Effect of n-pentanol addition on performance and emission characteristics of a single cylinder DI diesel engine under the influence of different EGR and injection timings

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Abstract - *Effective utilization of renewable alcohols as fuel for internal combustion engines has several benefits as it reduces the usage of non-renewable fossil fuels. In the present work the influence of EGR rate and injection timing on the performance and emission characteristics of a single cylinder, four stroke, direct injection diesel engine has been experimentally investigated using D70P30 (70% diesel and 30% pentanol) blend as fuel. To conduct 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) under peak load at 5.3 bmep. Results indicate that at the same EGR rate and injection timing D70P30 blend shown a 10% and 25% reduction in NOx and smoke density respectively. When the EGR rate is increased there is a significant reduction in NOx emission with heavy penalty in smoke emission and combustion behavior of the engine. Advancing the injection timing reduced the smoke emission by 60% and 22% increase in NOx concentration also gave better combustion behavior due to prolonged ignition delay. It may be concluded that n-pentanol can be an excellent substitute for fossil diesel and long term durability tests have to be carried out for its commercial usage in the conventional diesel engines*.

Keywords: *n-pentanol, Ignition Delay, Injection Timing, Exhaust Gas Recirculation*

INTRODUCTION

Better fuel economy and higher power with lower maintenance cost has increased the popularity of diesel engine vehicles[1]. Diesel engines are used for bulk movement of goods, powering stationary equipment and to generate electricity more economically than any other device in this size range. Most of the global car markets, record diesel car sales have been observed in recent years. The exhorting anticipation of additional improvements in diesel fuel and diesel vehicle sales in future have forced diesel engine manufacturers to upgrade the technology in terms of power, fuel economy and emissions[2]. Diesel emissions are categorized as carcinogenic. The stringent emission legislations are compelling engine manufacturers to develop technologies to combat exhaust emissions. NOx comprise of nitric oxide and nitrogen dioxide (NO_2) and both are considered to be deleterious to humans as well as environmental health. NO_2 is considered to be more toxic than NO. It affects human health directly and is precursor to ozone formation, which is mainly responsible for smog formation. The ratio of NO2 and NO in diesel engine exhaust is quite small but NO gets quickly oxidized in the environment. forming NO_2. Since diesel engine mainly emits NO hence attention has been given to reduce the NO formation.

To reduce the use of fossil fuels, research is underway to develop cost-effective methods of producing (chemically identical) bio-pentanol with fermentation. Although lower alcohols like methanol and ethanol has the potential to reduce both the dependency upon petroleum-based fuels and the amount of anthropogenic greenhouse gas emissions, this fuel suffers from disadvantages, such as low energy density, high hygroscopicity, and high volatility. Higher molecular weight alcohols (e.g., n-pentanol and n-hexanol) exhibit higher reactivity that lowers their knock resistance, they are suitable for diesel engines. Fayyazbakhsh and Pirouzfar, **(2017)** reviewed oxygenated additives to reduce emissions, enhance fuel properties and improve the performance of DI diesel engine. Authors' review clearly indicated that addition of higher alcohols helps in lowering the soot emission; also adding the alcohols at certain temperatures creates a two-phase composition. To encounter this problem using additives which act like an interface between the pure diesel fuel and the alcohol thus prevents formation of a two-phase fuel at any given temperature. Li et al, **(2015)** [3] studied the effects of pentanol addition to diesel and biodiesel fuels in different ratios on the combustion and emission of a single-cylinder direct-injection diesel engine. Pentanol addition improved the spray characteristic and oxygen content of the blended fuels, which was beneficial for the fuel–air mixture formation and

soot reduction. Higher ITE and lower ISFC were also observed for the pentanol blends. Soot emissions decreased with the addition of pentanol and the NOx emissions decreased simultaneously at low-middle load while increased at high load compared to the diesel fuel. The THC emission decreased for all the oxygenated blended. Melvin Victor et al, **(2017)** [4] studied the combined effect of exhaust gas recirculation and injection timing on combustion and emission characteristics of DI diesel engine. Parameters were designated as, injection timing (21°, 23° and 25° CA bTDC) and exhaust gas recirculation (EGR) rates (10, 20 and 30%). Result indicate that at 25°CA bTDC under 30% EGR presented the longest ignition delay with 2% increase in peak pressure and peak heat release rates (HRR) when compared to baseline diesel operation. HEX30 at similar conditions was also beneficial in terms of reduced smoke density by 35.9% with a slight penalty in NOx emissions by 3%. Biomass-derived 1-hexanol could be a promising and viable biofuel for existing diesel engines with some modifications.
Rajesh Kumar and Saravanan, **(2016)** [5] with an objective to achieve simultaneous reduction of smoke and NOx emissions using a combination of low EGR, retarded injection timing and diesel fuel reformulation (with low cetane number alcohols) to enable a partially premixed low temperature combustion (LTC) mode in DI diesel engine. Two higher alcohol/diesel blends, B40 (40% iso-butanol–60% diesel) and P40 (40% n-pentanol–60% diesel) blends were prepared and tested under the combination of three EGR rates (10%, 20% and 30%) and two injection timings (23_ and 21_ CA bTDC) at high loads and constant engine speed. The performance and emission characteristics of the engine under these conditions are investigated. B40 presented better smoke suppression characteristics than P40. Smoke emissions of both blends increased drastically beyond 30% EGR. HC emissions increased and CO emissions remained low for both blends at all EGR rates. The combination of low EGR, late injection and higher alcohol/diesel blends can achieve partially premixed LTC and reduce smoke and NOx emissions simultaneous.

It is a well known fact that EGR and injection timing has a significant effect on performance, combustion and emission characteristics of the engine. Rajesh Kumar and Saravanan, (2015) [6] in this work, the effects of blending n-pentanol, a second generation biofuel with diesel on the performance and emission characteristics of a diesel engine under exhaust gas recirculation (EGR) conditions are investigated. Tests were performed on a single-cylinder, constant-speed, un-modified, direct-injection diesel engine using four n-pentanol/diesel blends: 10%, 20%, 30% and 45% (by volume). The possibility of using a high pentanol/diesel blend (45%) was also explored with an objective to maximize the renewable fraction in the fuel. Three EGR rates (10%, 20% and 30%) were utilized with an intention to reduce the high nitrogen oxides (NOx) that were prevalent at high engine loads using these blends. It was found that simultaneous reduction of NOx and smoke emissions can be achieved using the combination of pentanol/diesel blends and a medium EGR rate (20–30%) with a small drop in performance. Datta and Mandal, (2015) [7] numerically investigated the effect of injection timing on performance and emission characteristics of a CI engine fuelled with diesel and methyl soyate and make a comparison between the two. The simulations have been carried out for three different injection timings of 17°, 20°and 23° bTDC. It has been observed that there is a decrease in the brake thermal efficiency and an increase in the brake specific fuel consumption with the advancement in injection timing for both the fuels, the performance of diesel being better than the biodiesel. Exhaust gas temperature increases along with the NOx and CO2 emissions, while the particulate matter and smoke emissions decrease with the advancement in injection timing. NOx, CO2 emissions and exhaust temperature are found to be more, while PM and smoke emissions are less for methyl soyate when compared to diesel. Nwafor, (2004) [8] investigated the effect of injection timing on emission characteristics of diesel engine running on biofuel. The test results show that the lowest carbon monoxide (CO) and CO, emissions were obtained with the advanced injection unit. The hydrocarbon (HC) emissions of the engine running on vegetable oil fuels were significantly reduced compared to the test results on baseline diesel fuel. The advanced injection system showed a slight increase in fuel consumption. The exhaust temperatures were high and delay period was reduced with the advanced injection unit.

The properties of D70P30 blend 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.

I. EXPERIMENTAL INVESTIGATION

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

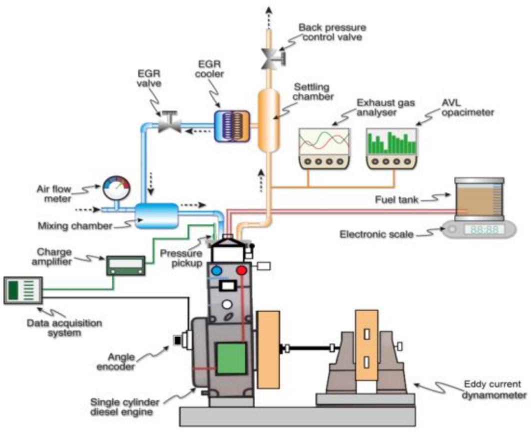

Fig.1 Layout of the experimental setup

Table 1 shows the main properties of diesel, n-pentanol and test blend for this study. The ultra-low sulfur diesel was procured from ESSAR petroleum; Chennai with a cetane number of 54 is used as the baseline fuel. From baseline study, it has been observed that neat diesel produces high exhaust emissions due to lack of oxygen during the combustion process. Hence in order to enhance the combustion process thereby reducing smoke emissions, high oxygenated n-pentanol (CAS NO: 71-41-0) certified to the purity of 98% was used as an additive which was procured from Merck Millipore. D70P30 (70% waste plastic oil, 30% pentanol) were prepared at the mixing ratio of volume. Mixing lower volatility n-pentanol to higher volatility ultra low sulfur diesel (ULSD) could promote the evaporation of the blend.

Table 1 Properties of test fuels

Properties	Test method	ULSD	n-pentanol	D70P30
LHV (MJ/kg)	ASTM D240	41.82	36.4	39.669
ν at 30°C (mm2/s)	ASTM D445	3.80	3.32	3.527
ρ (kg/m3)	ASTM D4052	838	821.8	831.04
Cetane number	ASTM D4737	54	23	-
Flash point (°C)	ASTM D93	70	59	63.7

LHV – low heating value; ν – kinematic viscosity; ρ – density; CCI – calculated cetane index; P– n-pentanol

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

1.1 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,

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

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 [9, 10], to determine the EGR rates.

1.2 Experimental procedure

Experiments were performed under steady-state condition and at peak load, which corresponds to a brake mean effective pressure of 5.3 bar. Performance and emission characteristics of the test engine were recorded at nine operating conditions by progressively increasing the three cold 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. The fuel blend ratio was designated as D70P30 and was kept in observation for 45 days before conducting this study to ensure that there is no phase separation. The baseline tests were conducted with neat diesel at same operating conditions as stated above. The injection timing was advanced or retarded by 2°CA bTDC by adding or removing the shim respectively which is located in between the engine and fuel pump. The EGR rate and injection timing were varied for each trial and the recordings were made.

II. Result and Discussion

The combustion and emission characteristics of the engine fueled with Diesel/n-pentanol blend were discussed with reference to baseline engine fueled with neat diesel operated under the influence of various injection timing and EGR rates.

2.1 Performance analysis

2.1.1 Brake thermal efficiency

Fig. 2 predicts brake thermal efficiency at various EGR rates and injection timing at peak load condition. D70P30 blend deliver slightly lower performance compared to diesel owing to their low heating values and hence requiring more quantity of fuel to be pumped to produce the same amount of power by the engine and hence a drop in performance for alcohol blends was realized.

From the plots it may be noted that for diesel BTE varies from a maximum value of 39.12% at 10% EGR and 23 °bTDC to a minimum value of 34.45% at 30% EGR and 25 °bTDC. For D70P30 blends it varies from 38.9% to 35.58%. Escalating EGR rates decline the BTE irrespective of test fuels which indicates that EGR have significant effect on BTE and this decline is mainly due to the reduction of air-fuel ratio resulting from the recirculation of exhaust gas, which dilutes the oxygen concentration of the fresh intake charge to a large extent.

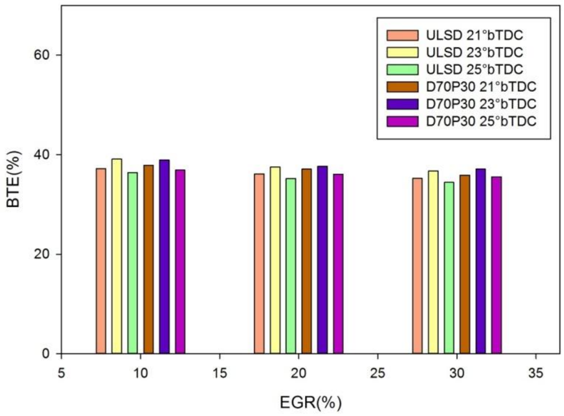

Fig.2 Fig.2 EGR vs Brake thermal efficiency at 5.3 bmep

2.1.2 Brake specific energy consumption

Fig. 3 depicts the EGR rate versus brake specific fuel consumption at different injection timings corresponding to 5.3 bmep. At same operating conditions the BSEC in case of D70P30 was lower compared to diesel, this may be due to dominance of oxygen content over its lower heating value of the blend which enhances the combustion process resulting in lower. As the EGR rate is increased the BSEC increased; the reason can be attributed to the dilution of the fresh air with exhaust gas causing incomplete combustion, and also a drop in available torque. As a consequence the engine governor supplies more fuel to maintain the constant speed operation of the engine.

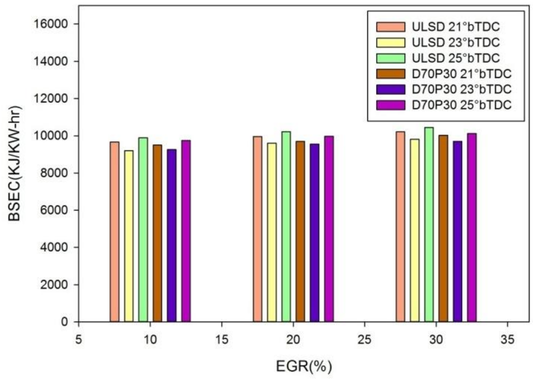

Fig.3 EGR vs Brake specific energy consumption at 5.3 bmep

2.2 Emission analysis

2.2.1 Oxides of Nitrogen

Fig. 4 depicts the NOx emission at a varying EGR rate and injection timing. Maximum NO_x is observed for ULSD, which is 1043 ppm at 10% EGR, 25°CA bTDC and minimum NO_x is observed for WPO, which is 495 ppm at 30% EGR, 21°CA bTDC. For the same injection timing and EGR rates D70P30 blend exhibit lower NO_x emission than that of diesel due to shorter combustion period, which results in lower in-cylinder temperature with subsequent reduction in NOx.

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 due to the rise in total heat capacity of the combused gases by EGR [11], 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 NO_x emission.

The NO_x emission is in increasing trend as the injection timing escalates from 21°CA bTDC to 25°CA bTDC at any given EGR rate, this may be due to advancement in injection timing increase the delay period for both the fuels which in turn increases peak cylinder pressure and temperature with subsequent increase in NO_x emission

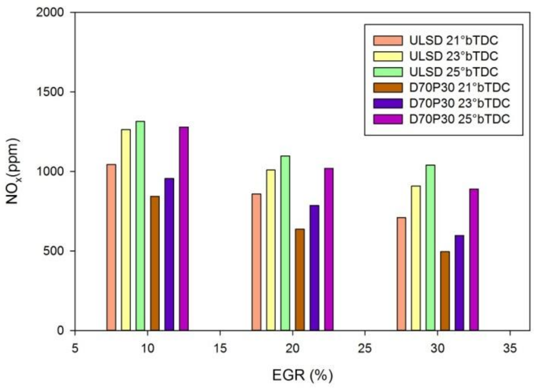

Fig.4 EGR vs oxides of nitrogen at 5.3 bmep

2.2.2 Smoke Density

Fig. 5 depicts the smoke density with varying injection timing and EGR rates. The maximum smoke emission was observed for ULSD, which is 368 mg/m^3 at 21°CA bTDC, 30% EGR and minimum smoke density is observed for ULSD, which is 38 mg/m^3 at 25°CA bTDC, 10% EGR. For the same injection timing and EGR rates as expected from previous studies, ULSD has shown a significant increase in smoke emissions, this may be due to lack of oxygen content in the neat diesel and it is seen from the plot that addition of n-pentanol to diesel have reduced the smoke emission significantly. 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].

There is a general decrease in smoke emission as injection timing increases from 21°CA bTDC to 25°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.

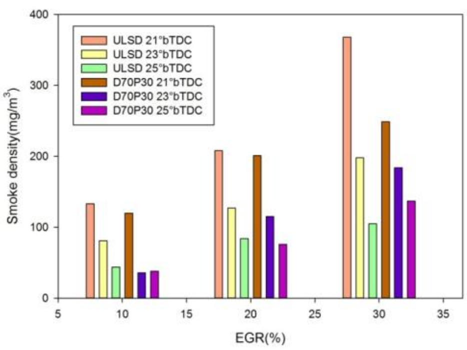

Fig.5 EGR vs Smoke density at 5.3 bmep

2.2.3. Carbon Monoxide

Fig. 6 shows the variation of CO emission versus EGR rates under the influence of different injection timings. The maximum CO emission is observed with D70P30 blend, which is 0.25 % volume at 21°CA bTDC, 30% EGR rate and lowest with ULSD, which is 0.02% at 25°CA bTDC, 10% EGR. For the same injection timing and EGR rates ULSD exhibit lower CO emission than that of D70P30, this may be due to the lower cetane number of the blend, which cause longer ignition delay and shorter combustion periods.

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.

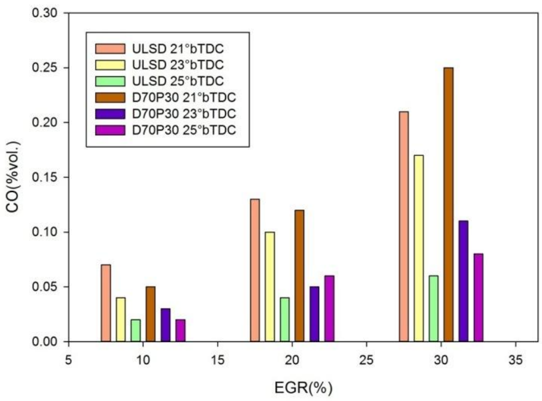

Fig.6 EGR vs Carbon monoxide at 5.3 bmep

2.2.4 Unburned Hydrocarbon

Fig. 7, 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. It presents the unburned hydrocarbon emission versus EGR rates at different injection timing.

The maximum hydrocarbon emission was observed for D70P30 blend, which is 31 ppm at 21°CA bTDC, 30% EGR and minimum for both ULSD, which is 11 ppm at 25°CA bTDC, 10% EGR. For the same injection timing and EGR rate, D70P30 blend shows higher UHC than that of diesel this is because D70P30 blend produce relatively higher concentrations of reactive hydrocarbons to participate in the combustion.

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[13].

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.

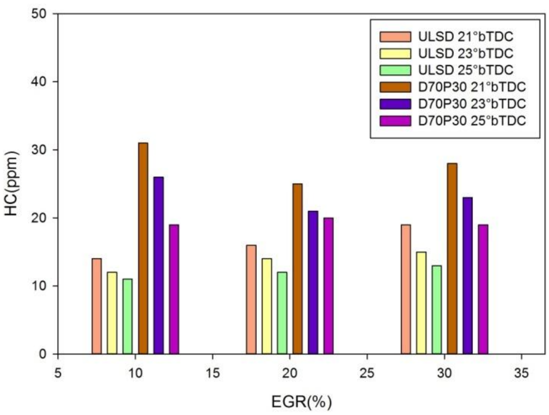

Fig.7 EGR vs Hydrocarbon at 5.3 bmep

3. CONCLUSION

The combined effect of the exhaust gas recirculation and injection timing on performance and emission characteristics of diesel engine that use D70P30 blend 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 D70P30 blend a reduction in 10% of NO_x emission and 25% of smoke density was achieved.
- When the EGR rate is increased from 10% to 30%, except NO_x concentration all other emission concentration increases. There was 23% and 21% of NO_x reduction and 60% and 56% of smoke density increase for D70P30 blend and diesel operations respectively.
- When the injection timing was advanced from 21°CA bTDC to 25°CA bTDC except NO_x concentration, all other emission concentration decreased.

It may be concluded that n-pentanol can be an excellent substitute for fossil diesel and long term durability tests have to be carried out for its usage in the conventional diesel engines.

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