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Performance of Biodiesel in Low Heat Rejection Diesel Engine with Catalytic Converter

N. Janardhan, P.Ushasri, M.V.S. Murali Krishna, P.V.K.Murthy

Abstract*—Investigations were carried out to evaluate the performance of a low heat rejection (LHR) diesel engine consisting of air gap insulated piston with 3-mm air gap, with superni (an alloy of nickel) crown and air gap insulated liner with superni insert with different operating conditions of jatropha oil based bio-diesel with varied injection timing and injection pressure. Performance parameters were determined at various values of brake mean effective pressure (BMEP) of the engine. The effect of void ratio, temperature of catalyst, space velocity on the reduction of oxides of nitrogen (NOx) in the exhaust of the engines was studied. Exhaust emissions of smoke and oxides of nitrogen (NOx) were determined at various values of BMEP. The emission levels of NOx in LHR engine were controlled by means of the selective catalytic reduction technique using lanthanum ion exchanged zeolite (catalyst-A) and urea infused lanthanum ion exchanged zeolite (catalyst-B) with different versions of the engine at peak load operation of the engine. Conventional engine (CE) showed deteriorated performance, while LHR engine showed improved performance with bio-diesel at recommended injection timing of 27^{o}bTDC (before top dead centre) and pressure of 190 bar. The performance of both version of the engine improved with advanced injection timing and higher injection pressure when compared with CE with pure diesel operation. Peak brake thermal efficiency increased by 10%, smoke levels decreased by 15% and NOx levels increased by 41% with vegetable oil operation on LHR engine at its optimum injection timing, when compared with pure diesel operation on CE at 27^{o}bTDC and 190 bar. NOx emissions reduced by 40-50% by this technique with catalyst-A and catalyst-B.

Index Terms*—Alternate fuels, Brake thermal efficiency, Catalytic reduction, Exhaust gas temperature.

I. INTRODUCTION

In the scenario of increase of vehicle population at an alarming rate due to advancement of civilization, use of diesel fuel in not only transport sector but also in agriculture sector leading to fast depletion of diesel fuels, increase of pollution levels with these fuels and increase of economic burden on Govt. of India as Government has to spend huge foreign currency for importing crude petroleum to meet the fuel needs of the automotive vehicles, the search for alternate fuels has become pertinent for the engine manufacturers, users and researchers involved in the combustion research.

It is well known fact that about 30% of the energy supplied is lost through the coolant and the 30% is wasted through friction and other losses, thus leaving only 30% of energy utilization for useful purposes. In view of the above, the major thrust in engine research during the last one or two decades has been on development of LHR engines.

Rudolph diesel, the inventor of the engine that bears his name, experimented with fuels ranging from powdered coal to peanut oil. Several researchers [1-5] experimented the use of vegetable oils as fuel on conventional engines (CE) and reported that the performance was poor, citing the problems of high viscosity, low volatility and their polyunsaturated character. Not only that, the common problems of crude vegetable oils in diesel engines are formation of carbon deposits, oil ring sticking, thickening and gelling of lubricating oil as a result of contamination by the vegetable oils.

Hence the above mentioned problems with crude vegetable can be solved by converting the crude oil into biodiesel. The process [6] of converting the crude vegetable oil into methyl esters was carried out by heating the oil with the methanol in the presence of the catalyst (Sodium hydroxide). Investigations were carried out [7-14] on CE with bio-diesel and reported that combustion characteristics and exhaust emissions were compatible with diesel fuel.

Hence crude vegetable oil and biodiesel require hot combustion chamber provided by LHR engine which permits efficient combustion of alternate and renewable fuels like alcohols and vegetable oils. However, alcohols have low cetane number and hence engine modification is necessary if alcohol is to be used as fuel in diesel engine.

Various concepts of LHR engines are being developed employing the techniques like ceramic coating in the components, air gap in the piston and the other components etc. The main purpose of this study [15] was to evaluate the heat losses at different engine loads and speeds with and without ceramic-coated diesel engine. The results showed a reduction in heat losses to the coolant and an increase in exhaust energy at all load levels. Though ceramic coatings provided insulation and improved brake specific fuel consumption (BSFC), peeling of coating was reported by various researchers [16-18] after certain hours of trials. Experiments were conducted [19-21] on turbo charged LHR engines with pure diesel operation with ceramic coating on inside portion of cylinder head, piston crown and valves and reported increase of torque in the range of 1.5-2% and brake specific fuel consumption decreased by 8% Smoke levels decreased by 20%. However, NOx emissions increased marginally when compared with standard diesel.

Experiments were conducted [22-26] on LHR engine with ceramic coated piston crown, liner and inner surface of

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N. Janardhan, Mechanical Engineering Department Chaitanya Bharathi Institute of Technology, Gandipet, Hyderabad, Andhra Pradesh, India.

P.Ushasri, College of Engineering, Osmania University, Hyderabad, Andhra Pradesh, India.

M.V.S. Murali Krishna, Mechanical Engineering Department Chaitanya Bharathi Institute of Technology, Gandipet, Hyderabad, Andhra Pradesh, India.

P.V.K.Murthy, Mechanical Engineering Department Vivekananda Institute of Science and Information Technology, Shadnagar, Mahabubnagar Dist., Andhra Pradesh, India.

cylinder head with vegetable oil based bio diesel and reported that LHR engine reduced smoke and marginally increased NOx emissions and thermal efficiency.

Out of the total amount of heat rejected to the various components piston and liner are found to be the major contributors through which heat rejection take place to the coolant. It is also found that the coatings provided on the moving piston of an engine create problems. The technique of providing air gap in the piston is less effective in achieving lower brake specific fuel consumption and reduction of pollutants. Also creating an air gap in the piston involved the complications of joining two different metals. Investigations were carried out [27] on LHR engine with air gap insulated piston with pure diesel. However, the bolted design employed by them could not provide complete sealing of air in the air gap. Experiments were conducted [28] conducted experimental investigations on jatropha oil with LHR engine, which consisted of ceramic-coated cylinder head and air gap cylinder liner. It was reported that the improvement in the performance and reduction in pollution levels of hydrocarbon and smoke with LHR version of the engine with jatropha oil when compared with conventional engine. Addition of ignition improvers to jatropha oil further improved the performance and reduced the pollution levels.

Experiments were conducted [29-30] on LHR engine with air gap insulated piston with pure diesel where it was made a successful attempt of screwing the crown made of low thermal conductivity material, nimonic (an alloy of nickel) to the body of the piston, by keeping a gasket, made of nimonic, in between these two parts. However, low degree of insulation provided by these researchers was not able to burn low cetane fuels of vegetable oils. That too, their work was limited to pure diesel only. It also provides lower degree of insulation causing combustion chamber of diesel engine less hot. Hence the technique of air gap insulated piston and air gap insulated liner is finding favor from the various researchers from the point of view of effectiveness ease of manufacturer and operation.

Investigations were carried out [6] on LHR engine which consisted air gap insulated piston with superni crown and air gap insulated liner with superni insert with alternate fuels of different forms (crude vegetable oils and methyl esters or biodiesel)of vegetable oils at different operating conditions (normal temperature and preheated temperature) and alcohols. It was reported that LHR engine improved the efficiency and decreased pollution levels with vegetable oil operation, when compared with pure diesel operation on CE.

Studies were made [31] on high grade LHR engine consisted of air gap insulated piston with superni crown, air gap insulated liner with superni insert and ceramic coated cylinder head with jatropha oil and pongamia oil based bio-diesel. It was reported that LHR engine improved the performance and decreased smoke levels. However, it increased NOx levels in comparison with pure diesel operation on CE.

The major pollutants emitted from diesel engine are smoke and NOx. Excessive breathing of smoke causes [32-33] tuberculosis and may also lead to death. It also causes detrimental effects on animal and plant life besides environmental [34] disorders. Inhaling of oxides of nitrogen causes dizziness, vomiting sensation, severe headache etc. Hence globally, stringent regulations are made for permissible pollutants in the exhaust of the engines. There were many methods to reduce NOx emissions in the engine, out of which exhaust gas recirculation [35] was simple one. However, it increased fuel consumption. The selective catalytic reduction technique [36] was becoming increasingly popular and cost effective method in reduction of NOx levels. The modified zeolites [37-38] were cheaper and reduced NOx over wide range of air-fuel ratios and temperature.

From above discussions, it was clear that performance of CE is deteriorated with crude vegetable oil and improved with bio-diesel. Peeling of ceramic coating of LHR engine was noticed after certain hours of operation and life test was necessary to ensure the sustainability of coating. Hence LHR engine with air gap piston and air gap liner was finding favor as it was simple in construction. The performance further improved with LHR engine with reduction of smoke levels. However, it increased NOx levels.

The present paper attempted to evaluate the performance of LHR engine, which contained air gap piston with superni crown and air gap insulated liner with superni (a low thermal conductivity material, an alloy of nickel) insert with different operating conditions of vegetable oil based bio-diesel coupled with catalytic converter to reduce NOx levels with varying engine parameters of change of injection pressure and timing and compared with CE with pure diesel operation at recommended injection timing and injection pressure.

II. METHODOLOGY

LHR diesel engine contained a two-part piston; the top crown made of low thermal conductivity material, superni-90 screwed to aluminum body of the piston, providing a 3-mm air gap in between the crown and the body of the piston. The optimum thickness of air gap in the air gap piston was found to be 3-mm [29] for improved performance of the engine with diesel as fuel. A superni-90 insert was screwed to the top portion of the liner in such a manner that an air gap of 3-mm was maintained between the insert and the liner body. At 500^{o}C the thermal conductivity of superni-90 and air are 20.92 and 0.057 W/m-K respectively. The process of converting the jatropha oil into methyl esters was carried out by heating the oil with the methanol in the presence of the catalyst (Sodium hydroxide). In the present case, crude jatropha oil was stirred with methanol at around 60-70^{o}C with 0.5% of NaOH based on weight of the oil, for about 3 hours. At the end of the reaction, excess methanol was removed by distillation and glycerol, which separated out was removed. The methyl esters were treated with dilute acid to neutralize the alkali and then washed to get free of acid, dried and distilled to get pure vegetable oil esters. The esters were used in present study. Preheated temperature is that temperature when vegetable oil is heated (125^{o}C) till its viscosity was matched to that of diesel fuel. The properties of the vegetable oil ester and the diesel used in this work are presented in Table-1.

Table I Properties of test fuels

Test Fuel	Viscosity at 25°C (Centi-poise)	Density at 25 °C	Cetane number	Calorific value (kJ/kg)
Diesel	12.5	0.84	55	42000
Jatropha oil (esterified) (EJO)	53	0.87	55	35500

Experimental setup used for the investigations of LHR diesel engine with jatropha oil based bio-diesel operation is shown in Figure 1. CE had an aluminum alloy piston with a bore of 80 mm and a stroke of 110 mm. The rated output of the engine was 3.68 kW at a speed of 1500 rpm. The compression ratio was 16:1 and manufacturer's recommended injection timing and injection pressures were 27°bTDC and 190 bar respectively. The fuel injector had three holes of size 0.25-mm. The combustion chamber consisted of a direct injection type with no special arrangement for swirling motion of air. The engine was connected to electric dynamometer for measuring its brake power. Burette method was used for finding fuel consumption of the engine, while air-consumption with air-box method. The naturally aspirated engine was provided with water-cooling system in which inlet temperature of water was maintained at 60°C by adjusting the water flow rate. Engine oil was provided with a pressure feed system. No temperature control was incorporated, for measuring the lube oil temperature. Copper shims of suitable size were provided in between the pump body and the engine frame, to vary the injection timing and its effect on the performance of the engine was studied, along with the change of injection pressures from 190 bar to 270 bar (in steps of 40 bar) using nozzle testing device.

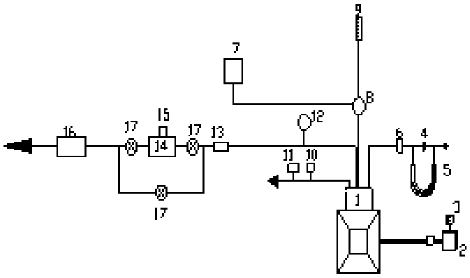

Fig 1. Experimental Set-up

1.Engine, 2.Electical Dynamo meter, 3.Load Box, 4.Orifice meter, 5.U-tube water manometer, 6.Air box, 7.Fuel tank, 8. Pre-heater, 9.Burette, 10. Outlet jacket water temperature indicator, 11. Outlet-jacket water flow meter, 12. Exhaust gas temperature indicator, 13. AVL Smoke meter. 14. Catalytic chamber, 15. Nozzle, 16. Netel Chromatograph NOx analyzer. 17. Control valve.

The maximum injection pressure was restricted to 270 bar due to practical difficulties involved. Exhaust gas temperature (EGT) was measured with thermocouples made of iron and iron-constantan. Exhaust emissions of smoke and NO_x were recorded by AVL smoke meter and Netel Chromatograph NOx analyzer respectively at various values of BEMP. The catalyst was prepared [36] by using zeolite and lanthanum ion salt. Ion exchange was done by stirring 500 grams of zeolite in a 2N solution of lanthanum (III) salt for 5-6 hours at 70-80°C. Ion exchanged zeolite was recovered by filtration and activated by calcinations in an oven at 400°C for 3 hours and was furnace cooled to retain mechanical properties. Modified zeolite (Catalyst-A) so obtained was placed in catalytic chamber which had a cylindrical shape with a diameter of 120 mm and length 600 mm. Infusion of urea on lanthanum exchanged zeolite (catalyst-B) was made by gravity feed dosing system. A nozzle was used to generate fine spray of urea solution into exhaust gas before it entered into catalytic chamber containing lanthanum exchanged zeolite. NOx emissions were controlled with use of different catalysts in both versions of the engine at peak load operation of the engine.

III.RESULTS AND DISCUSSION

A. Performance Parameters

Fig. 3 indicates that CE with biodiesel showed the deterioration in the performance for entire load range when compared with the pure diesel operation on CE at recommended injection timing. Although carbon accumulations on the nozzle tip might play a partial role for the general trends observed, the difference of viscosity between the diesel and biodiesel provided a possible explanation for the deterioration in the performance of the engine with biodiesel operation.

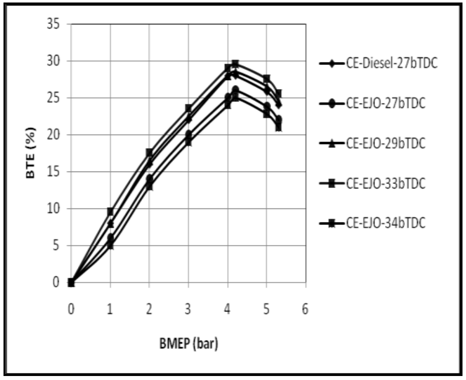

Fig.2 Variation of BTE with BMEP in CE with various injection timings with EJO operation at an injection pressure of 190 bar with EJO operation.

The amount of air entrained by the fuel spray was reduced, since the fuel spray plume angle was reduced, resulting in slower fuel- air mixing. In addition, less air entrainment by the fuel spay suggested that the fuel spray penetration might increase and resulted in more fuel reaching the combustion chamber walls. Furthermore droplet mean diameters (expressed as Sauter mean) were larger for biodiesel leading to reduce the rate of heat release as compared with diesel fuel. According to the qualitative image of the combustion under the biodiesel operation with CE, the lower BTE was attributed to the relatively retarded and lower heat release rates. BTE increased with the advancing of the injection timing in CE with biodiesel at all loads, when compared with CE at the recommended injection timing and pressure. This was due to initiation of combustion at earlier period and efficient combustion with increase of air entrainment in fuel spray giving higher BTE. BTE increased at all loads when the injection timing was advanced to 33°bTDC in the CE at the normal temperature of biodiesel. The increase of BTE at optimum injection timing over the recommended injection timing with biodiesel with CE could be attributed to its longer ignition delay and combustion duration. BTE increased at all with CE with pure diesel operation.

loads when the injection timing is advanced to 33°bTDC in CE, at the preheated temperature (PT) of bio-diesel. The performance improved further in CE with the preheated biodiesel for entire load range when compared with normal vegetable oil. Preheating of the biodiesel reduced the viscosity, which improved the spray characteristics of the oil.

From Fig. 3 it is noticed that LHR version of the engine showed the improved performance for the entire load range compared

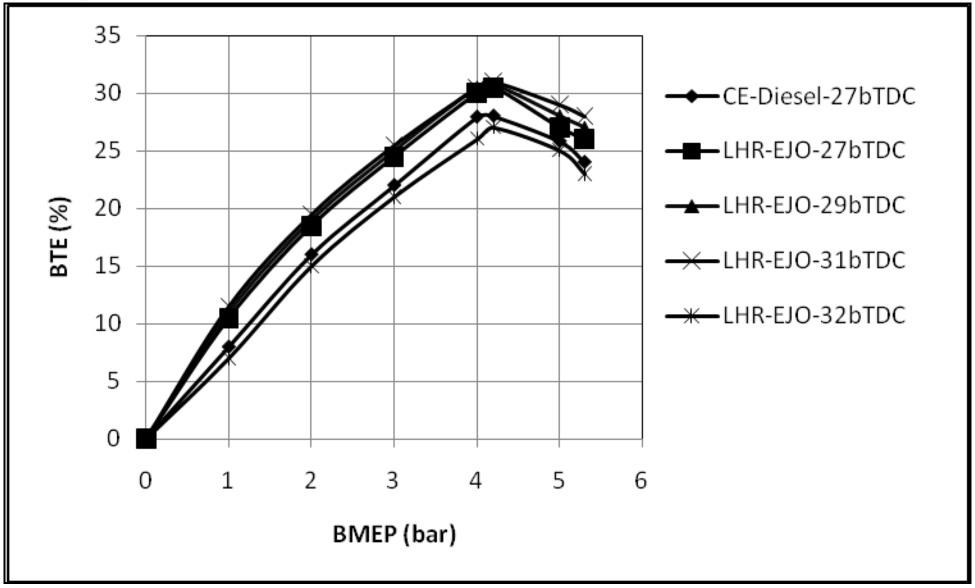

Fig.3 Variation of BTE with BMEP in LHR engine with various injection timings with EJO operation at an injection pressure of 190 bar with EJO operation.

High cylinder temperatures helped in better evaporation and faster combustion of the fuel injected into the combustion chamber. Reduction of ignition delay of the biodiesel in the hot environment of the LHR engine improved heat release rates and efficient energy utilization. Preheating of biodiesel improved performance further in LHR version of the engine. The optimum injection timing is found to be 31°bTDC with LHR engine with normal bio-diesel operation. Since the hot combustion chamber of LHR engine reduced ignition delay and combustion duration and hence the optimum injection timing was obtained earlier with LHR engine when compared with CE with the biodiesel operation.

Injection pressure was varied from 190 bars to 270 bar to improve the spray characteristics and atomization of the biodiesel and injection timing was advanced from 27 to 34°bTDC for both versions of the engine. From Table 1, it was noticed that improvement in the peak BTE was observed with the increase of injection pressure and with advancing of the injection timing with biodiesel in both versions of the engine.

Table II. Data of Peak BTE

Injection Timing (° bTDC)	Test Fuel	Peak BTE (%)											
		Conventional Engine (CE)						Low heat rejection (LHR) Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	28	--	29	---	30	--	29	--	30	--	30.5	--
	EJO	26	27	27	28	28	29	30.5	31	31	31.5	31.5	32.5
30	DF	29	---	30	--	30.5	--	29.5	--	30.5	--	31	--
	EJO	27	27.5	27.5	28	28	28.5	30.7	31.2	31.2	31.7	31.7	32.7
31	DF	29.5	--	30	--	31	--	30	--	31	--	31	--

	CJO	27	27.2	28	28.5	27.5	28	--	--	--	--	--	--
	EJO	28	28.5	28.5	29	29.5	30	31	31.5	31.5	32	32	32.5
32	DF	30		30.5		30.5							
	EJO	29	29.5	29.5	30	29	29.5						
33	DF	31		31		30	---	--	--	--	--	--	-
	EJO	29.5	30	29	29.5	28.5	29	--	--	--	--	--	--

DF- Diesel Fuel, NT-Normal EJO, PT-Preheated EJO

The improvement in BTE at higher injection pressure was due to improved fuel spray characteristics. However, the optimum injection timing was not varied even at higher injection pressure with LHR engine, unlike the CE. Hence it was concluded that the optimum injection timing is 33°bTDC at 190 bar, 32°bTDC at 230 bar and 31°bTDC at 270 bar for CE. The optimum injection timing for LHR engine was 31°bTDC irrespective of injection pressure. Peak BTE was higher in LHR engine when compared with CE with different operating conditions of the biodiesel. Preheating of the biodiesel improved the performance in both versions of the engine compared with the biodiesel at normal temperature. Preheating reduced the viscosity of the vegetable oils, which reduced the impingement of the fuel spray on combustion chamber walls, causing efficient combustion thus improving BTE.

From Table III it is evident that brake specific energy consumption (BSEC) at peak load operation decreased with the increase of injection pressure and with the advancing of the injection timing at different operating conditions of the biodiesel. With biodiesel operation, LHR engine showed lower value of BSEC at different injection timing and injection pressure when compared with CE. This confirmed that performance of LHR engine improved due to effective utilization of energy when compared with CE with biodiesel operation. Preheated biodiesel showed lower value of BSEC when compared with normal BSEC. This was due to reduction of improved characteristic of fuel with preheating

Table III. Data of BSEC at peak load operation

Injection Timing (° bTDC)	Test Fuel	BSEC (kW/ kW)											
		Conventional Engine						LHR Engine					
		Injection Pressure (Bars)						Injection Pressure (Bars)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	4.00	--	3.92	--	3.84	--	4.16	---	4.08	--	4.00	--
	EJO	4.70	4.50	4.50	4.45	4.45	4.40	3.80	3.76	3.76	3.72	3.72	3.68
30	DF	3.92	---	3.88	--	3.84	--	4.08	--	4.00	--	3.90	--
	EJO	4.50	4.45	4.45	4.35	4.40	4.30	3.78	3.74	3.74	3.70	3.70	3.66
31	DF	3.84	--	3.80	--	3.77	--	3.86		3.85		3.84	
	EJO	4.25	4.20	4.20	4.15	3.8	3.77	3.76	3.72	3.72	3.68	3.68	3.64
32	DF	3.82	---	3.78	--	3.79	--	--	--	--	--	--	--
	EJO	3.84	3.80	3.80	3.77	3.82	3.79	---	---	----	--	---	----
33	DF	3.77	--	3.77	--	3.84	---	--	----	----	----	---	---
	EJO	3.8	3.77	3.84	3.80	4.05	4.00	--	--	--	--	--	--

Fig.4 denotes that CE with biodiesel operation at the recommended injection timing recorded higher EGT at all loads when compared with CE with pure diesel operation. Lower heat release rate and retarded heat release associated with high specific energy consumption caused increase in EGT in Conventional Engine.

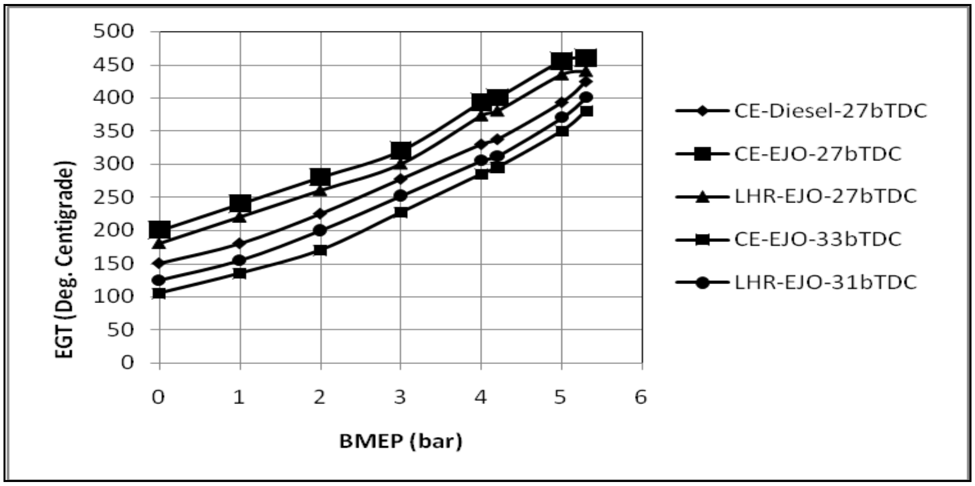

Fig.4 Variation of EGT with BMEP in both versions of the engine at recommended and optimized injection timing at an injection pressure of 190 bar with EJO operation.

Ignition delay in the CE with different operating conditions of biodiesel increased the duration of the burning phase. LHR engine recorded lower value of EGT when compared with CE with biodiesel operation. This was due to reduction of ignition delay in the hot environment with the provision of the insulation in the LHR engine, which caused the gases expand in the cylinder giving higher work output and lower heat rejection. This showed that the performance was improved with LHR engine over CE with biodiesel operation. At optimized injection timing, the value of EGT decreased in both versions of the engine with biodiesel operation. This was due to initiation of combustion at early and improved air utilization in both versions of the engine.

Table-4 shows that the value of EGT at peak load decreased with increase of injection pressure and with advanced injection timing in both versions of the engine with biodiesel. Preheating of the biodiesel further reduced the value of EGT, compared with normal biodiesel in both versions of the engine.

Table IV. Data of EGT at peak load operation

Injection timing (° b TDC)	Test Fuel	EGT at the peak load (°C)											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	425	--	410	---	395	--	475	---	460	--	445	--
	EJO	460	440	440	420	420	400	440	420	420	400	400	380
30	DF	400	---	425	--	410	---	455	---	440	--	425	--
	EJO	440	420	420	420	400	380	420	400	400	380	380	360
31	DF	380	---	360	--	340	---	435	---	420	---	400	---
	EJO	420	400	400	380	380	360	400	380	380	360	360	340
32	DF	360		340		360			--		--		--
	EJO	400	380	380	360	400	380	--	--	--	--	--	--
33	DF	340	---	480	---	440	--	--	--	--	---	--	--
	EJO	380	360	400	380	420	400	--	--	--	---	----	--

Fig.5 indicates volumetric efficiency (VE) decreased with an increase of BMEP in both versions of the engine with test fuels. This was due to increase of gas temperature with the load. At the recommended injection timing, VE in the both versions of the engine with bio-diesel operation decreased at all loads when compared with CE with pure diesel operation. This was due increase of temperature of incoming charge in the hot environment created with the provision of insulation, causing reduction in the density and hence the quantity of air with LHR engine. Increase of deposits in CE was responsible for reduction of VE in CE. However, when the injection timing was advanced, VE increased marginally in both versions of the engine. This was due to decrease of un-burnt fuel fraction in the cylinder leading to increase in VE in CE and reduction of gas temperatures with LHR engine.

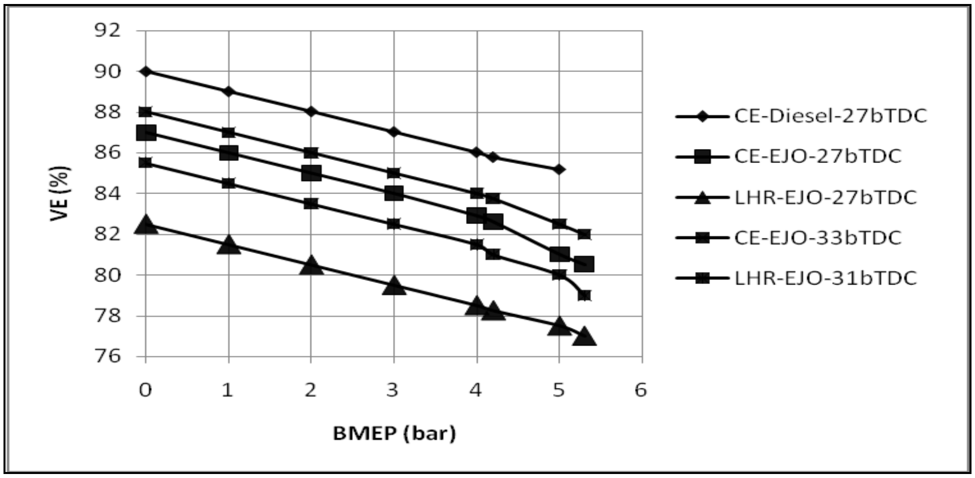

Fig.5 Variation of VE with BMEP in both versions of the engine at recommended and optimized injection timing at an injection pressure of 190 bar with EJO operation

Table V. shows that VE increased marginally in CE and LHR engine at optimized injection timings when compared with recommended injection timings with vegetable oil operation. VE increased marginally with the advancing of the injection timing and with the increase of injection pressure in both versions of the engine. This was due to improved fuel spray characteristics and evaporation at higher injection pressures leading to marginal increase of VE. This was also due to the reduction of residual fraction of the fuel, with the increase of injection pressure. Preheating of the vegetable oil marginally improved VE in both versions of the engine, because of reduction of un-burnt fuel concentration with efficient combustion, when compared with the normal temperature of the biodiesel.

Table V. Data of Volumetric Efficiency at peak load operation

Injection timing (^{o} bTDC)	Test Fuel	Volumetric efficiency (%) at peak load											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	85	--	86	--	87	--	78	--	80	--	82	--
	EJO	80.5	81.5	81.5	82.5	82.5	83	77	78	79.5	80.5	80.5	81.5
30	DF	86	--	87	--	88	---	80	--	82	--	83	--
	EJO	81	82	82	83	83	83.5	79	79.5	79.5	81	81	82
31	DF	87	--	87.5	--	89	--	82	--	83	--	84	--
	CJO	80	81	81	82	82	83	--	--	--	--	--	--
	EJO	81.5	82.5	82.5	83	83	84	81	82	82	82.5	82.5	83.5
32	DF	87.5	--	88	--	87	--	-	--	-	--	--	-
	EJO	81.5	82.5	82.5	83.5	83.5	84.5	--	--	--	--	--	--
33	DF	89	--	89	--	86	--	--	--	--	--	--	--
	EJO	82	83	83	84	84	85	--	--	--	--	--	--

B. Exhaust Emissions

Fig.6 shows that the value of smoke intensity increased from no load to full load in both versions of the engine with test fuels. During the first part, the smoke level was more or less constant, as there was always excess air present. However, in the higher load range there was an abrupt rise in smoke levels due to less available oxygen, causing the decrease of air-fuel ratio, leading to incomplete combustion, producing more soot density. The variation of smoke levels with the BMEP typically showed a U-shaped behavior due to the pre-dominance of hydrocarbons in their composition at light load and of carbon at high load. Drastic increase of smoke levels was observed at the peak load operation in CE at different operating conditions of the biodiesel, compared with pure diesel operation on CE. This was due to the higher value of the ratio of C/H of bio-diesel (0.83) when compared with pure diesel (0.45). The increase of smoke levels was also due to decrease of air-fuel ratios and VE with biodiesel when compared with pure diesel operation However, LHR engine marginally decreased smoke levels due to efficient combustion and less amount of fuel accumulation on the hot combustion chamber walls of the LHR engine compared with the CE. Density influences the fuel injection system. When the injection timing was advanced, smoke levels decreased with both version of the engine with biodiesel operation. This was due to improved VE and air-fuel ratios.

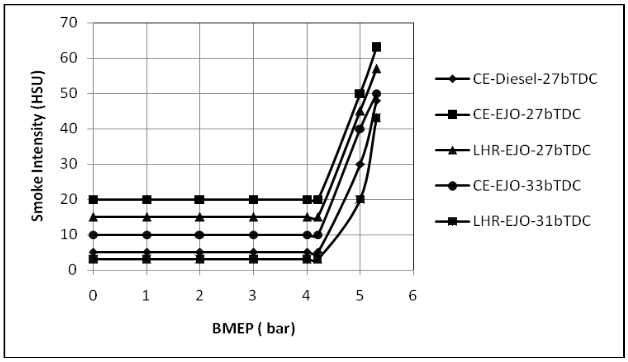

Fig.6 Variation of smoke intensity with BMEP in both versions of the engine at recommended and optimized injection timing at an injection pressure of 190 bar with EJO operation

Table.VI indicates smoke levels decreased at optimized injection timings and with increase of injection pressure in both versions of the engine, with different operating conditions of the biodiesel. This was due to improvement in the fuel spray characteristics at higher injection pressures and increase of air entrainment, at the advanced injection timings, causing lower smoke levels. Smoke levels were related to the density of the fuel. Smoke levels were higher with biodiesel as they have higher density Decreasing the fuel density tends to increase spray dispersion and spray penetration.. Preheating of the biodiesel reduced smoke levels in both versions of the engine, when compared with normal temperature of the biodiesel. This was due to i) the reduction of density of the vegetable oils, as density is directly proportional to smoke levels, ii) the reduction of the diffusion combustion proportion in CE with the preheated biodiesel, iii) the reduction of the viscosity of the biodiesel, with which the fuel spray does not impinge on the combustion chamber walls of lower temperatures rather than it directs into the combustion chamber.

Table VI. Data of Smoke Levels in Hartridge Smoke Unit (HSU) at peak load operation

Injection timing (°bTDC)	Test Fuel	Smoke intensity (HSU) at peak load											
		Engine version											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	48	--	38	--	34	--	55	--	50	--	45	--
	EJO	63	58	58	53	53	50	57	54	54	49	49	44
30	DF	36	--	34	--	32	--	45	--	42	--	41	--
	EJO	60	57	57	54	54	51	44	42	42	40	41	40
31	DF	33	---	32	--	30	--	43	--	41	--	40	--
	EJO	57	54	54	51	51	48	43	41	41	40	40	39
32	DF	32	--	31	--	32	--	--	--	--	---	--	--
	EJO	52	49	49	46	46	43	--	--	--	--	--	-
33	DF	30	---	30	--	35	--	-	--	--	--	--	--
	EJO	50	47	47	44	44	41	--	--	--	--	-	--

Fig.7 indicates that NOx levels were lower in CE while they were higher in LHR engine at different operating conditions of biodiesel when compared with diesel operation on CE at all loads. This was due to lower heat release rate and high duration of combustion causing lower gas temperatures with the biodiesel operation on CE, which reduced NOx levels. Increase of combustion temperatures with the faster combustion and improved heat release rates in LHR engine caused higher NOx levels. NOx levels increased in CE and decreased in LHR with biodiesel operation with advanced injection timing when compared with pure diesel operation on CE. This was due to increase of residence time and ignition delay with CE and decrease gas temperatures in LHR engine.

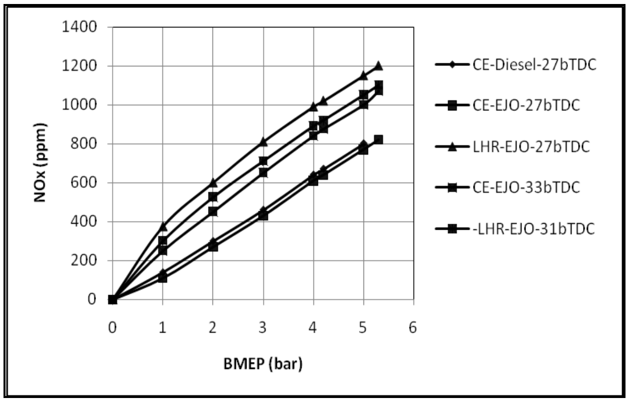

Fig.7 Variation of NOx levels with BMEP in both versions of the engine at recommended and optimized injection timing at an injection pressure of 190 bar with EJO operation

Table.VII denotes that NOx levels increased with the advancing of the injection timing and decreased with increase of injection pressure in CE with different operating conditions of biodiesel. Residence time increased, when the injection timing was advanced with the biodiesel operation on CE which caused higher NOx levels. With the increase of injection pressure, fuel droplets penetrate and find oxygen counterpart easily and increased air fuel ratio and also turbulence of the fuel spray increased the spread of the droplets thus leading to decrease in NOx levels in both versions of the engine with biodiesel. This was also due to improvement of air fuel ratios with good spraying characteristics of the fuel. As expected, preheating of the biodiesel marginally decreases NOx levels in both versions of the engine, when compared with the normal biodiesel. This was due to improved air fuel ratios with which combustion temperatures decrease leading to decrease NOx emissions in both versions of the engine

Table VII. Data of NOx levels at peak load operation

Injection timing (^{o}bDC)	Test Fuel	NOx levels (ppm) at peak load											
		Engine version											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	850	----	810	----	770	---	1300	--	1280	--	1260	--
	EJO	820	800	800	780	780	760	1200	1180	1180	1110	1140	1075
30	DF	900	---	850	---	800	--	1225	--	1205	--	1185	--
	EJO	860	840	840	820	820	800	1120	1100	1100	1070	1070	1050
31	DF	1020	---	970	---	920	---	1150	--	1130	--	1110	--
	EJO	950	900	900	850	850	830	1100	1080	1080	1060	1060	1040
32	DF	1105	----	1050	---	1000	---	--	--	--	--	--	--
	EJO	1030	1000	1010	980	990	970	--	--	--	--	--	-
33	DF	1190	----	1140	---	1100	---	--	--	--	--	--	-
	EJO	1070	1030	1040	1000	1010	990	--	-	--	--	--	-

Since NOx emissions increased with LHR engine, now the attention was focused in reducing NOx emissions by employing catalytic converter. From Table 8, it is observed that higher levels of NOx emissions in LHR engine in comparison with CE was due to the high temperatures in the combustion chamber leading to formation of high NOx levels by oxidation of nitrogen by oxygen. The presence of catalysts (A and B) has significantly reduced NOx levels in the exhaust of the engines. The hydrolysis of urea in catalyst-B gives ammonia which also reduced NOx to nitrogen. A decline in percentage reduction of NOx content with catalyst-B on LHR version of the engine compared to CE could be due to dissociation of urea at higher temperature.

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Table VIII.. Data of NOx emissions at peak load operation with Catalytic Converter

NOx emissions (ppm) at peak load					
Injection timing (^{o}bTDC)	Fuel/Catalyst	Engine version			
		CE		LHR Engine	
		Injection pressure (bar)		Injection pressure (bar)	
		190	270	190	270
27	Diesel/ (No catalyst)	850	770	1300	1260
	EJO/(No catalyst)	820	780	1200	1140
	EJO/(Catalyst-A)	410	360	600	540
	EJO/(Catalyst-B)	490	440	720	670
31	Diesel/ (No catalyst)	1020	920	1150	1110
	EJO/(No catalyst)	--	--	1100	1060
	EJO/(Catalyst-A)	---	--	600	550
	EJO/(Catalyst-B)	--	--	660	610
33	Diesel/ (No catalyst)	1190	1100	--	--
	EJO/(No catalyst)	1070	1010	--	--
	EJO/(Catalyst-A)	535	500	---	--
	EJO/(Catalyst-B)	650	610	---	--

Curves in Fig.8 indicate that the catalysts were more efficient in NOx reduction at a void ratio of 0.6, (The parameter, void ratio is given by volume occupied by catalyst to volume of catalytic chamber) beyond which a declination in catalytic activity was observed with biodiesel operation. This could be due to reduction in extent of exposure of catalyst to the exhaust gases. This was also due to increase of backpressure on engine beyond void ratio of 0.6.

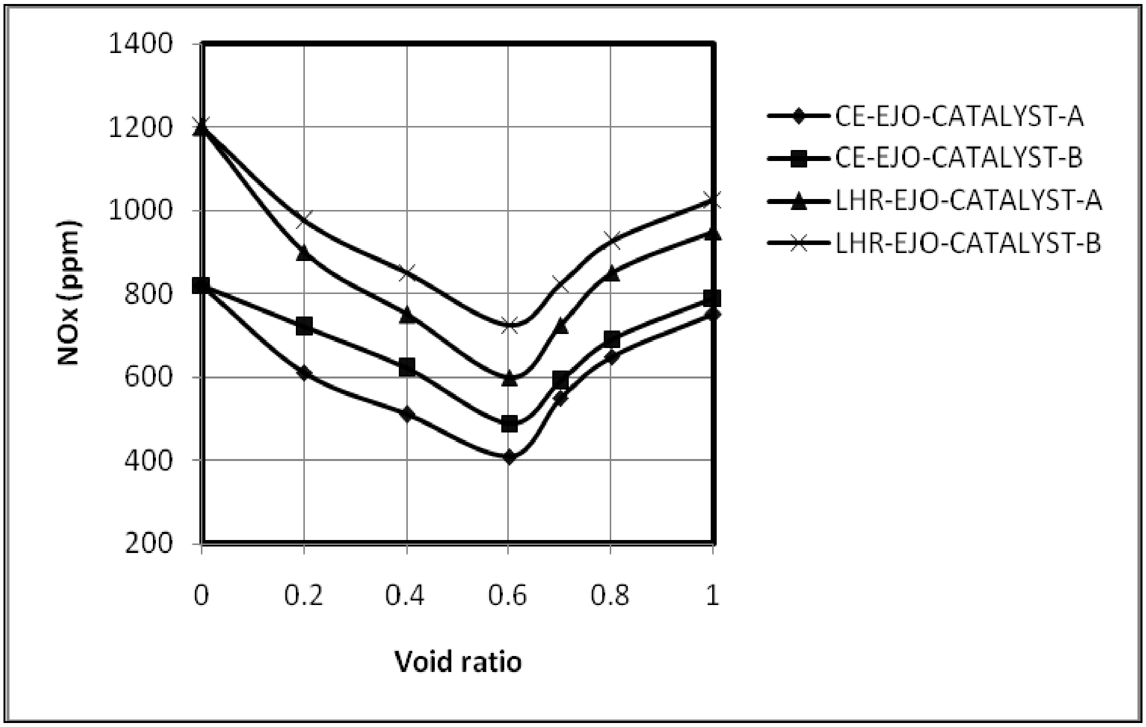

Fig.8 Variation of NOx levels with void ratio with different catalyst with both versions of the engine with EJO operation at peak load operation.

From Figure 9 it is evident that with biodiesel operation on CE version of the engine, with catalyst-A, the reduction efficiency increased from 40 to 50% at 300^{o}C and when the catalyst temperature was increased to 390^{o}C the reduction efficiency decreased to 30%.

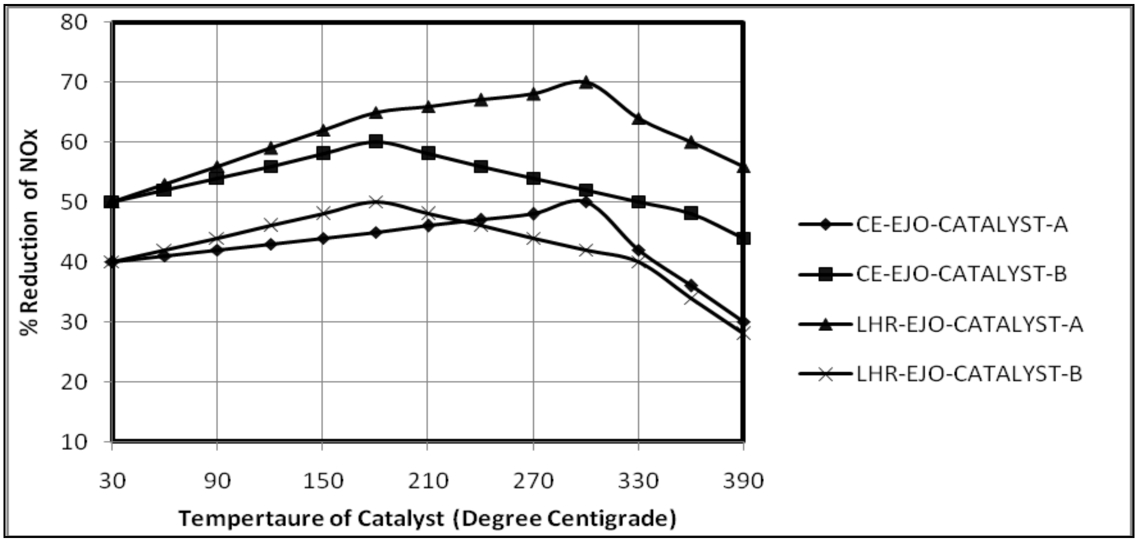

Figure 9. Variation of % reduction of NOx levels with temperature of the different catalysts with EJO operation with both versions of the engine at peak load operation.

With catalyst-B, the reduction in NOx levels was maximum (60%) at catalyst temperature of 175°C and beyond which the reduction efficiency decreases. On LHR version of the engine, when catalyst-A was used, NOx reduction efficiency increased from 50 to 70% with increase in catalyst temperature from room temperature to 300°C. With catalyst-B, the NOx reduction efficiency increased from 40 to 50%, with increase in catalyst temperature from room temperature to 175°C and further increment in temperature decreased the efficiency of the catalyst. Thus higher temperature of exhaust gases of LHR version of the engine and higher temperature of catalyst caused decomposition of urea leading to decrease in NOx reduction efficiency.

Figure 10 signifies that NOx reduction efficiency decreased when space velocity (Space velocity is a ratio of exhaust gas flow rate in m^3/h to the volume of catalytic chamber) increased beyond 300/h.

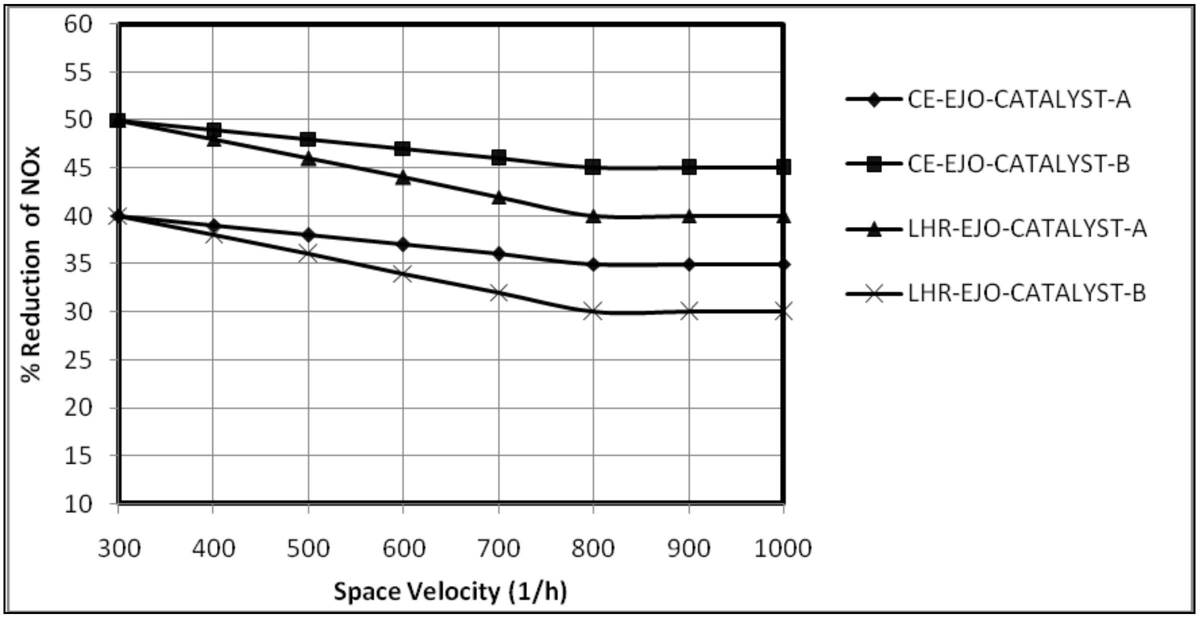

Fig.10. Variation of % reduction of NOx levels with space velocity in both versions of the engine with different catalysts.

This could be due to insufficient time for reduction reaction in presence of catalyst. The catalyst performance decreased with increase in space velocity and later it became constant at higher space velocities beyond 800/h. Thus, the lanthanum based zeolite supported catalytic reduction of NOx levels in the exhaust. CE with catalyst- B showed higher reduction of percentage of NOx beyond 800/h when compared with other version of the engine with other type of catalysts.

IV.CONCLUSIONS

Improvement in the performance was observed with biodiesel operation with the advancing of the injection timing and with the increase of injection pressure on both versions of the engine. CE with bio-diesel operation showed the optimum injection timing at 33^{o}bTDC, while the optimum injection was 31^{o}bTDC for the LHR engine at an injection pressure of 190 bars. At the recommended injection timing and pressure, bio-diesel operation on CE increased smoke levels drastically and decreased NOx levels, while LHR engine decreased smoke levels and increased NOx levels when compared with pure diesel operation on CE. Preheating of the bio-diesel decreased smoke levels and NOx levels slightly in both versions of the engine. Increase of injection pressure decreased pollution levels marginally in both versions of the engine. When the injection timing was advanced, NOx emissions increased in CE and decreased in LHR engine. The catalysts showed maximum efficiency in reduction of NOx levels at void ratio of 0.6. The optimum space velocity for efficient reduction of NOx levels was found to be 300/h. The increase in catalyst temperature increased the NOx reduction efficiency up to certain level beyond which the efficiency decreased. About 40-50% decrease in NOx emissions was observed by catalytic reduction.

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