INFLUENCE OF HEXANOL-DIESEL BLENDS ON CONSTANT SPEED DIESEL ENGINE

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ABSTRACT

As an attempt to suggest an alternate fuel for diesel with less emission, the effects of Diesel-hexanol blends, blended in different percentage ranging from 10%-50% by volume were experimentally investigated on a single-cylinder, water-cooled, direct injection diesel engine developing a power output of 5.2 kW at 1500 rev/min and the results show improved performance with blends compared to neat fuel with substantial reductions in smoke and increase of NOx emissions. Combustion analysis show peak pressure and rate of pressure rise were increased with increase in hexanol. For this reason it is examined the use of hot exhaust gas recirculation (EGR) to control NOx emissions. From the analysis of experimental findings it is revealed the use of EGR causes a sharp reduction of NOx with a slight reduction of engine efficiency which in any case does not alter the benefits obtained from the oxygenated fuel.

Key words: *blended fuel; hexanol; exhaust gas recirculation; performance, emission characteristics*

1. Introduction

A method to curtail emissions of smoke and other pollutants from diesel engines is to enhance the oxygen supply to their combustion chamber. This can be accomplished by enriching either the intake air stream or the fuel stream with oxygen. Experimental studies concerning the oxygen-enrichment of intake air, have revealed large decrease of ignition delay, drastic decrease of soot emissions as well as reduction of CO and HC emissions while, brake specific fuel consumption (BSFC) remained unaffected and increasing of power output is feasible[1]. However, this technique was accompanied by considerable increase of NOx emissions. Also it requires minor modifications in the intake system like carburetor or separate fuel injector for inducted fuel. Zaidi et al conducted an experimental study of a DI diesel engine to observe the influence of partial premixing fumigation of the intake air with diesel fuel on the exhaust emissions and reported, the degree of premixing of fuel in the form of fully vaporized superheated fuel vapor in comparison to that of fine spray with the intake air reduced NOx by 45%, UHC by 50%, TPM by 40%, SOF by 50% and Carbon by 40% [2]. C. Sundar Raj used a microprocessor controlled electronic fuel injector for fumigating methanol in the air intake system [3]. He also compared the results with methyl ethyl ketone (MEK) and found a fumigation rate of 0.4 gm/min of methanol and 0.6 gm/min of MEK gave improved results in terms of efficiency and emission [4]. The use of oxygenates to produce cleaner burning diesel fuels was initially considered over fifty years ago. Since that time, the addition of numerous oxygenated compounds to diesel fuel has been reported. Low molecular weight alcohols such as ethanol and t-butyl alcohol have been reported to reduce emissions [1]. However, both the low flash points and high water partitioning of these alcohols make them unacceptable. Also, when ethanol content in the blends reaches 20–40%, high concentration of additives are needed to ensure the mixture homogeneity in the presence of high water contents, and to attain the required cetane number for suitable ignition [5],[6].

Carbonates, including dimethyl carbonate, diethyl carbonate, and dimethyl dicarbonate, have been successfully demonstrated to reduce particulate [7]. Dimethyl carbonate suffers from having a low flash point. Diglyme is one oxygenate that has been included in several studies [8]. While diglyme has acceptable fuel blending properties, its high cost makes its use prohibitive. Other oxygenates that have

been investigated include various ethers, glycol ether acetates, and ketones [9]. The effect of 1, 4 dioxane on ethanol diesel blends were investigated and reported that even though 10% dioxane is capable to stabilize 30% ethanol with 60% diesel with significant reductions in emissions, 70% diesel-20% ethanol with 10% dioxane is the optimum mixture [10]. Kitamura et al reported that the potential of oxygenated fuels to suppress soot precursor formation is dominated by molecular structure as well as fuel oxygen contents [11]. Miyamoto et al found when oxygen content in the fuel reaches approximately 30% by mass, smokeless combustion in diesel engines could be realized [12].
Hexanol is an organic alcohol with a six carbon chain and a condensed structural formula of $CH_3(CH_2)_5OH$. It is produced industrially by the oligomerization of ethylalcohol which can be produced from crops, corns, vegetables and other feedstock such as wastes from agricultural food and beverage processing and hence, a renewable oxygenated hydrocarbon is investigated in this study. Aloko et al characterized the effect of hexanol – diesel blends and reported that many properties like density, flash point, viscosity of the blends are well above the requirement than that of the Standard ASTM norms for a diesel engine. He also indicates that 5% Hexanol with diesel by volume is having the required diesel properties and increases anniline point (responsible for particle emission), hence the fuel can perform well with less emission [13]. Gupta and Agarwal studied the effect of ethanol diesel emulsion by using hexanol as surfactant and reported that the fuel is capable of increase efficiency with significant improvements in emission [14]. Previous studies reveal that hexanol has not been addressed as alternate for diesel fuel. Hence, to validate the favorable properties of the hexanol as alternate for diesel fuel this investigation was made.

The effects of EGR on diesel combustion were investigated in a single-cylinder, heavy-duty research engine by Husberg et al and found NOx emissions were reduced from over 500 ppm at 0% EGR to 5 ppm at 55% EGR, and higher levels of EGR (approximately 35% or more) reduce efficiency[15]. Kouremenos revealed from their experimental and theoretical study that the use of EGR causes a sharp reduction of NOx and an increase of soot emissions[16]. Dederichs outlined the main technical issues of EGR technology for thermal barrier coated HD engines with EGR up to 30% and more of the exhaust gases and found the same results[17]. Dürnholz reported in particular, it was found that so called "hot EGR" which keeps the temperature of the re circulated exhaust gases at a very high level, not only helps to reduce NOx but also contributes distinctly to achieve lower hydrocarbon (HC) and PM emissions. In addition, there is no adverse affect of EGR on the fuel economy [18]. The findings from smoke point measurements and high-pressure combustion tests reveals that oxygenates are effective soot suppressants in diesel combustion, and motivated to studies on oxygenates to find the solution for simultaneous reduction in smoke and NOx emissions without affecting the performance EGR is solicited.

2. Fuel properties of diesel and hexanol

General fuel properties of hexanol and diesel are presented in Table 1. It can be seen that, as an oxygenated additive, hexanol has several favorable properties for on board storage.

Table 1Chemical properties of Diesel, hexanol and ethanol

Fuel properties	Diesel	Hexanol	Ethanol
Molecular Formula	CxHy	$CH_3(CH_2)_4CH_2OH$	C_2H_5OH
Molecular weight	190–220	102.18	46
Density at 20 °C (×10^3 kg/m^3) Check the units	0.829	0.8218	0.79
Latent heat of evaporation (kJ/Kg)	250	486	846
Boiling point (°C)	180–360	175 - 203	78.4
Flash point (°C)	65–88	68	13
Viscosity (mPa s)	3.35	5.32	1.20
% of oxygen by weight	0	15.7	34.7
Heat Value (kJ/kg)	42000	39100	29700
Cetane number	45-50	42	8

The tested heat values of Hexanol Diesel blends is tabulated in Table 2

Table 2 – Heat values of the tested fuel

Hexanol ratio	Heat value KJ/Kg
O% (Neat Diesel)	42000
10%	41710
20%	41420
30%	41130
40%	40840
50%	40550
100% (Hexanol)	39100

3. Parameter tested and experimental procedure

Experiments were conducted on a, single-cylinder, water-cooled, direct injection diesel engine developing a power output of 5.2 kW at 1500 rev/min connected with a water cooled eddy current dynamometer. The engine was operated at a constant speed of 1500 rpm and standard injection pressure of 220 Kgf/cm2. The specification of the engine is given in Table 3. The fuel flow rate was measured on volume basis using a burette and a stop watch. K-type thermocouple and a digital display were employed to note the exhaust gas temperature.

Table 3 Engine specification

Type	Vertical, Water Cooled, Four Stroke
Number of Cylinder	One
Bore	87.5 mm
Stroke	110 mm
Compression Ratio	17.5:1
Maximum Power	5.2 kW
Speed	1500 Rev/min
Dynamometer	Eddy Current
Injection Timing	23° Before TDC
Injection Pressure	220 kgf/cm2 , Direct Injection

Smoke level was measured using a standard AVL437C smoke meter. Exhaust emissions of unburned hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), oxides of nitrogen (NOx) were measured on the dry basis. A Non Dispersive Infrared (NDIR- AVL-444 digas) analyzer was used. The analyzer was periodically calibrated according to the instructions of the manufacturer and the error analysis is tabulated in Table 4. Hydrocarbons and NOx were measured in parts per million (ppm) and carbon monoxide, carbon dioxide and oxygen emissions were measured in terms of percentage volume. AVL Combustion analyzer with 619 Indi meter Hardware and Indwin software version 2.2 is used to measure in cylinder pressure, heat release rate, IMEP etc., The schematic experimental setup is shown in Fig.1.

Table 4 Error Analysis

Parameters	O_2	NOx	HC	CO	Fuel Volumetric Flow rate	BSFC	BTE
% of error	1.05	0.94	1.03	0.09	±1	±1.5	±1.5

Base data was generated with standard diesel fuel. Subsequently five fuel blends ranging from 10% to 50% of hexanol by volume were prepared and tested. Readings were taken, when the engine was operated at a constant speed of 1500 rpm for all loads. Parameter like engine speed, fuel flow and the emission characteristic like NOx and smoke were recorded. The performance of the engine was evaluated in terms of brake thermal efficiency, brake power, brake specific fuel consumption from the above parameters. The combustion characteristics like cylinder pressure and heat release rate were noted for different blends. The experiments were repeated for the same fuels with 25% EGR which was found as optimum and the results were compared. The EGR ratio is determined as the ratio of CO_2 concentration of intake air to as that of the exhaust gas

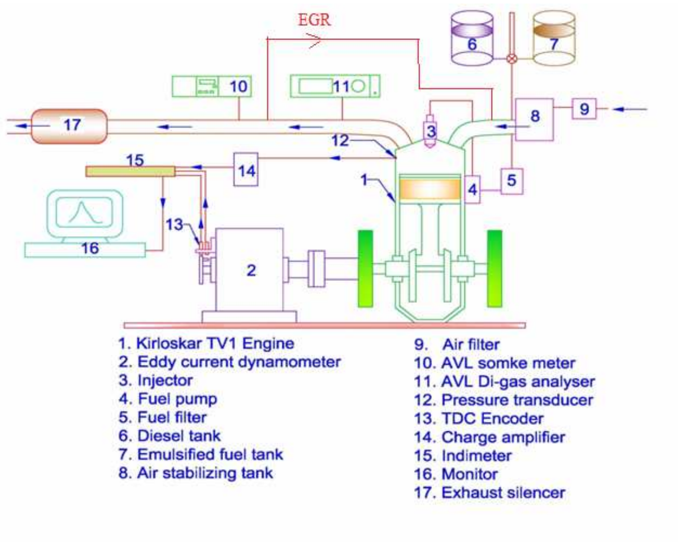

Fig. 1. Experimental setup

4. Results and discussions

Fig. 2 shows the brake specific fuel consumption for the neat diesel fuel and the various percentages of the hexanol in its blends with diesel fuel at peak load (maximum brake power). The lower heat value of the hexanol makes heat value of the mixture to decrease and hence the BSFC to increase for higher blends. Among the blends 10% hexanol shows minimum brake specific fuel consumption to other blends. Slight increase in BSFC is observed for EGR as some of the intake air is replaced with hot exhaust gases as illustrated by Husberg [15].

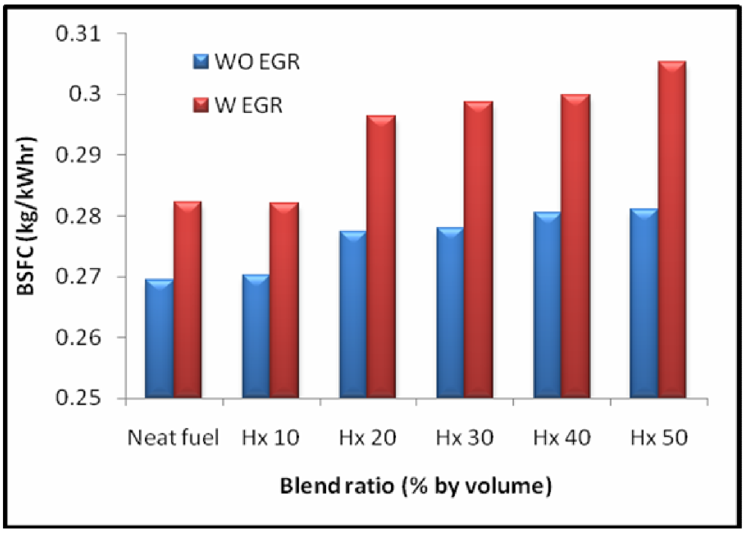

Fig. 2 Variation of BSFC for D:Hx blends at peak load

The presence of oxygen due to the addition of hexanol in the diesel fuel, improve the combustion, especially diffusion combustion and hence increase the brake thermal efficiency. Fig. 3 shows, at the peak load, the brake thermal efficiency for the neat diesel fuel and the various percentages of the hexanol in its blends with diesel fuel. This can be attributed to the higher premixed combustion part possessed by the hexanol blends because of the lower cetane number of hexanol, leading to higher percentage of 'constant volume' combustion, and to the lower heat losses and 'leaner' combustion. From the figure it is observed that the brake thermal efficiency of 10% Hexanol blends recorded a maximum of 33.9% efficiency. However, the efficiency of higher blends decreases as the calorific value of the mixture decreases with the increase in hexanol ratio. EGR slightly reduces the brake thermal efficiency as the amount of fresh oxygen available for combustion gets decreased due to replacement by exhaust gas [15].

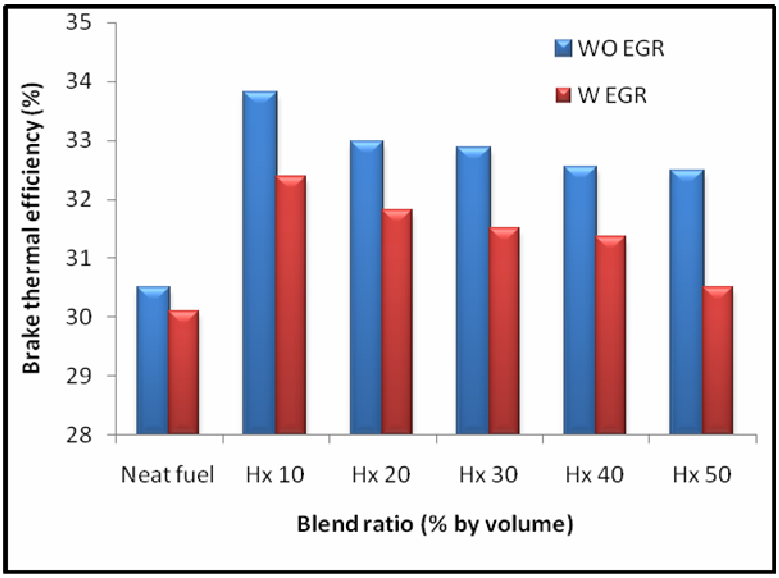

Fig. 3 Brake thermal efficiency for D:Hx blends at peak load

Fig. 4 shows the exhaust smoke (soot) density for the neat diesel fuel and the various percentages of the hexanol in its blends with diesel fuel. One can observe that the soot emitted by the hexanol–diesel fuel blends is significantly lower than that for the corresponding neat diesel fuel case, with the reduction being higher the higher the percentage of hexanol in the blend. This may be attributed to the engine running overall ‘leaner’, with the combustion being now assisted by the presence of the fuel-bound oxygen of the hexanol. In other words addition of hexanol reduces smoke density uniformly at peak load because of the decreased quenching distance and the increased lean flammability limit due to the high combustion temperature. The presence of oxygen in the fuel assists in permitting the oxidation reactions to proceed close to completion. It is also evident that the heat release rate of oxygenated fuels is high due to improved injection spray quality and causes less smoke [19]. The results reveal that the tendency to generate soot from the fuel-rich regions inside diesel diffusion flame is decreased by hexanol in the blends. With the use of EGR, the change in oxygen concentration causes the change in the structure of the flame and hence changes the duration of combustion. EGR increase the smoke density due to deterioration in diffusion combustion [16].

Nitrogen oxides emissions are predominately temperature phenomena, the presence of oxygen increase the heat release rate for the oxygenated fuel and hence the NOx emission will be high[5]. The anticipated increase in NOx emissions as a function of increasing hexanol concentration is apparent in Fig. 5. EGR is a useful technique for reducing NOx formation in the combustion chamber. Exhaust consists of CO2; N2 and water vapors mainly. When a part of this exhaust gas is re-circulated to the cylinder, it acts as diluents to the combusting mixture. This also reduces the O2 concentration in the combustion chamber [15]. The specific heat of the EGR is much higher than fresh air; hence EGR increases the heat capacity (specific heat) of the intake charge, thus decreasing the temperature rise for the same heat release in the combustion chamber [17].

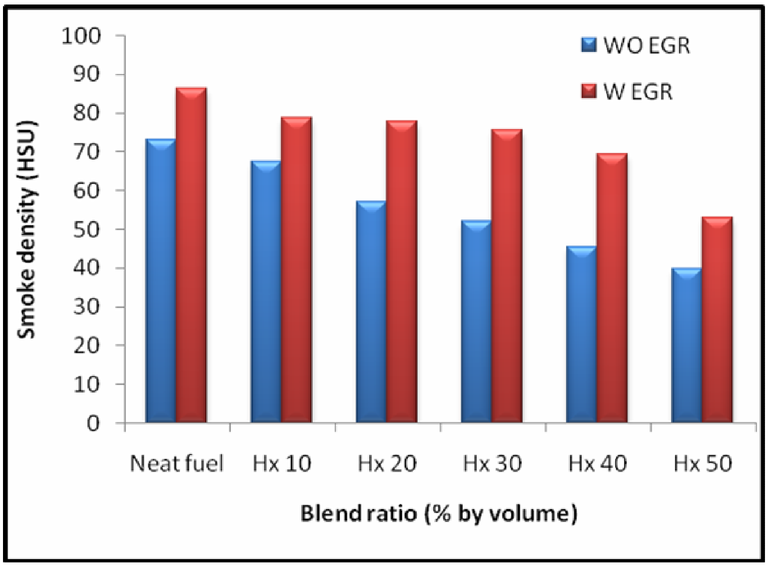

Fig. 4 Variation of smoke density for D:Hx blends at peak load

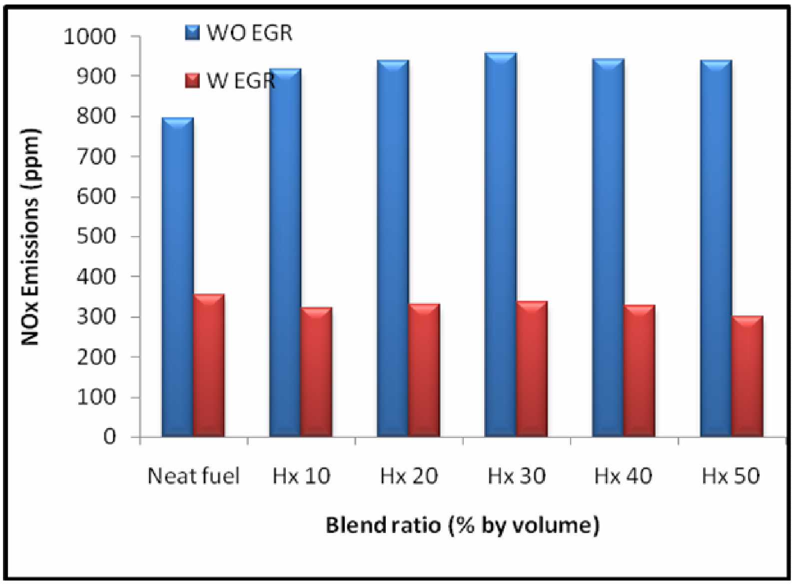

Fig. 5 NOx emissions for D:Hx blends at peak load

Hexanol contain oxygen molecule that improves the combustion process of the engine. Fig. 6 illustrates cylinder pressure traces of hexanol blended diesel fuels. It is found that at the same engine speed and maximum load, the ignition delay for the oxygenated blend is higher (the pressure rise due to combustion starts later) than the corresponding one for the neat diesel fuel case, with no appreciable difference in the maximum pressure due to the lower cetane number of hexanol. C.D. Rakopoulos et al. obtained the same result for 15% ethanol [19].

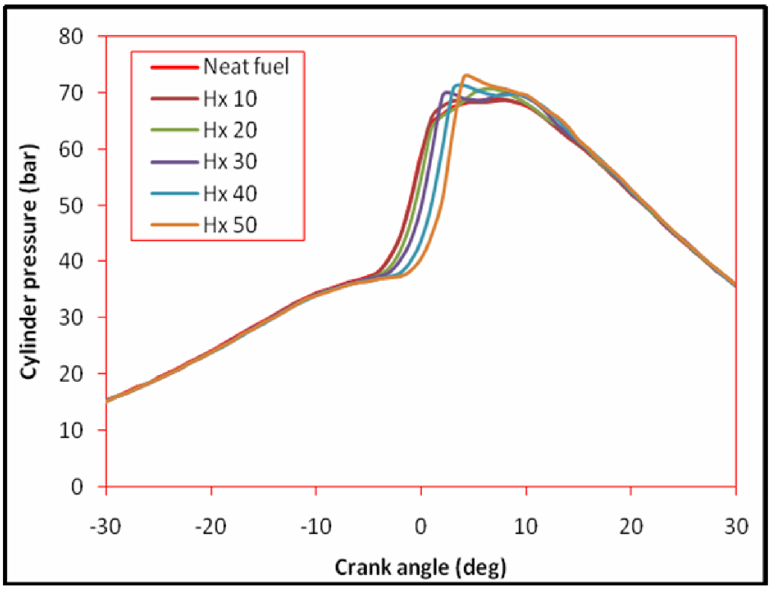

Fig. 6 Variation of cylinder pressure with crank angle for D:Hx blends at peak load

Fig.7 shows the cylinder pressure traces with respect to the crank position for diesel and Hx10 fuel with and without EGR. From the figure it is observed that the engine with EGR is having longer delay period compared standard engine and hence reduces the maximum pressure.

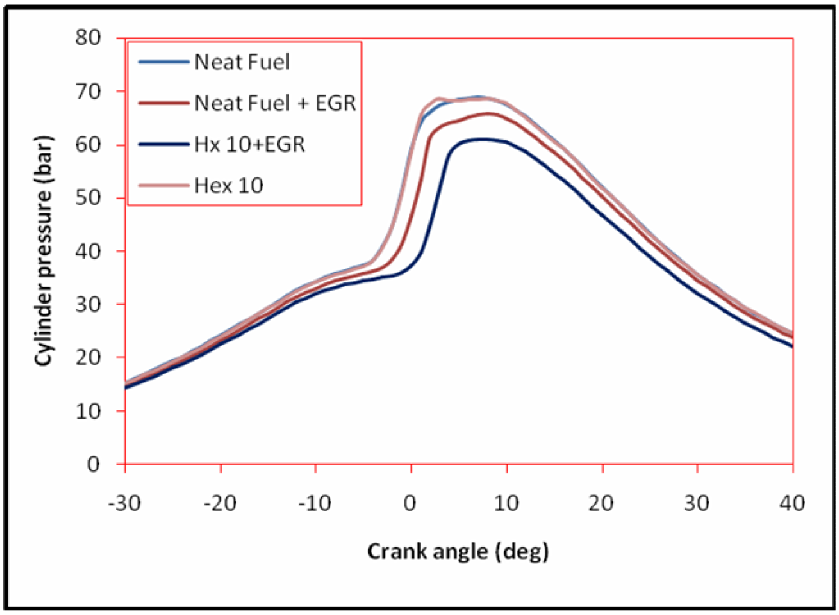

Fig. 7 Effect of EGR on cylinder pressure with crank angle at peak load

It is observed from the Fig.8, that the ignition delay for the oxygenated blend is higher than the corresponding one for the neat diesel fuel case, while its premixed combustion peak is much higher and sharper. It is the lower cetane number of hexanol that causes the increase of ignition delay and so the increased amount of 'prepared' fuel (to this end may also assist the easier evaporation of hexanol) for combustion after the start of ignition but is not reflected in pressure, probably because of the counteracting effect of later combustion in a lower temperature environment. The higher heat release rate in diffusion combustion of the oxygenated fuel increase the net heat release rate, consequently oxygenated fuel has controlled rate of pre-mixed combustion.

The effect of EGR on heat release rate for the neat fuel and Hx10 at maximum loading conditions is illustrated in Fig. 9. EGR increases the delay without many variations in the heat release rate. The effect of EGR on heat release rate may be due to dilution caused by increasing amounts of inert gases in the mixture, which reduces the adiabatic flame temperature.

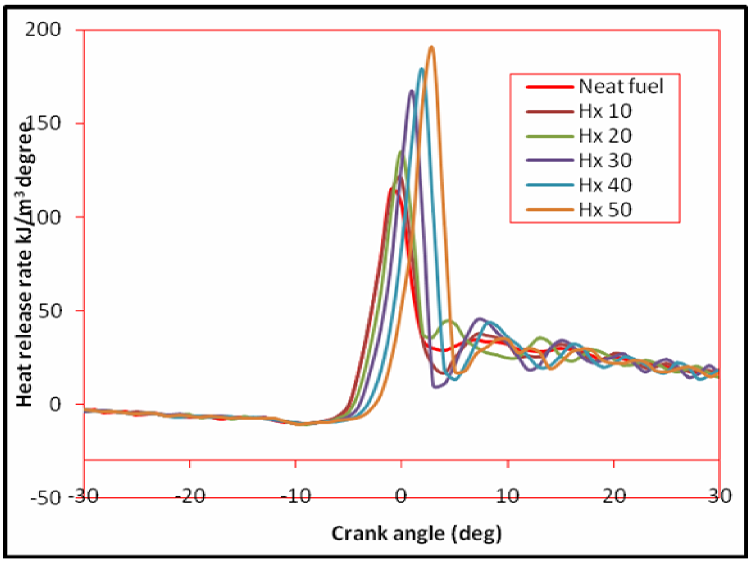

Fig. 8 Heat release rate with crank angle for D:Hx blends at peak load

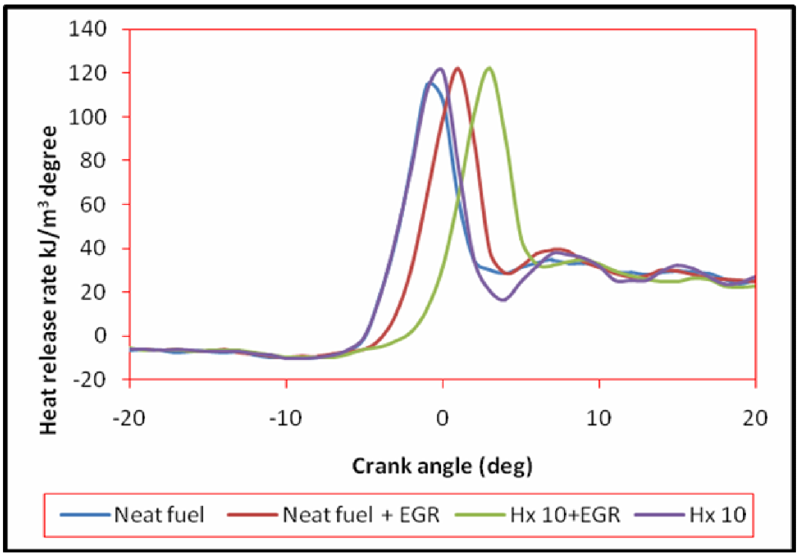

Fig. 9 Effect of EGR on heat release rate with crank angle at peak load

5. Conclusions

An extended experimental study is conducted to evaluate and compare the use of hexanol as supplement to the conventional diesel fuel at blend ratios (by volume) ranging from 10 to 50% in a constant-speed, DI diesel engine located at the authors' laboratory.

From the analysis results, it is revealed that with the use of the hexanol blends against the neat diesel fuel,

- The ignition delay is increased; maximum cylinder pressures are hardly affected. Whereas, EGR increases the delay and decreases the combustion pressure; maximum heat release rate is hardly affected.
- The smoke density was significantly reduced and reduction is higher for the higher percentage of hexanol in the blend. EGR increase the smoke density due to deterioration in diffusion combustion.
- The NOx emissions were increased with the use of the hexanol–diesel fuel blends. But 60% reduction in NOx emissions was observed with EGR as it acts as diluents to the combusting mixture.
- Little increase in specific fuel consumption with slight increase of brake thermal efficiency were also observed.

On the whole it is concluded that simultaneous reduction of NOx and smoke without affecting the performance of a diesel engine can be obtained by using hexanol diesel blends with hot EGR compared with neat diesel

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Acronyms

BSFC	- Brake Specific Fuel Consumption
CO	- Carbon Monoxide
D	- Diesel
EGR	- Exhaust Gas Recirculation
HC	- Hydro Carbon
HSU	- Hat ridge Smoke Unit
Hx	- Hexanol
W EGR	- With Exhaust Gas Recirculation
WO EGR	- Without Exhaust Gas Recirculation

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