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Exhaust Emissions and Combustion Characteristics of Jatropha Oil in Crude Form and Biodiesel of Low Heat Rejection Diesel Engine

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Abstract*—Investigations were carried out to study the exhaust emissions 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, air gap insulated liner with superni insert and ceramic coated cylinder head with different operating conditions of crude jatropha oil (CJO) and biodiesel with varied injection timing and injection pressure. Performance parameters and exhaust emissions were determined at various values of brake mean effective pressure (BMEP) with different versions of the engine with varied injection timing and injection pressure with different operating conditions of jatropha oil in crude form and biodiesel. Combustion characteristics of the engine were measured with TDC (top dead centre) encoder, pressure transducer, console and special pressure-crank angle software package at peak load operation of the engine. Conventional engine (CE) showed deteriorated performance, while LHR engine showed improved performance with crude vegetable operation at recommended injection timing and pressure and 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. Relatively, smoke levels decreased by 27% and NOx levels increased by 49% with crude vegetable oil operation on LHR engine at its optimum injection timing, when compared with pure diesel operation on CE at manufacturer's recommended injection timing. Biodiesel operation further decreased smoke levels and increased NOx emissions.

***Index Terms*—Alternate Fuel, CE, LHR engine, Vegetable oil**

I. INTRODUCTION

Use of diesel fuel in not only transport sector but also in agriculture sector leading to fast depletion of diesel fuels and increase of pollution levels with these fuels, the search for alternate fuels on has become pertinent for the engine manufacturers, users and researchers involved in the combustion research. Vegetable oils and alcohols are the probable candidates to replace conventional diesel fuel, as they are renewable.

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Most of the alcohol produced in India is consumed in Petro-chemical industries. The alcohols have low cetane number, and hence engine modification is necessary [1-2] if they are to be used as fuel in diesel engine. Rudolph diesel inventor of the engine that bears his name, experimented [3] with fuels ranging from powdered coal to peanut oil. Several researchers [4-7] 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. The presence of the fatty acid components greatly affects the viscosity of the oil. The above mentioned problems are reduced if crude vegetable oils are converted into biodiesel, which have low molecular weight, low dense and low viscosity when compared with crude vegetable oils. Investigations were carried out [8-12] with biodiesel with CE and reported that performance improved and reduced smoke emissions and increased NOx emissions. The drawbacks associated with crude vegetable oil and biodiesel call for LHR engine. 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. The concept of LHR engine is to reduce coolant losses by providing thermal resistance in the path of heat flow to the coolant, there by gaining thermal efficiency. Several methods adopted for achieving LHR to the coolant are i) using ceramic coatings on piston, liner and cylinder head ii) creating air gap in the piston and other components with low-thermal conductivity materials like superni, cast iron and mild steel etc. Investigations were carried out by various researchers [13-15] on ceramic coated engines with pure diesel operation and reported brake specific fuel consumption (BSFC) was improved in the range 5-9% and pollution levels decreased with ceramic coated engine. Experiments were carried out [16] on ceramic coated LHR engine with vegetable oil operation and reported that LHR engine marginally improved efficiency of the engine. Studies were also made on ceramic coated LHR engine with biodiesel operation and reported that performance improved and decreased smoke emissions and increased NOx emissions. The technique of providing an air gap in the piston involved the complications of joining two different metals. Investigations were carried out [17] 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. Investigations [18] were carried out with air gap insulated piston with nimonic crown with pure diesel operation with varied injection timing and reported brake specific fuel consumption was improved by 8%. Experiments were conducted [19-21] experiments on LHR engine, with an air gap insulated piston and air gap insulated liner with vegetable oil and reported that LHR engine improved the thermal efficiency and decreased smoke emissions and increased NOx emissions. Experiments were conducted [22-24] with air gap insulated piston with superni crown and air gap insulated liner with superni insert and ceramic coated cylinder head with varied injection timing and injection pressure with different alternate fuels like vegetable oils and reported that LHR engine improved the performance with alternate fuels. Experiments were conducted [25-26] on different degrees of insulation and reported that performance was improved with higher degree of insulation.

Little literature was reported on study of exhaust emissions with crude vegetable oil and biodiesel in LHR engine which contained air gap insulated piston, air gap insulated liner and ceramic coated cylinder head with varied injection timing and injection pressure. The present paper attempted to study the exhaust emissions of LHR engine, which consisted of air gap insulated piston, air gap insulated liner and ceramic coated cylinder head with jatropha oil in crude form and biodiesel with varied injection pressure and injection timing and compared with pure diesel operation on CE at recommended injection timing and injection pressure.

II. METHODOLGY

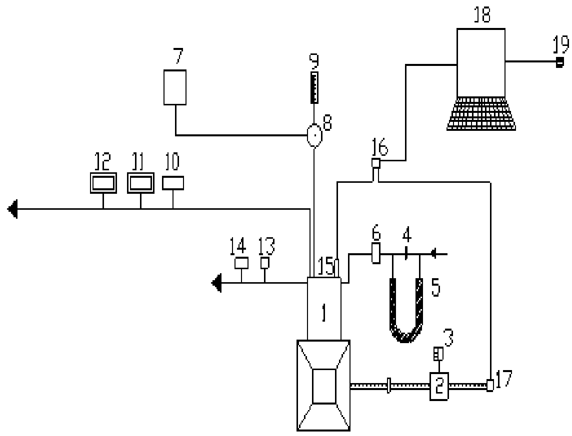
LHR diesel engine contained a two-part piston; the top crown made of low thermal conductivity material, superni-90 screwed to aluminum body of the piston, providing a 3-mm-air gap in between the crown and the body of the piston. The optimum thickness of air gap in the air gap piston was found to be 3-mm [23], for improved performance of the engine with superni inserts 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 is 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. Partially stabilized zirconium (PSZ) of thickness 500 microns was coated by means of plasma coating technique.

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. The properties of the test fuels and diesel used in this work are presented in Table-1.

Table 1: Properties of Test Fuels

Test Fuel	Viscosity at 25^{o}C (centi-poise)	Density at 25^{o}C	Cetane number	Calorific value (kJ/kg)
Diesel	12.5	0.84	55	42000
Bio diesel (EJO)	53	0.87	55	35500
Crude Jatropha oil (CJO)	125	0.90	45	36000

Experimental setup used for the study of exhaust emissions from LHR diesel engine with crude jatropha oil and jatropha oil based bio-diesel is shown in Figure 1. CE had an aluminum alloy piston with a bore of 80 mm and a stroke of 110mm. 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^{o}bTDC and 190 bar respectively. The fuel injector had three holes of size 0.25mm. 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.



1.Engine, 2.Electical Dynamo meter, 3.Load Box, 4.Orifice meter, 5.U-tube water manometer, 6.Air box, 7.Fuel tank, 8, Three way valve, 9.Burette, 10. Exhaust gas temperature indicator, 11.AVL Smoke meter, 12.Netel Chromatograph NOx Analyzer, 13.Outlet jacket water temperature indicator, 14. Outlet-jacket water flow meter, 15.Piezo-electric pressure transducer, 16.Console, 17.TDC encoder, 18.Pentium Personal Computer and 19. Printer.

Fig.1 Experimental Set-up

The naturally aspirated engine was provided with water-cooling system in which inlet temperature of water was maintained at 60^{o}C by adjusting the water flow rate. The 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. The maximum injection pressure was restricted to 270 bar due to practical difficulties involved. Exhaust emissions of smoke and NO_x were recorded by AVL smoke meter and Netel Chromatograph NOx analyzer respectively at various values of BMEP. Piezo electric transducer, fitted on the cylinder head to measure pressure in the combustion chamber was connected to a console, which in turn was connected to Pentium personal computer. TDC encoder provided at the extended shaft of the dynamometer was connected to the console to measure the crank angle of the engine. A special P-θ software package evaluated the combustion characteristics such as peak pressure (PP), time of occurrence of peak pressure (TOPP) and maximum rate of pressure rise (MRPR) from the signals of pressure and crank angle at the peak load operation of the engine. Pressure-crank angle diagram was obtained on the screen of the personal computer. The accuracy of the instrumentation used in the experimentation is 0.1%.

III. RESULTS AND DISCUSSION

A. Exhaust Emissions

CE with vegetable oil showed the deterioration in the performance for entire load range when compared with the pure diesel operation on CE at recommended injection timing. This was due to higher viscosity and longer duration of combustion of the fuel. BTE increased at all loads when the injection timing was advanced to 32^{o}bTDC in CE, with crude vegetable oil operation. The increase of BTE at optimum injection timing over the recommended injection timing with vegetable oil with CE was attributed to its longer ignition delay and combustion duration.

LHR version of the engine showed the improved performance for the entire load range compared with CE with pure diesel operation. High cylinder temperatures helped in better evaporation and faster combustion of the fuel injected into the combustion chamber. The optimum injection timing was found to be 31^{o}bTDC with LHR engine with normal crude vegetable oil operation.

CE with bio-diesel showed the compatible performance for entire load range when compared with the pure diesel operation on CE at recommended injection timing. BTE increased at all loads when the injection timing was advanced to 33^{o}bTDC in CE, at different operating conditions of the bio-diesel.

LHR version of the engine showed the improved performance for the entire load range compared with CE with pure diesel 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. The optimum injection timing was found to be 32^{o}bTDC with LHR engine with normal bio-diesel operation.

It is observed from Figure 2, that the value of smoke intensity increased from no load to full load in both versions of the engine. 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 brake power, 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 crude vegetable oil, compared with pure diesel operation on CE. This was due to the higher value of the ratio of C/H of vegetable oil (0.83) when compared with pure diesel (0.45).

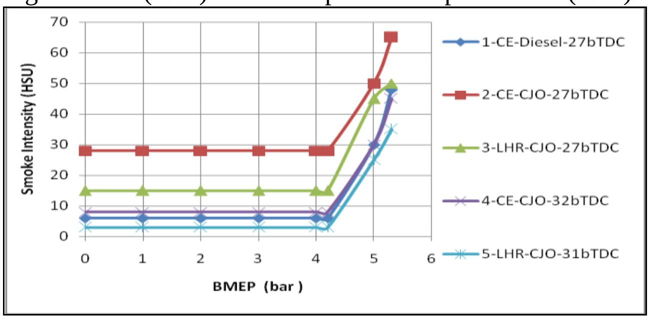


Fig.2 Variation of smoke intensity in Hartride Smoke Unit (HSU) with BMEP in both versions of the engine at recommended and optimized injection timings with crude vegetable oil operation.

The increase of smoke levels was also due to decrease of air-fuel ratios and VE with crude vegetable oil when compared with pure diesel operation. Smoke levels were related to the density of the fuel. Since vegetable oil had higher density compared to diesel fuels, smoke levels were higher with vegetable oil. However, LHR engine marginally reduced smoke levels due to efficient combustion and less amount of fuel accumulation on the hot combustion chamber walls of the LHR engine at different operating conditions of the crude vegetable oil compared with the CE. Density influences the fuel injection system. Decreasing the fuel density tends to increase spray dispersion and spray penetration. Preheating of the vegetable oils reduced smoke levels in both versions of the engine, when compared with normal temperature of the vegetable oils. 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 vegetable oil, iii) the reduction of the viscosity of the vegetable oil, with which the fuel spray does not impinge on the combustion chamber walls of lower temperatures rather than it directs into the combustion chamber.

From Table 2 it is evident that 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 vegetable oil. 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. Crude vegetable oil at its different operating conditions gave higher value of smoke levels in comparison with biodiesel in both versions of the engine. Due to higher molecular weight, crude vegetable oil has low volatility and because of their un-saturation, crude vegetable oil is inherently more reactive than biodiesel, which results that they are more susceptible to oxidation and thermal polymerization reactions. By the esterification process, the viscosity of the vegetable oil was brought down many times lower than the viscosity of the raw or crude vegetable oil. This was because of the removal of glycerol molecules, which caused the vegetable oil to be more viscous. Since there was drop in the viscosity, naturally the density of the esterified oil was also dropped at the room temperature. Volatility of the vegetable oil also increased with the esterification process. Hence biodiesel reduced smoke levels when compared to the crude vegetable oil in both versions of the engine.

Table 2. Data of smoke levels at peak load operation

Injection timing (°bTDC)	Test Fuel	Smoke intensity (HSU)											
		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	48	--	38	--	34	--	55	--	50	--	45	--
	CJO	65	60	63	58	58	54	45	40	40	35	35	30
	EJO	60	55	55	50	50	45	40	35	35	30	30	25
30	EJO	55	50	50	45	45	40	35	30	30	25	25	20
	CJO	60	55	55	50	45	55	40	35	35	30	30	25
31	EJO	50	45	45	40	40	35	30	25	25	20	20	18
	CJO	55	50	50	45	55	52	35	30	30	25	25	22
32	EJO	45	40	40	35	45	40	25	20	25	20	20	16
	CJO	50	45	55	52	52	49	--	--	--	---	--	--
33	EJO	40	35	45	40	50	45	-	--	--	--	--	--

Curves from Figure 3 indicate that NOx levels were lower in CE while they are higher in LHR engine at different operating conditions of the crude vegetable oil when compared with diesel operation. At part load, NOx concentrations were less in both versions of the engine. This was due to the availability of excess oxygen. At remaining loads, NOx concentrations steadily increased with the load in both versions of the engine. This was because, local NOx concentrations raised from the residual gas value following the start of combustion, to a peak at the point where the local burned gas equivalence ratio changed from lean to rich. At peak load, with higher peak pressures, and hence temperatures, and larger regions of close-to-stoichiometric burned gas, NOx levels increased in both versions of the engine. This was due to lower heat release rate because of high duration of combustion causing lower gas temperatures with the vegetable oil operation on CE, which reduced NOx levels. Though amount of fuel injected decreased proportionally as the overall equivalence ratio was decreased, much of the fuel still burns close to stoichiometric.

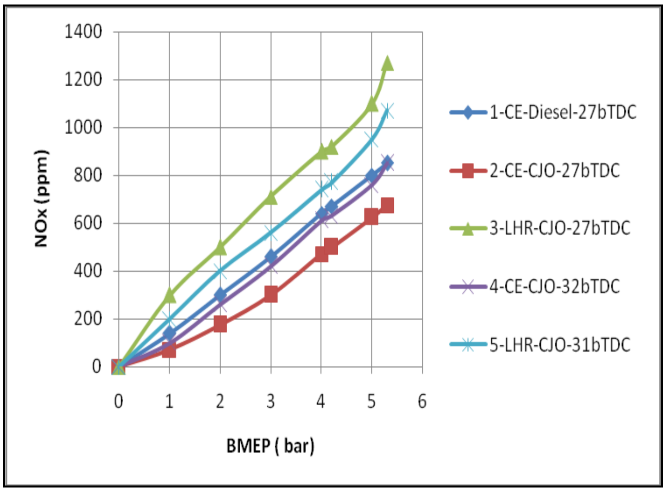


Fig.3 Variation of NOx levels with BMEP in both versions of the engine at recommended and optimized injection timings

Thus NOx emissions should be roughly proportional to the mass of fuel injected (provided burned gas pressures and temperature do not change greatly). Increase of combustion temperatures with the faster combustion and improved heat release rates in LHR engine cause higher NOx levels. At optimized injection timings, NOx levels increased in CE and decreased in LHR engine when compared at recommended injection timing. This was due to increase of resident time with CE and reduction of gas temperatures with LHR engine.

NOx levels increased with the advancing of the injection timing and with increase of injection pressure in CE with different operating conditions of crude vegetable oil and biodiesel as noticed in Table.3. With the increase of injection pressure, fuel droplets penetrate and find oxygen counterpart easily. Turbulence of the fuel spray increased the spread of the droplets thus leading to decrease in NOx levels. As expected, preheating of the vegetable oil further decreased NOx levels in both versions of the engine when compared with the normal vegetable oil. This was due to improved heat release rates and air fuel ratios leading to decrease NOx levels in LHR engine. Biodiesel gave marginally higher NOx levels in comparison with crude vegetable oil in both versions of the engine at different operating conditions. This was due to efficient combustion with biodiesel, which is high cetane value of fuel, leading to generate high combustion temperatures and hence higher NOx levels.

Table 3 Data of NOx emissions at peak load operation

Injection timing (° b TDC)	Test Fuel	NOx levels (ppm)											
		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	850	----	890	----	930	---	1300	--	1280	--	1260	--
	CJO	675	650	650	600	600	550	1270	1230	1230	1210	1180	1115
	EJO	820	770	770	720	720	670	1325	1275	1275	1225	1225	1175
30	EJO	920	870	870	820	820	770	1300	1250	1250	1200	1200	1150
	CJO	750	700	700	650	650	600	1170	1150	1150	1120	1120	1100
31	EJO	970	920	920	870	870	820	1250	1200	1200	1150	1150	1100
	CJO	800	750	750	700	700	650	1070	1000	1000	950	950	900
32	EJO	1020	970	970	920	920	870	1200	1150	1150	1150	1150	1100
	CJO	850	800	800	750	750	700	--	--	--	--	--	-
33	EJO	1110	1060	1060	1010	1010	---	--	--	--	--	--	-

B. Combustion Characteristics

From Table 9, it could be seen that with crude vegetable oil operation, peak pressures were lower in CE while they were higher in LHR engine at the recommended injection timing and pressure, when compared with pure diesel operation on CE. This was due to increase of ignition delay, as vegetable oils require large duration of combustion. Mean while the piston started making downward motion thus increasing volume when the combustion takes place in CE. LHR engine increased the mass-burning rate of the fuel in the hot environment leading to produce higher peak pressures. The advantage of using LHR engine for vegetable oils was obvious as it could burn low Cetane and high viscous fuels. Peak pressures increased with the increase of injection pressure and with the advancing of the injection timing in both versions of the engine, with crude vegetable oil and biodiesel. Higher injection pressure produces smaller fuel particles with low surface to volume ratio, giving rise to higher PP. Peak pressures were found to be lower with crude vegetable oil in comparison with biodiesel in both versions of the engine at different operating conditions of the test fuels. This was due to low cetane value of crude vegetable oils. With the advancing of the injection timing to the optimum value with the CE, more amount of the fuel accumulated in the combustion chamber due to increase of ignition delay as the fuel spray found the air at lower pressure and temperature in the combustion chamber. When the fuel- air mixture burns, it produced more combustion temperatures and pressures due to increase of the mass of the fuel. With LHR engine, peak pressures increases due to effective utilization of the charge with the advancing of the injection timing to the optimum value. The value of TOPP decreased with the advancing of the injection timing and with increase of injection pressure in both versions of the engine, at different operating conditions of crude vegetable oil and biodiesel. TOPP was more with different operating conditions of crude vegetable oil in CE, when compared with pure diesel operation on CE. This was due to higher ignition delay with the vegetable oil when compared with pure diesel fuel. This once again established the fact by observing lower peak pressure and higher TOPP, that CE with crude vegetable oil operation showed the deterioration in the performance when compared with pure diesel operation on CE. Preheating of the vegetable oil and biodiesel showed lower TOPP, compared with test fuels at normal temperature. This once again confirmed by observing the lower TOPP and higher PP, the performance of the both versions of the engine improved with the preheated crude vegetable oil and biodiesel compared with the normal vegetable oil. This trend of increase of MRPR indicated better and faster energy substitution and utilization by vegetable oil, which could replace 100% diesel fuel. However, these combustion characters were within the limits hence the crude vegetable oil and biodiesel could be effectively substituted for diesel fuel.

Table 9. Data of PP, MRPR, TOPP and TOMRPR at peak load operation

Injection timing (°bTDC)/ Test fuel	Engine version	PP(bar)				MRPR (Bar/deg)				TOPP (Deg)			
		Injection pressure (Bar)				Injection pressure (Bar)				Injection pressure (Bar)			
		190		270		190		270		190		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27/Diesel	CE	50.4	--	53.5	---	3.1	---	3.4	--	9	-	8	--
	LHR	46.1	--	51.1	--	2.7	--	2.9	--	11	--	9	--
27/ CJO	CE	46.5	49.6	51.3	52.4	2.6	2.7	2.9	3.0	11	10	11	10
	LHR	62.8	63.8	67.3	67.5	3.6	3.7	3.8	3.9	9	8	9	9
27/EJO	CE	48.6	50.4	52.5	53.6	2.7	2.8	3.0	3.1	11	10	11	10
	LHR	64.8	65.4	69.5	70.6	3.6	3.8	3.9	4.0	9	8	9	9
31/ CJO	LHR	65.8	66.5	67.8	68.6	3.7	3.9	3.9	4.1	8	8	8	8
32/CJO	CE	51.8	52.5	52.7	53.6	3.3	3.4	3.4	3.5	8	8	8	8
32/EJO	LHR	66.8	67.7	69.8	70.7	3.8	3.9	4.0	4.2	8	8	8	8
33/EJO	CE	52.8	53.6	54.7	54.6	3.4	3.5	3.5	3.6	8	8	8	8

V. CONCLUSIONS

smoke levels decreased by 17% and NOx levels increased by 49%, PP increased by 24% and TOPP was found to be lower with LHR engine in comparison with CE with pure diesel operation. Smoke levels improved with advanced injection timing and with an increase of injection pressure with vegetable oil operation.

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