CO_2

4.3 Variation in Emission parameters

The variation in UBHC emission for straight diesel, WPO 15%, 25% and 35% blends at low load, part load and full load are shown in Figure (7). The main reason behind the formation of UBHC emission was due to incomplete combustion and flame quenching near the wall and cold regions. From the figure it can be noticed that UBHC emission was higher during low loading condition which may be due to lower operating and exhaust temperature and availability of more oxygen which may not take part in combustion during starting. At low loads, UBHC was found to be 0.18 g/kWh for straight diesel whereas WPO blends showed 0.21 g/kWh to 0.68 g/kWh variation. Another reason for higher UBHC emission during low load may be due to poor atomization and increase in kinematic viscosity. WPO 25% blend showed 0.5 g/kWh at low load, 0.21 g/kWh at part load and 0.1 g/kWh of UBHC emission at full load condition whereas WPO 35% blend exhibited a higher emission of UBHC on comparison of straight diesel and other WPO blends (i.e.) 0.68 g/kWh at low load, 0.38 g/kWh at part load and 0.16 g/kWh at full load. It can be also seen from the Figure (7) that at full load condition, the UBHC emission of straight diesel and all blends of WPO were very low which may be due to enhanced combustion and reduction in flame quenching near the walls of the combustion cylinder [7,20].

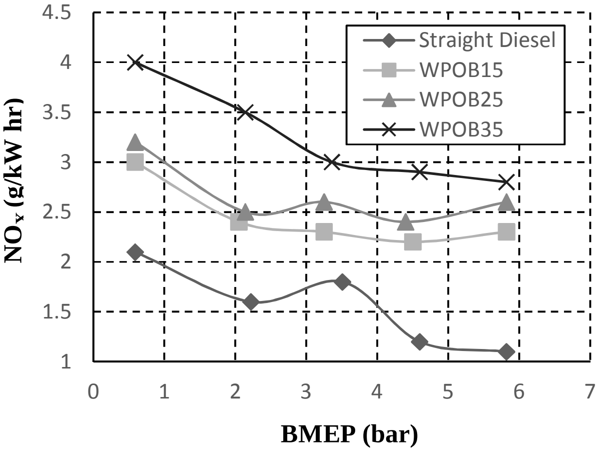

Figure 10. Comparison of Brake Mean Effective Pressure with NO$_x$

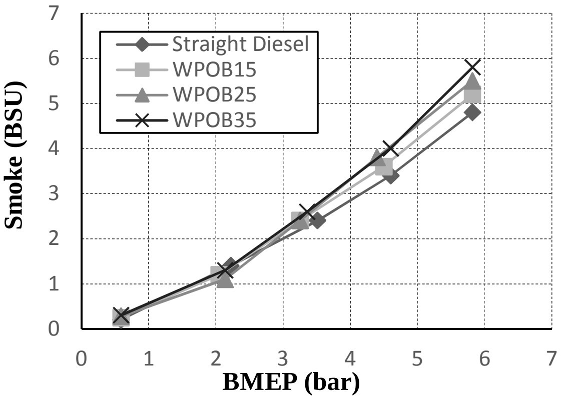

Figure 11. Comparison of Brake Mean Effective Pressure with Smoke

Carbon monoxide emission was formed as an intermediate product of combustion which may be due to poor atomization and insufficient quantity of oxygen during combustion process. With respect to compression ignition engine, CO emission is one of the most important factor which is to be controlled effectively. Figure (8) shows the variation of CO emission for straight diesel, WPO 15%, 25% and 35% at low load, part load and full load condition. At low load, the CO emission was found to be 0.112 g/kWh, 0.312 g/kWh, 0.356 g/kWh and 0.504 g/kWh for straight diesel, WPO 15%, 25% and 35% blends respectively. As the load increases, the CO emission continuously increases upto 0.652 g/kWh for WPO 35% blend which shows the presence of insufficient quantity of oxygen for CO_2 conversion at part loads. At full loading condition, the CO emission of straight diesel and WPO blends show an increasing trend between 0.752 g/kWh and 1.223 g/kWh for all blends of fuel which may be due to poor homogeneity of air fuel mixture, lack of oxygen and incomplete combustion at higher loads.

The Figure (10) shows the variation of oxides of nitrogen for straight diesel, WPO 15%, 25% and 35% at low load, part load and full load condition. The main reason of NO_x formation depends on in-cylinder and combustion temperature which results in the formation of mono-atomic oxygen having higher affinity towards N_2 to form NO, NO_2 and NO_3. At low load operations, the NOx formation of WPO blends was found to be higher than straight diesel and at part load conditions, NO_x emission was noticed to be 1.83 g/kWh for straight diesel, 2.305 g/kWh for WPO 15% blend, 2.689 g/kWh for WPO 25% blend and 3.125 g/kWh for WPO 35% blend. Generally, NO_x emission shows a decreasing trend between 4.2 g/kWh and 1.12 g/kWh at all loads. At full load operations, the NO_x

emission for straight diesel, WPO 15%, 25% and 35% blends were 1.1 g/kWh, 2.3 g/kWh, 2.6 g/kWh and 2.89 g/kWh respectively, which may be due to less fuel accumulation in the previous cycle which results in lesser premixed combustion period. It was also noticed that the operating temperature and exhaust gas temperature at full load was found to be lower than low and part load operations.

Generally, CO_2 emission signifies the effectiveness of combustion and performance to a greater extent. CO_2 is formed as a result of complete combustion in which all the carbon atoms in the fuel is oxidized to carbon-di-oxide. With respect to the ideal combustion equation, CO_2 and H_2O are the products of fuel and air in the presence of heat during combustion. Figure (9) shows the variation of CO_2 emission of straight diesel and WPO blends. At low load operations, CO_2 emission was found to be varying between 7.88 g/kWh to 10.25 g/kWh which may be due to poor atomization and lesser operating temperature. At part load condition, the CO_2 emission is gradually reduced with diesel and WPO blends which may be due to reduction in calorific value of the fuel. At full load operations, it can be seen that straight diesel, WPO 15%, 25% and 35% blends exhibit 0.221 g/kWh, 2.158 g/kWh, 1.869 g/kWh and 1.110 g/kWh CO_2 emission respectively which may be due to poor homogenization of air fuel mixture at high load and lack of oxygen during combustion [2,16-18].The variation of smoke emission for straight diesel, WPO 15%, 25% and 35% blends at all loads are shown in Figure (11). Generally smoke emission is formed due to poor premixed combustion and incomplete combustion phase. It can be noticed that smoke emission shows an increasing trend from low load to full load across all fuels with straight diesel being the lowest. At low load, smoke emission was found to be 1.43 BSU for straight diesel whereas WPO 15%, 25% and 35% exhibited 1.20 BSU, 1.16 BSU and 1.30 BSU respectively. As the load is increased, the smoke emission was also increased upto 5.87 BSU for WPO 35% blend ratio. The variation in smoke emission for all fuel shows minimal variation as shown in figure ( ).

CONCLUSION

From the experimental investigation conducted, the following results were concluded,

- The designed and developed PBR reactor was capable of producing 450 ml of waste plastic oil per cycle in an efficient way.
- The GC/MS analysis and physio-chemical properties of WPO and its blends revealed the presence of alkenes, alkanes and petroleum derivatives which are more suited to be a substitute for petroleum diesel.
- The performance of blended WPO with straight diesel was very effective in compression engine without any engine modification upto 35% blend ratio.
- The BSEC of WPO with straight diesel was found to be higher than straight diesel which showed more fuel consumption than diesel with relative lower BTE.
- The mechanical efficiency of WPO blends and straight diesel was found to be almost similar at all loads which showed that frictional loss between moving parts are also same.
- The UBHC emission of WPO 35% blends was noticed to be higher on comparison with other blends of WPO and straight diesel, CO and NO_x also showed a similar trend with all loads.
- The CO_2 emission was found to decrease with increasing in WPO blends at all loads and the smoke emission was noticed to be similar with all blends of WPO and straight diesel at all loading condition.

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