Experimental investigation on combustion and emission characteristics of DI diesel engine fueled with waste plastic oil derived from municipal solid waste under the influence of n-hexanol addition, cold EGR and injection timing

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Abstract *- To avoid the problems associated to fossil fuels, it becomes necessary to use cleaner and renewable energy sources. However, these new energy sources should compete with the prices of fossil fuels. Waste plastic oil from municipal soil waste can be an excellent alternative fuel. One disadvantage of using neat waste plastic oil is the attribute to high carcinogenic smoke emissions, hence with necessary additive this fuel can serve the transport sector. In this study waste plastic oil was blended with a renewable component n-hexanol by 70%WPO and 30% n-hexanol, combustion and emission characteristics of the blend has been studied under the influence of cold EGR and varying injection timing. Results indicated that addition of n-hexanol to the waste plastic oil has brought down the smoke emissions almost twice when compared with its pure component at all operating condition. The test blend has shown a high premixed combustion phase compared to baseline fuels, however there was a slight penalty in* NO_x *emission which was curtailed by introduction of EGR.*

Keywords - *Waste plastic oil, Diesel Engine, Emission, municipal solid waste.*

I. INTRODUCTION

Transport is an indispensable part of present day life, the financial improvement of a country largely relay upon the simple access to individuals and products guaranteed by contemporary transport technology [1]. These positive aspects are closely connected with the risks to the environment and human health caused by transport, especially road transport. According to world health organization (WHO) report, in the top 20 polluted cities across the globe, 13 are in India and New Delhi tops the list, scrutinizing the cause uncontrolled vehicular traffic seems to be the primary reason. Air pollution has become a major threat to human health and brings both acute and chronic respiratory diseases [2-4][2-4][2-4][2-4][2-4][2-4]. In India, health cost due air pollution has been estimated around 3 per cent of its GDP and increasing automobile population will increase its share in the future. The outdoor air pollution from automobile is one of the major contributors to bring down the ambient air quality which badly affects both environment and human health, especially young children due to the immaturity of their respiratory systems. Ageing of vehicle add most environmental issues; hence it is essential to enhance the technological parameters by introducing new technologies, implementation of periodic inspection with maintenance and introducing cleaner fuels which may reduce exhaust emission concentration.

Urban planning and development also strongly influence the air quality, accessibility of public transport and non-motorized transportation options have significant effect. It has been assessed that urban outdoor air contamination to cause 1.3 million deaths across the globe every year. Urban trips cover less distance which leads to decrease in catalytic converter effectiveness as time taken for engine operation is very less resulting to high average emission per distance driven. To counter the transport emissions, governments all over the world strive to take stringent actions by enforcing stricter emission regulation standards (the Bharath Stage emission standards called BS IV which is currently enforced by Govt. of India and future legislation such as BS V and BS VI) which will reduce exhaust pollutant from engines. Implementation of advanced technologies have greater effect in lowering emission levels from vehicles, enhancing research in these areas should be promoted, along with periodic vehicle inspection to bring down the emission level due to badly maintained vehicles. Usage of cleaner fuels can be a possible measure for effective reduction in specific emissions; therefore, many ongoing researches are made to find a possible alternative for fossil fuel without any compromise in performance of the engine. The waste plastic oil is one such alternative whose properties were similar to that of diesel and hence can be an excellent fuel in diesel engines.

Plastics turned into a basic requirement for current life [5-7][5-7][5-7][5-7][5-7][5-7][5-7]. A few plastics are reused, awfully many are not, which covered in landfills or littered where they can enter sensitive marine biological systems. Plastics are originated from fossil fuels. From research findings, it has been observed that the use of waste plastic oil as a neat fuel leads increase the soot emission. High soot emissions are usually attributed to the high aromatic compounds. Devaraj et al. blended diethyl ether at 5% and 10% with WPPO and found that there was a dramatic decrease in smoke emissions because the addition of oxygenate additive increases the combustion efficiency. Kaimal et al. blended pyrolysis oil with diesel at PO25, PO50 and PO75 blend proportion and studied the combustion characteristics and observed that peak pressure of the engine running on neat plastic oil was increased by about 6% but it showed poor thermal efficiency also combustion characteristics were greatly influenced by the physical properties of the fuel. Senthilkumar et al. prepared plastic oil emulsion, and its use in diesel engine simultaneously reduced NOx and smoke emission when compared to diesel. Mani et al. observed that the retarded injection timing decreased the NOx, CO, HC while smoke increased at all test conditions. The above studies reveal that the use of sole waste plastic oil at standard operating conditions might increase the carcinogenic smoke emission, hence it is necessary to optimize the parameters to have eco-friendly and efficient running condition of the engine using waste plastic oil.

The waste plastic oil extraction by pyrolysis is a very cost-effective method and its capacity to convert the maximum energy of plastic waste to valuable yield. Pyrolysis can be done thermally and catalytically, catalytic pyrolysis is more advantageous since it can be operated at a lower temperature range with greater yield of liquid oil. Waste plastic oil extracted from mixed waste plastics by catalytic pyrolysis using ZSM-2 as a catalyst and the properties of neat WPO was tested using ASTM methods and found to be closer to diesel and their combustion and emission characteristics to be measured in a single cylinder, water cooled, diesel engine by varying injection timing and EGR rates and optimizing the best operating conditions which reduces the prominent smoke emission which was reported in the literatures.

II. EXPERIMENTAL INVESTIGATION

Tests were carried out in a single cylinder, 4 stroke, water-cooled, direct injection diesel engine whose layout is in Fig.1.

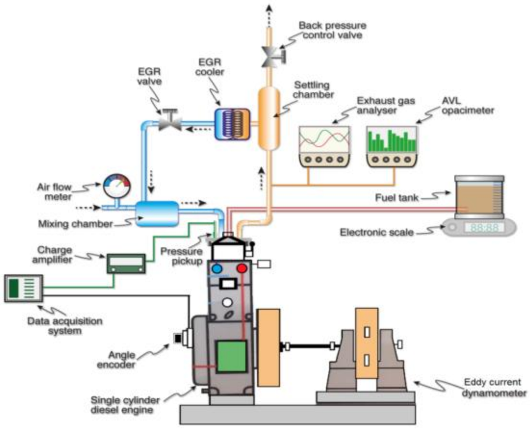

Fig.1 Layout of the experimental setup

W70H30 (70% waste plastic oil, 30% hexanol) were prepared at the mixing ratio of volume. Mixing lower volatility n-pentanol to higher volatility waste plastic oil could promote the evaporation of the blend.

Table 1 Properties of test fuels

Properties	Test method	ULSD	WPO	n-hexanol	W70H30
LHV (MJ/kg)	ASTM D240	41.82	40.35	36.4	39.165
ν at 30°C (mm2/s)	ASTM D445	3.80	2.16	3.32	2.382
ρ (kg/m3)	ASTM D4052	838	813	821.8	815.64
Cetane number	ASTM D4737	54	51	23	-
Flash point (°C)	ASTM D93	70	38	59	44.3

LHV – low heating value; ν – kinematic viscosity; ρ – density; CCI – calculated cetane index; WPO – waste plastic oil; H – n-hexanol

Table.2.Engine Specifications

Type	:	Single cylinder vertical water cooled, 4 stroke Diesel Engine
Bore	:	87.5 mm
Stroke	:	110 mm
Cylinder diameter	:	0.0875 m
Stroke length	:	0.1m
Compression ratio	:	17.5 : 1
Power	:	4.4 KW
Speed	:	1500 rpm
Loading device	:	Eddy current dynamometer

2.1 EGR setup

EGR method is an efficient method used for reduction of high NOx emission from diesel engines. In this study cooled EGR technique is adopted since it has numerous advantages over hot EGR, usage of greater proportion of EGR is achieved as cooling increases the density of the re-circulated exhaust gas. The stipulated quantity of exhaust gas is directed to the EGR cooler which acts as a heat exchanger, where cooling of hot exhaust gases is achieved by the surrounding cooling water which was maintained at a constant temperature. In this study, temperature drop in exhaust gas is achieved upto 35°C. EGR rate is controlled by an EGR valve. Orifice meter is used for measuring the flow rate of exhaust gas. Re-circulated exhaust gas and incoming air is mixed well in a mixing chamber before they inducted inside the combustion chamber. EGR quantity was determined using the relation,

$$EGR\% = \left[\frac{(CO_2)_{intake}}{(CO_2)_{exhaust}}\right] \times 100 \qquad (1)$$

The quantity of CO_2 in the exhaust was measured by the AVL 444N gas analyzer by adjusting the control valve to vary the flow rate of the exhaust until the quantity of CO_2 in the intake reaches the desired value. The similar method was used in authors previous work [8, 9], to determine the EGR rates.

2.2 Experimental procedure

All the tests were performed under steady state condition and at peak load, which corresponds to brake mean effective pressure (bmep) of 5.3 bar, reason for testing at peak load is that EGR effectiveness will be maximum. In this study, we recorded the combustion and emission characteristics under nine operating conditions at three EGR rates (i.e. 10%, 20% and 30%) and three injection timings (i.e. 21°CA bTDC, 23°CA bTDC and 25°CA bTDC), whereas injection pressure is held constant at 21 Mpa. By adding or removing the number of shims under the fuel injection pump, injection timing is varied. Shims are of thickness 0.4mm each which can advance or retard the timing by 2° CA. The EGR rate is increased by opening EGR valve gradually and observed that the increasing EGR rate beyond 30% smoke emission increased heavily; hence EGR rate is restricted to 30% for this study. Each test was repeated two times and ensured the repeatability of the observation.

III. Result and Discussion

Many research studies have shown that engine run with waste plastic oil, operating at standard injection timing produces high exhaust emission. Hence to reduce NOx and smoke emissions EGR rate and injection timing have been varied and experimented to find optimum parameter with which engine can operate with waste plastic oil/n-hexanol blends. The EGR rate was varied as 10%, 20% and 30%, while the injection timing was varied as retarded injection timing of 21°CA bTDC, standard injection timing of 23°CA bTDC and advanced injection timing of 25°CA bTDC. The effects of these parameters on the combustion and emission characteristics were investigated on a 4.4 kW single cylinder, constant speed DI diesel engine using waste plastic oil against diesel operation.

3.1 Combustion Characteristics

3.1.1. Cylinder Pressure – Crank Angle Diagram

Figure 2,3,4 presents the variation of in-cylinder pressure with crank angle of diesel, waste plastic oil and W70H30 blend under the influence of different EGR rates and injection timing. Highest peak pressure for W70H30 blend is 70.432 bar at the 10 % EGR rate and 25°CA bTDC against 72.321bar and 70.331 bar for baseline ULSD and WPO at same operating conditions. A Lowest peak pressure of 59.071 bar at 30% EGR and 21°CA bTDC was obtained for W70H30 blend when compared to 60.532 bar and 57.846 bar at the same operating condition of ULSD and WPO respectively. At same given EGR rate and injection timing WPO presents lower peak pressure than that of diesel, this is because the pressure rise due to combustion starts later, which eventually bring down the peak pressure of WPO even though the ignition delay period of WPO is high. Pressure rise due to combustion starts later since more energy is spent to break down the heavy hydrocarbon chains (C_{13} to C_{22}). Lower viscosity, CCI and calorific value of WPO also have a significant effect on decreasing the peak pressure. Addition of n-hexanol to WPO slightly increases the peak pressure due to high premixed combustion phase of the blend.

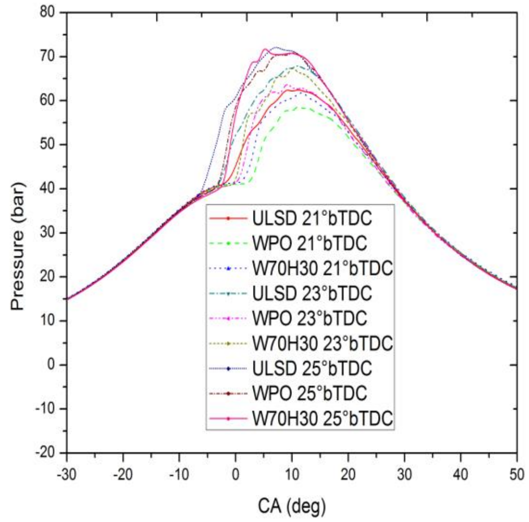

Fig.2 Variations of in-cylinder pressure vs.CA (10% EGR) and vs. CA (b1, b2, b3) at bmep= 5.3 bar and speed = 1500 rpm for test fuel at various injection timings and EGR

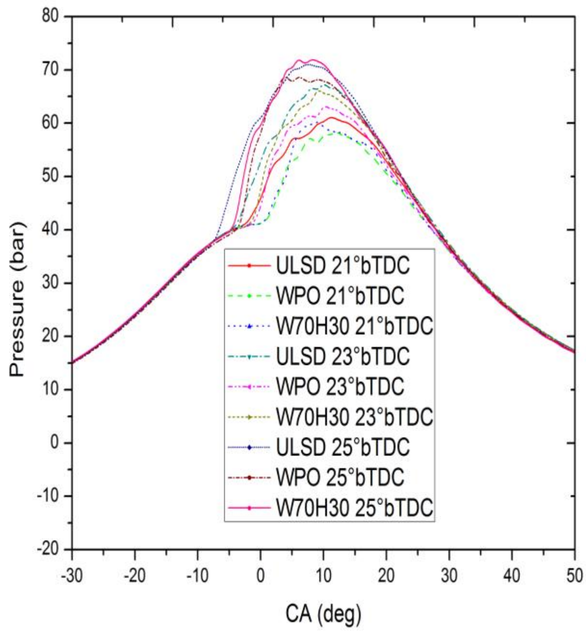

Fig.3 Variations of in-cylinder pressure vs.CA (20% EGR) and vs. CA (b1, b2, b3) at bmep= 5.3 bar and speed = 1500 rpm for test fuel at various injection timings and EGR

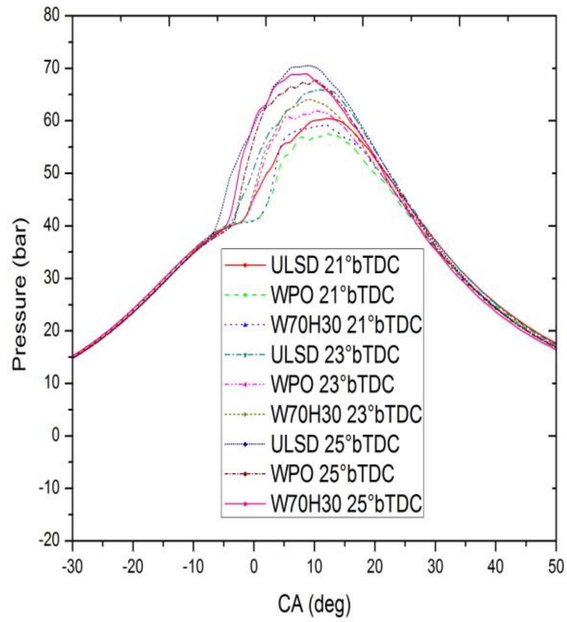

Fig.4 Variations of in-cylinder pressure vs.CA (30% EGR) and vs. CA (b1, b2, b3) at bmep= 5.3 bar and speed = 1500 rpm for test fuel at various injection timings and EGR

Increasing the EGR rate from 10% to 30% reduces the peak pressure for all the test fuels operating at different injection timing, this may be due to the fact that the introduction of exhaust gas into the intake reduces the oxygen available for combustion and specific heat capacity of mixture gas increases, which eventually reduces the in-cylinder temperature with subsequent decrease in peak pressure. In this study EGR rate is restricted up to 30% since a further increase in EGR percentage leads to heavy smoke emissions which have a direct effect on air pollution.

Escalating Injection timing from 21°CA bTDC to 25°CA bTDC increase the peak pressure of both the fuel, this is because advancement in injection timing causes larger combustion period that allows the fuel to burn for a longer duration to give higher peak cylinder pressure also increase in ignition delay period can be a dominant factor since longer ignition delay leads to a better air fuel mixture preparation which results in better combustion and higher peak cylinder pressure[10]. Retarded injection timing causes lower peak cylinder pressure because most of the combustion process has taken place during the expansion stroke which allows the engine to operate with minimum peak cylinder pressure.

3.1.2 Heat Release Rate – Crank Angle Diagram

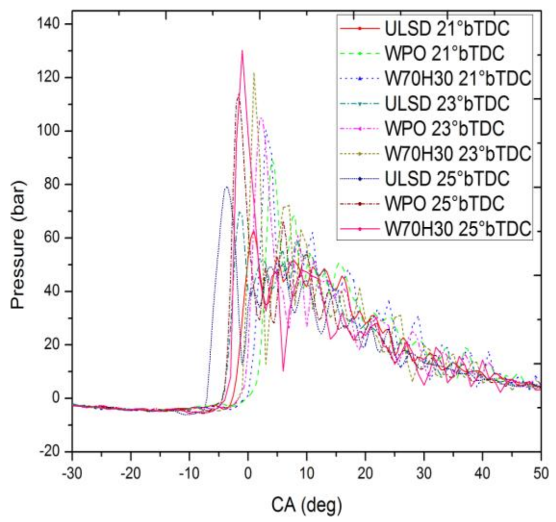

Fig.5 HRR vs.CA (10% EGR) and vs. CA (b1, b2, b3) at bmep= 5.3 bar and speed = 1500 rpm for test fuel at various injection timings and EGR

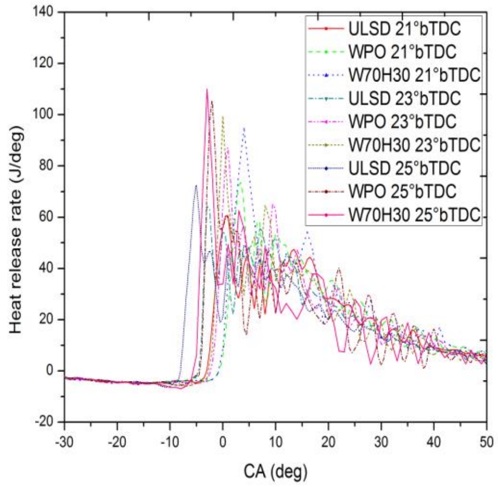

Fig.6 HRR vs.CA (20% EGR) and vs. CA (b1, b2, b3) at bmep= 5.3 bar and speed = 1500 rpm for test fuel at various injection timings and EGR

Figure5,6,7.(b1,b2,b3), presents the variation of heat release rate with crank angle of diesel, waste plastic oil and W70H30 blend under the influence of different EGR rates and injection timing..Highest heat release rate of 130.25 J/deg at the 10 % EGR rate and 25°CA bTDC was obtained from W70H30 blend operation when compared to 78.158 J/deg and 110 J/deg at the same operating condition for diesel operation

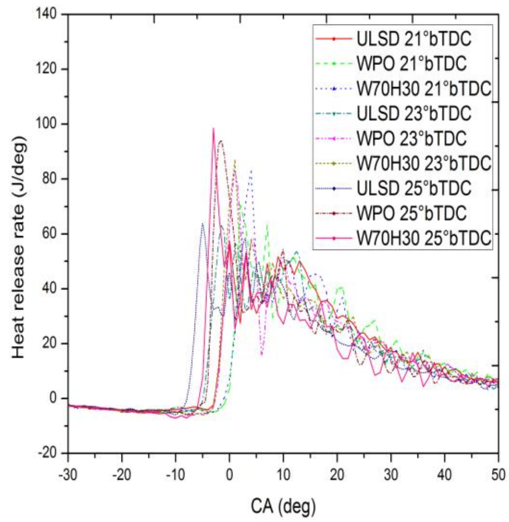

Fig.7 HRR vs.CA (30% EGR) and vs. CA (b1, b2, b3) at bmep= 5.3 bar and speed = 1500 rpm for test fuel at various injection timings and EGR

A Lowest heat release rate among W70H30 blend was 82.98 J/deg against 57.437 J/deg and 70.748 J/deg for ULSD and WPO operation respectively at 30% EGR and 21°CA bTDC.At same given EGR rate and injection timing W70H30 blend presents higher peak heat release rate than that of diesel and WPO, this is because the longer ignition delay period of W70H30 blend, where more amount of fuel is accumulated before the start of combustion which results in higher heat release rate during premixed combustion phase, where the most of air fuel mixture undergo rapid burning releasing the high amount of heat[11]. Ignition delay might be due to more energy is spent to break down the heavy hydrocarbon chain and also due to 39% of aromatic compounds present in the WPO. Increasing the EGR rate from 10% to 30% reduces the peak heat release rate. Introduction of EGR in the intake reduces the peak in-cylinder temperature, which eventually reduces the peak heat release rate, also increasing the percentage of EGR reduces the oxygen concentration available for combustion which could be another factor for reduction in peak heat release rate. Escalating Injection timing from 21°CA bTDC to 25°CA bTDC increase the peak heat release rate, advancement of injection timing increases the ignition delay causing high premixed combustion resulting in a higher heat release rate.

3.2. Emission Parameters

3.2.1 Smoke Density

Figure 3 depicts the smoke density with varying injection timing and EGR rates. The maximum smoke emission was observed for WPO, which is 336 mg/m3 at 21°CA bTDC, 30% EGR. For the same injection timing and EGR rates as expected from previous studies, WPO has shown a significant increase in smoke emissions.

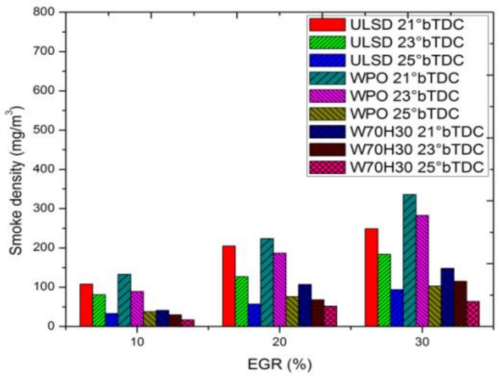

Fig. 8 EGR rate vs. Smoke density at different IT

Increasing the EGR rate from 10% to 30% increases the smoke emissions this due to the fact that recirculation of exhaust gas has already contain suspended soot particles and during combustion process part of the soot particles do not take part in combustion due to non-availability of oxygen, hence smoke emission increases with EGR and increasing the EGR percentage multiplies the smoke emissions[12].

High smoke emissions are attributed to the high aromatic content and low volatility of plastic oil[13]. Low viscosity property of WPO is also another factor since more fuel is injected which promotes diffusion combustion resulting in more smoke emission. From the plot it is clear that addition of n-hexanol to WPO has brought down the smoke emissions drastically, almost twice lower smoke emission was observed than that of neat WPO at all operating conditions, this is because oxygenated nature of n-hexanol improves the combustion characteristics of the blend leading to cleaner combustion thereby reducing the smoke emission.There is a general increase in smoke emission as injection timing increases from 21°CA bTDC. It has been observed that advancement in injection timing reduced the smoke emission to a greater extent even though EGR ratio increases, this is because the advancement of injection timing provides more time for combustion as the fuel is injected earlier into the combustion chamber, this leads to better combustion and reduces carbon soot particles.

3.2.2. Oxides of Nitrogen

Figure 4 depicts the NOx emission at a varying EGR rate and injection timing. Maximum NOx is observed for ULSD, which is 1703 ppm at 10% EGR, 25°CA bTDC and minimum NOx is observed for WPO, which is 706 ppm at 30% EGR, 21°CA bTDC. For the same injection timing and EGR rates W70H30 blend exhibit higher NOx emission than that of diesel and WPO this may be due to the dominance of oxygen content and lower cetane number over the cooling effect caused by the high latent heat of vaporization of W70H30 blend[14]. Addition of hexanol to WPO further decreases the cetane number of the blend which leads to a longer ignition delay. Hence more fuel blend gets injected into the cylinder during this period and when this high quantity of fuel gets combusted during the premixed combustion phase, it results in elevated gas temperatures favoring NOx emissions

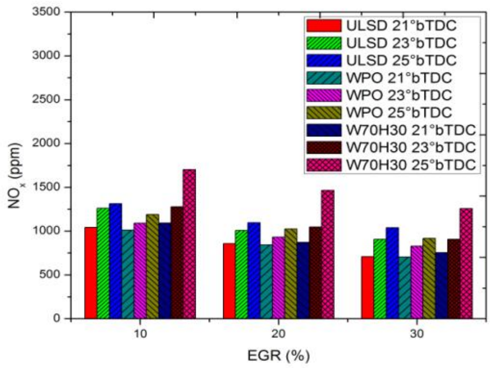

Fig. 9 EGR rate vs. NO_x at different injection timing

As the EGR rate is increased from 10% to 30% there seen a significant reduction in NOx emission for any given injection timing, this may be due to the rise in total heat capacity of the combusted gases by EGR, which lowers the peak temperature. The presence of inert gases in the EGR absorbs energy released during combustion, which reduces the peak combustion temperature in the combustion chamber, and it also `replaces the oxygen in the combustion chamber thus reducing NOx emission.

The NOx emission is in increasing trend as the injection timing escalates from 21°CA bTDC to 25°CA bTDC at any given EGR rate, advancing the injection timing increase the delay period for both the fuels which in turn increases peak cylinder pressure and temperature with subsequent increase in NOx emission and also the residence time for reactions to take place increases, causing a favorable condition for N2 to react with O2 at high temperature forming NOx. Retarded injection timing shows a significant reduction in NOx emission because part of combustion takes place in the expansion stroke which reduces the in-cylinder pressure and temperature.

3.2.3. Carbon Monoxide

Figure 5 shows the variation of CO emission versus EGR rates under the influence of different injection timings. The maximum CO emission is observed with ULSD, which is a 0.21 %

volume at 21°CA bTDC, 30% EGR rate and it was minimum with W70H30 blend, which is 0.01% at 10% EGR irrespective of corresponding injection timing. For the same injection timing and EGR rates W70H30 blend exhibit lower CO emission than that of ULSD and WPO, this may be due the dominance of oxygen concentration in the blend which leads to localized combustion zones.

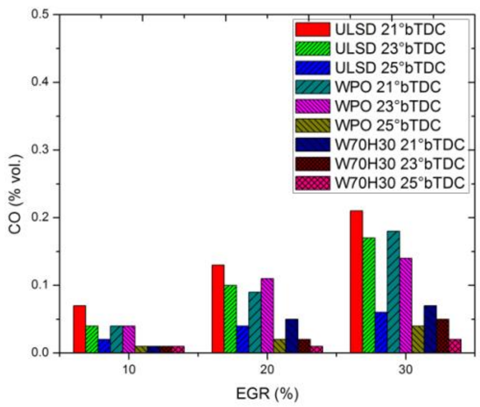

Fig. 10 EGR rate vs. NO_x at different injection timing

As the EGR rate is varied from 10% to 30% at any given injection timings CO emission increases this may be due to oxygen availability for combustion decreases as exhausted gas is recirculated which prevents the oxidation process thus by increasing the CO emissions. Also increase in EGR percentage brings down the combustion temperature resulting incomplete combustion, which increases the CO emission. There is a general decrease in CO emission when injection timing is varied from 21°CA bTDC to 25°CA bTDC. Advancing the injection timing leads to more complete combustion and ample of time is available for oxidization of the fuel which reduce the CO emission.

3.2.4 Unburned Hydrocarbon

Fig.6 depicts hydrocarbon emission versus EGR rate. Hydrocarbon emission is the consequence of incomplete combustion of the hydrocarbon fuel, which is a useful measure of combustion inefficiency.

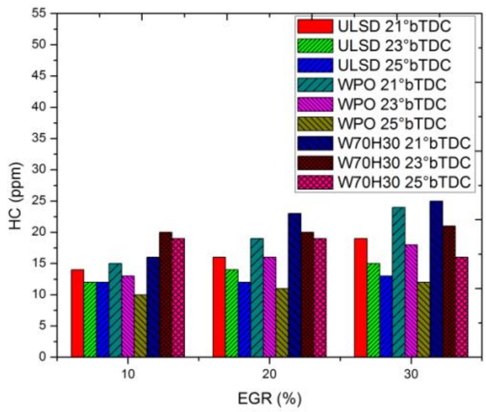

Fig. 11 EGR rate vs. HC emission at different injection timing

It presents the unburned hydrocarbon emission versus EGR rates at different injection timing. The maximum hydrocarbon emission was observed for W70H30 blend, which is 25 ppm at 21°CA bTDC, 30% EGR and minimum for WPO, which is 10 ppm at 25°CA bTDC, 10% EGR. For the same injection timing and EGR rate, W70H30 blend shows comparatively higher UHC than that of reference fuels this is because W70H30 blend have lower cetane number compared with the other fuel, which results in longer ignition delay and thus lead to a broader lean combustion zone and quenching effect.As EGR rate escalates from 10% to 30% there is an increase in UHC for both the fuel, this is because the increase in the EGR rate reduces the temperature available for combustion thus reducing the combustion efficiency thereby resulting in high UHC emission.

Injection timing plays a major part in controlling UHC, from the plot it is evident that advancing the injection timing, reduce the UHC significantly. The advancement in injection timing leads to more complete combustion of the fuel as combustion temperature increases and more time is available for braking hydrocarbon chains in the fuel.

IV. CONCLUSION

This study, prepared waste plastic oil through the catalytic pyrolysis of mixed waste plastics. The combined effect of the exhaust gas recirculation and injection timing on combustion and emission characteristics of diesel engine that use waste plastic oil/n-hexanol blends were investigated under nine operating conditions at three EGR rates (i.e. 10%, 20% and 30%) and three injection timings (i.e. 21°CA bTDC, 23°CA bTDC and 25°CA bTDC) under peak load at 5.3 bmep. The following conclusions were arrived from the study.

- Under the same EGR rate and injection timing. It has been observed from the results that with W70H30 operation smoke density was reduced almost twice than that of WPO operation with slight penalty in NO_x emission. There was 2% reduction in peak cylinder pressure and 39% increase in peak heat release rate with W70H30 against ULSD.

- When the EGR rate is increased from 10% to 30%, except NO_x concentration all other emission concentration increases.
- When the injection timing was advanced from 21°CA bTDC to 25°CA bTDC except N_{Ox} concentration, all other emission concentration decreased. The peak cylinder pressure and peak heat release rate followed increasing trend.
- Unburnt hydro carbon emission followed increasing trend with W70H30, whereas CO emission was lowest for the same.

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