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Comparative Studies on Exhaust Emissions from a High Grade Low Heat Rejection Diesel Engine with Carbureted Alcohol and Crude Jatropha Oil

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Abstract*—Investigations were carried out to study the exhaust emissions from high grade 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 normal temperature condition of crude jatropha oil and carbureted alcohol (ethanol / methanol) with varied injection timing and injection pressure and compared with methanol operation over ethanol operation and also with pure diesel operation on conventional engine (CE). Exhaust emissions of smoke and oxides of nitrogen (NOx) were recorded by AVL Smoke meter and Netel Chromatograph NOx analyzer respectively at different values of brake mean effective pressure (BMEP). Aldehydes were measured by dinitrophenyl hydrazine (DNPH) method at peak load operation of the engine. Smoke levels and NOx levels decreased by 47% 12% respectively with LHR engine at 27^{o}bTDC and at an injection pressure of 190 bar with methanol operation in comparison with pure diesel operation on CE.

***Index Terms*— Crude Vegetable Oil, Methanol, Ethanol, CE, LHR engine, Emissions and Combustion characteristics.**

I. INTRODUCTION

Following fuel crisis and vehicular population growth, search for renewable and alternate fuels has become pertinent for the engine manufacturers, users and researchers involved in the combustion research. Vegetable oils, which are renewable, have properties compatible to diesel fuels. Hence these fuels (straight vegetable oils, SVO) can be directly substituted in diesel engines without the modification of the engine. However, higher viscosity and chemical composition of unprocessed vegetable oils and fats have been shown [1] to cause problems in a number of areas (i) piston ring sticking; (ii) injector and combustion chamber deposits; (iii) fuel system deposits; (iv) reduced power; (v) reduced fuel economy and (vi) increased exhaust emissions due to high value of C/H ratio (C= Number of carbon atoms, H= Number of hydrogen atoms in fuel composition).

Rudolph Diesel, [2] the inventor of the diesel engine that bears his name, experimented with fuels ranging from powdered coal to peanut oil. Several researchers [3-7] experimented the use of vegetable oils as fuel on conventional engines (CE) and reported that the performance was poor, citing the above mentioned problems of high viscosity, low volatility and their polyunsaturated character. Bio-diesels derived from vegetable oils present a very promising alternative to diesel fuel since biodiesels have numerous advantages compared to fossil fuels as they are renewable, biodegradable, provide energy security and foreign exchange savings besides addressing environmental concerns and socio-economic issues. Experiments were carried out [8-12] with bio-diesel on CE and reported performance was compatible with pure diesel operation on CE.

On the other hand alcohols are renewable and volatile fuels. There are many methods of inducting alcohols in diesel engines, out of which carburetion technique is simple one. Alcohol was inducted through a variable jet carburetor, installed in inlet manifold and diesel was injected in conventional manner. Investigations were carried out [13-16] with carbureted alcohol and diesel on CE and reported that exhaust emissions of smoke and NOx decreased n comparison with pure diesel operation on CE. However, alcohols have low Cetane number. Hence engine modification was necessary if alcohol was used as fuel in diesel engine. The drawbacks of the crude vegetable oil, biodiesel and alcohol call for hot combustion chamber provided by LHR diesel engine.

The major concept of LHR engine is to reduce heat loss to the coolant, by providing thermal insulation in the path of heat flow to the coolant. LHR engines were classified depending on degree of insulation, such as low grade, medium grade and high grade engines. In low grade LHR engines, ceramic coatings were provided on piston, liner and cylinder head while in medium grade LHR engines, air gap was created in the piston and other components with low-thermal conductivity materials like superni, cast iron and mild steel etc. High grade LHR engines were the combination of low grade and medium grade.

Investigations were carried out by various researchers [17-19] on low grade LHR ceramic coated diesel engines with pure diesel operation and reported that pollution levels of smoke decreased by 15% with ceramic coated engine. Experiments were carried out [20-23] with biodiesel in low grade LHR diesel engine and reported that there was reduction of smoke levels and increase of NOx levels.

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Creating an air gap in the piston involved the complications of joining two different metals like bolted and welded design adopted by researchers [24] in fixing the crown of the piston to the body of the piston could not withstand more than 78 hours. Later it was a successful attempt [25] 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. It was reported from these investigations that smoke levels decreased by 12% at advanced injection timing of 29.5^{o}bTDC.

Experiments were conducted [26-28] on medium grade LHR engine which consisted of air gap insulated piston with superni crown and air gap insulated liner with superni insert with advanced injection timings and increased injection pressure with vegetable oils and reported that smoke levels decreased by 20% and NOx levels increased by 45% at peak load operation with LHR engine.

Experiments were carried out [29-31] with high grade LHR engine, which consisted of air gap insulated piston, air gap insulated liner and ceramic coated cylinder head with vegetable oils and reported that LHR engine further increased NOx levels and decreased smoke levels.

Alcohols, both ethanol and methanol were used [32-34] in medium grade LHR engine along with vegetable oil and reported that smoke and NOx emissions decreased considerably with LHR engine due to effect of higher heat generated in the combustion space due to adiabatic conditions improved alcohol combustion with varying pilot quantities of diesel. Vegetable oils have Cetane number comparable with diesel fuel, but they have high viscosity and low volatility. Alcohols have low Cetane fuels, though they have got high volatility. In order to take advantage from high Cetane number and high volatility, both vegetable oils and alcohols can be used in LHR engine.

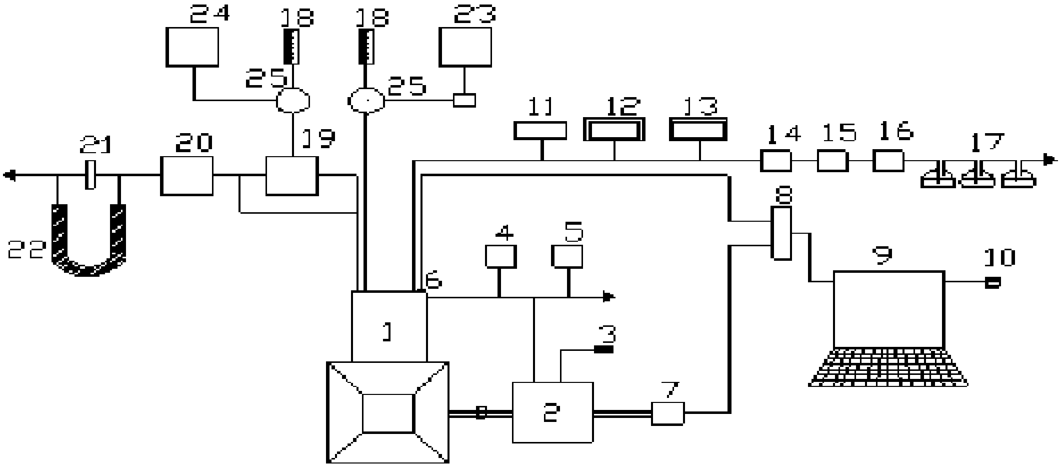
Smoke and NOx are the emissions from diesel engine cause [35-37] health hazards like inhaling of these pollutants cause severe headache, asthma, bronchitis, emphysema, lung cancer, nausea, slowing down of reflexes, vomiting sensation, respiratory problems, skin cancer, hemorrhage, dizziness, drowsiness, etc. The contaminated air containing carbon dioxide released from automobiles reaches ocean in the form of acid rain, there by polluting water. Hence control of these emissions is an immediate task and important.

As mentioned earlier, straight vegetable oil (SVO) cannot be used in diesel engines. Hence along with SVO, alcohol, which is volatile, was used in experimentation. The present paper attempted to study exhaust emissions from high grade LHR engine, which contained air gap piston, air gap liner and ceramic coated cylinder head with crude jatropha oil (CJO) with carbureted alcohol (ethanol/methanol) with varied injection pressure and injection timing and compared with methanol operation with ethanol operation on both versions of the engine and also with pure diesel operation on CE at 27^{o}bTDC and at an injection pressure of 190 bar.

II. METHODOLGY

Figure 1 shows the assembly details of air gap insulated piston, air gap insulated liner and ceramic coated cylinder head. 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 3mm-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 [27], for improved performance of the engine with superni insert 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 conductivities 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 experimental setup used for the investigations of LHR diesel engine with jatropha oil and carbureted alcohol 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^{o}bTDC and 190 bar respectively.



1.Engine, 2.Electical Dynamo meter, 3.Load Box, 4. Outlet jacket water temperature indicator, 5.Outlet-jacket water flow meter Orifice meter, 6. Piezo-electric pressure transducer, 7. TDC encoder 8.Console, 9. Pentium Personal Computer, 10. Printer, 11.Exhaust gas temperature indicator, 12.AVL Smoke meter, 13. Netel Chromatograph NOx Analyzer, 14. Filter, 15.Rotometer, 16.Hetaer,17. Round bottom flask containing DNPH solution, 18.Burette, 19.

Variable jet carburetor, 20. Air box, 21.Orifice meter, 22. U-tube water manometer, 23.Dieesl tank, 24.Alcohol tank, 25. Three-way valve.

Fig.1 Experimental Set-up

The fuel injector had 3 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. Alcohol was inducted through the variable carburetor jet; located at the inlet manifold of the engine at different percentages of diesel flow rate by mass basis and crude vegetable oil (CJO) was injected in conventional manner**.** Two separate fuel tanks and burette arrangements were made for measuring vegetable oil and alcohol consumptions**.** Air-consumption of the engine was measured by air-box method. 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. With alcohol-vegetable mixture operation, the major pollutant emitted from the engine is aldehydes. These aldehydes are carcinogenic in nature, which are harmful to human beings. The measure of the aldehydes is not sufficiently reported in the literature. DNPH method [32] was employed for measuring aldehydes in the experimentation. The exhaust of the engine was bubbled through 2,4 dinitrophenyl hydrazine (2,4 DNPH) solution. The hydrazones formed were extracted into chloroform and were analyzed by employing high performance liquid chromatography (HPLC) to find the percentage concentration of formaldehyde and acetaldehyde in the exhaust of the engine.

India with just 2.4% of the global area supports more than 16% of world's human population and 17% of the cattle population. According to economic survey (2000-2001), of the cultivable land area, about 175 million hectares are classified as waste and degraded or marginal land. If the non forest waste-lands could be used to cultivate plants which can survive on such soil and which can produce oilseeds, these could be effectively used to combat fuels shortage in the country and at the same time bring such degrade lands back to its productive capacity. Jatropha (Jatropha curcas, Ratanjyot) is a suitable candidate for its purpose. Jatropha oil known as moglaerand, beghierand, chandsaiyoti, or nepalam in Inida can be substituted for diesel. India imports jatropha oil of worth about 400 crores annually, which is used for making soap. Jatropha is a large shrub or small tree found throughout the tropical and subtropical regions of the world. The plant has several distinguishing and useful properties such as hardness, rapid growth easily propagation and wide ranging usefulness. It grows on any type of soil and is well adapted to cultivation. The plant has no major diseases or insect pests and is not browsed by cattle or sheep even during times of drought. The plant can survive for more than a year without water. Propagation is easily achieved by seed or stem cutting and its growth is rapid as is implied by its ability to form a thick live hedge nine months after planting. The plant starts yielding form the third year onwards and continues to yield for the next 25 years. The whole seeds can be crushed to yield about 25%oil. Double crushing can increase the yield to 28.5%and solvent extraction to 30%. The yield from established plantations in Brazil is around 1.5 to 2.3 tons per hectare. The seed and oil possess toxins and hence non-edible. The oil cake is also toxic and can be used only as manure and is very useful for this application with high nitrogen content and a favorable N: P: K ratio of 2.7:1.2:1. The properties of the diesel, vegetable oil, ethanol and methanol used in this work are presented in Table 1.

Table I. 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
Crude Jatropha oil (CJO)	125	0.90	45	36000
Ethanol	--	0.79	08	26880
Methanol	--	0.81	03	19740

III. RESULTS AND DISCUSSION

A. Performance Parameters

Investigations were carried out with the objective of determining the factors that would allow maximum use of alcohol in diesel engine with best possible efficiency at all loads.

Fig. 2 indicates that BTE increased at all loads with 35% methanol (M) induction and with the increase of methanol induction beyond 35%, it decreased at all loads in CE when compared with CE with diesel operation (standard diesel). The reason for improving the efficiency with the 35% methanol induction was because of improved homogeneity of the mixture with the presence of methanol, decreased dissociated losses, specific heat losses and cooling losses due to lower combustion temperatures. This was also due to high heat of evaporation of methanol, which caused the reduction the gas temperatures resulting in a lower ratio of specific heats leading to more efficient conversion of heat into work. Induction of methanol resulted in more moles of working gas, which caused high pressures in the cylinder. The observed increased in the ignition delay period would allow more time for fuel to vaporize before ignition started. This means higher burning rates resulted more heat release rate at constant volume, which was a more efficient conversion process of heat into work. Similar observations were made with ethanol also.

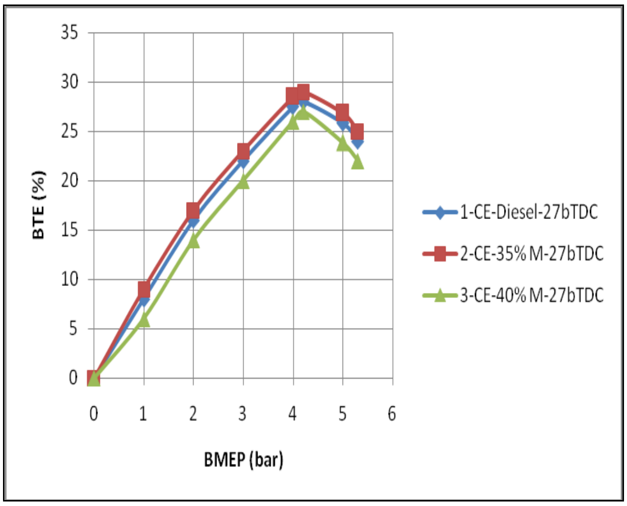


Fig.2 Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in conventional engine (CE) at different percentages of methanol (M) induction

Curves from Fig 3 indicate that LHR engine showed an improvement in the performance with the carbureted methanol at all loads when compared to the standard diesel engine. This was due to recovery of heat from the hot insulated components of LHR engine due to high latent heat of evaporation of the methanol, which lead to increase in thermal efficiency. The maximum induction of methanol is 60% in LHR engine, which showed improvement in the performance at all loads when compared to standard diesel engine.

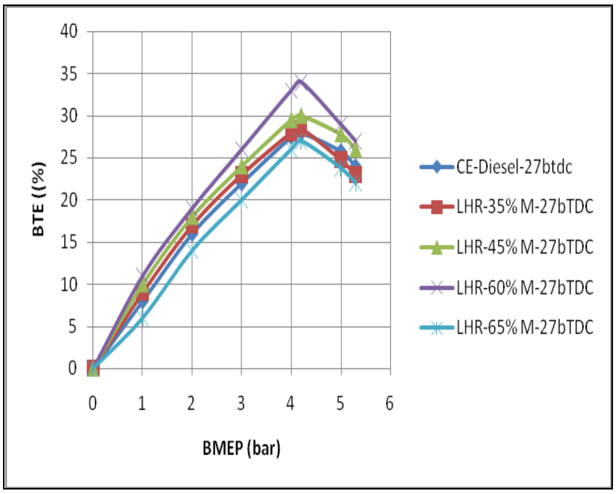


Fig.2. Variation of BTE with BMEP in LHR engine at different percentages of methanol (M) induction

However when the methanol induction was increased more than 60% in LHR engine, BTE is deteriorated at all loads when compared with standard diesel. This was due to increase of ignition delay. The optimum injection timings were at 33^{o}bTDC for CE, and at 32^{o}bTDC for LHR engine with pure diesel operation [28]. Similar trends were observed with vegetable oil operation also. However, the maximum induction of methanol was limited to 55% in the LHR engine at 32^{o}bTDC against 60% induction at 27^{o}bTDC, while maximum induction of methanol remained the same in CE at 33^{o}bTDC as in the case of 27^{o}bTDC.

B. Exhaust Emissions

Figure 4 indicates 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 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. Smoke density decreased with induction of alcohol. The combustion of injected fuel in case of pure vegetable oil operation was predominantly one of oxidation of products of destructive decomposition. In this case, there were greater chances of fuel cracking and forming carbon particles. On the other hand, the combustion of alcohol was predominantly a process of hydroxylation and the chances of fuel cracking were negligible.

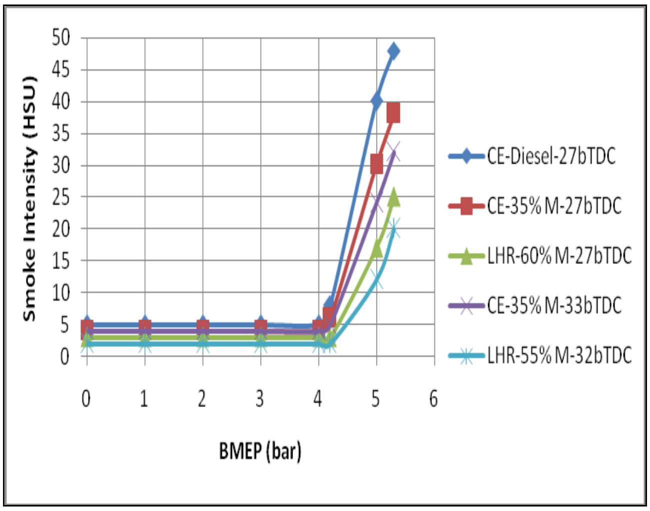


Fig 4 Variation of smoke intensity in Hartridge smoke unit (HSU) with BMEP with maximum percentage of methanol (M) induction in CE and LHR engine at recommended and optimum injection timings

Methanol does not contain carbon-carbon bonds and therefore cannot form any un-oxidized carbon particles or precursor to soot particles. One of the promising factor for reducing smoke levels with the alcohols was they contained oxygen in their composition which helped to reduce soot density. Soot emissions increased linearly with the increase of carbon to hydrogen atoms (C/H) ratio provided the equivalence ratio was not altered. This is because higher C/H lead to more concentration of carbon dioxide, which would be further, reduced to carbon. Consequently, induction of alcohol reduced the quantity of carbon particles in the exhaust gases as the values of C/H for diesel fuel, vegetable oil and methanol are 0.45, 0.83 and 0.25 respectively. Lower smoke levels were observed in both versions of the engine in dual fuel mode when compared with pure diesel operation on CE. LHR engine with 60% methanol induction showed lower smoke levels when compared with CE with 35% methanol induction. Smoke levels decreased with the increase of methanol induction in both versions of the engine. In dual fuel operation, smoke levels further decreased with the advancing of the injection timing and with increase of injection pressure in both versions of the engine as it is noticed from the Table 2, due to efficient combustion at higher injection pressures, which improved the atomization hence faster rate of combustion and shorter combustion duration at the advanced injection timings caused to reduce the smoke density in both versions of the engine. Smoke levels were marginally lower with methanol operation in comparison with ethanol operation in both versions of the engine as the value of C/H ratio of methanol (0.25) is lower than ethanol (0.33). Smoke levels were observed to be higher with LHR engine with pure diesel operation as it is noticed from Table.2 in comparison with pure diesel operation on CE. This was due to fuel cracking at higher temperature, leading to increase in smoke density. Higher temperature of LHR engine produced increased rates of both soot formation and burn up. The reduction in volumetric efficiency and air-fuel ratio were responsible factors for increasing smoke levels in the LHR engine near the peak load operation of the engine. As expected, smoke increased in the LHR engine because of higher temperatures and improper utilization of the fuel consequent upon predominant diffusion combustion. However, with dual operation with various percentage induction of alcohols, diesel fuel on both versions of the engine reduced smoke intensity in comparison with vegetable oil operation. This was due to lower value of C/H with diesel fuel in comparison with that of vegetable oil operation.

Table II. Comparative data on Smoke levels at peak load operation

IT	Test Fuel/ Engine Version	Alcohol induction on mass basis	Smoke levels at peak load operation (HSU)					
			Methanol			Ethanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
	CJO							
27	CE	0%	65	63	58	65	63	58
	LHR	0%	45	40	35	45	40	35
	CE	35%	38	33	28	42	37	32
		40%	--	--	25	--	--	30
	LHR	60%	25	20	15	30	25	20
32	LHR	55%	20	17	13	25	22	18
33	CE	35%	32	28	24	37	33	29
	Diesel							
27	CE	0%	48	38	34	48	38	34
	LHR	0%	55	50	45	55	50	45
	CE	35%	30	25	20	34	29	24
		40%	--	--	18	--	--	22
	LHR	60%	20	18	13	28	23	18
32	LHR	55%	18	15	11	23	20	16
33	CE	35%	30	26	22	35	31	27

The temperature and availability of oxygen are the reasons for the formation of NOx. Figure 5 indicates that for both versions of the engine, NOx concentrations raised steadily as the fuel/air ratio increased with increasing BMEP, at constant injection timing. 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. Though amount of fuel injected decreased proportionally as the overall equivalence ratio was decreased, much of the fuel still burns close to stoichiometric. Thus NOx emissions should be roughly proportional to the mass of fuel injected (provided burned gas pressures and temperature do not change greatly). From Figure, it is noticed that NOx emissions decreased with the increase of percentage of methanol induction in both versions of the engine, due to lower combustion temperature

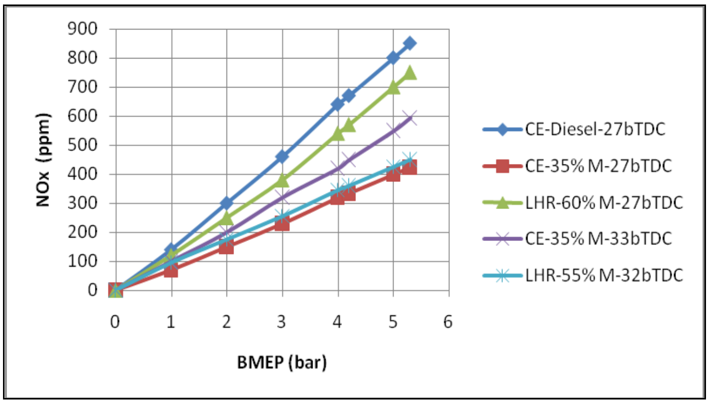


Fig.5 Variation of NOx levels with BMEP with maximum percentage of methanol (M) induction in CE and LHR engine at recommended and optimum injection timings

The low value of C/H ratio in methanol has indirect effect in reducing oxygen availability in the gases, which leads to the reduction of NOx. However, LHR engine with different percentages of methanol induction showed higher NOx levels compared with CE with 35% methanol induction, due to increase of gas temperatures in LHR engine. NOx levels further decreased with the increase of methanol induction in both versions of the engine. NOx levels increased marginally in CE while they decreased in LHR engine with the advancing of the injection timing. This is due to reduction of gas temperatures in the LHR engine at 32^{o}bTDC. However, they decreased with increase of injection pressure in both versions of the engine as noticed from Table 3. NOx levels were lower with methanol operation when compared with ethanol operation on both versions of the engine. This was due to decrease of gas temperatures because of high latent heat of evaporation of methanol.

With diesel mode operation, due to the reduction of fuel-air equivalence ratio with LHR engine, which was approaching to the stoichiometric ratio, causing more NOx concentrations in comparison with CE. In comparison with vegetable oil-alcohol, diesel-alcohol operation produced marginally higher NOx levels in both versions of the engine.

Table III. Comparative data on NOx levels at peak load operation

IT	Test Fuel/ Engine Version	Alcohol induction on mass basis	NOx at peak load operation (ppm)					
			Methanol			Ethanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
	CJO							
27	CE	0%	675	650	600	675	650	600
	LHR	0%	1270	1230	1180	1270	1230	1180
	CE	35%	425	375	325	475	425	375
		40%	--	--	300	--	--	350
	LHR	60%	750	700	650	800	750	700
32	LHR	55%	450	400	350	525	475	425
33	CE	35%	595	550	500	645	600	550
	Diesel							
27	CE	0%	850	890	930	850	890	930
	LHR	0%	1300	1280	1260	1300	1280	1260
	CE	35%	400	350	300	450	400	350
		40%	--	--	275	--	--	325
	LHR	60%	725	675	625	775	725	675
32	LHR	55%	425	375	325	500	450	400
33	CE	35%	570	525	475	625	575	525

This was due to high calorific value of the diesel causing high combustion temperatures leading to produced higher NOx levels.

The aldehydes are responsible for pungent smell of the engine and affect the human beings when inhaled in the large quantities. The volatile aldehydes are eye and respiratory tract irritants. Though Government legislation has not been pronounced regarding the control of aldehyde emissions, when more and more alcohol engines are coming to existence severe measures the controlling of aldehydes emitted out through the exhaust of the alcohol run engines will have to be taken as serious view. It could be seen from the Table 4, that formaldehyde emissions were low with pure diesel operation in both CE and LHR engine.

Table IV. Comparative data on Formaldehyde emissions at peak load operation

IT	Test Fuel/ Engine Version	Alcohol induction on mass basis	Formaldehyde emissions at peak load operation (% concentration)					
			Methanol			Ethanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
	CJO							
27	CE	0%	12.5	11.2	9.5	12.5	11.2	9.5
	LHR	0%	10.5	9.3	7.5	10.5	9.3	7.5
	CE	35%	28.3	26.2	24.1	18.3	16.3	14.2
		40%	--	--	26.4	--	--	16.4
	LHR	60%	30.2	28.2	26.6	24.3	22.1	20.4
32	LHR	55%	20.2	18.2	16.4	15.5	13.6	11.5
33	CE	35%	25.5	23.3	21.5	13.0	11.4	9.5
	Diesel							
27	CE	0%	9.0	8.1	6.9	9.0	8.1	6.9
	LHR	0%	8.0	7.2	5.4	8.0	7.2	5.4
	CE	35%	22.2	20.6	18.6	16.5	14.8	12.5
		40%	--	--	20.8	--	--	14.8
	LHR	60%	28.3	26.4	24.6	22.4	20.5	18.7
32	LHR	55%	18.4	16.5	14.5	13.7	10.5	8.6
33	CE	35%	23.4	21.6	19.4	12.0	10.5	8.5

Formaldehyde emissions increased drastically with methanol induction in both CE and LHR engine. With increased induction of methanol up to 60%, CE registered very high value of formaldehyde emissions in the exhaust, which showed the significant reduction in LHR engine. Hot environment of LHR engine completed combustion reactions and reduced the emissions of intermediate compounds, aldehydes. Hence it is concluded that LHR engine was more suitable for alcohol engines in comparison with pure diesel operation. However, formaldehyde emissions decreased with LHR engine in comparison with CE with the same amount of alcohol induction. This showed that LHR engine improved combustion and intermediate compounds were not formed during the combustion. Formaldehyde emissions were higher with methanol operation when compared with ethanol operation on both versions of the engine. Advanced injection timing and increase of injection pressure also improved the combustion in LHR engine by reducing the intermediate compounds like formaldehydes. This was due to initiation of combustion at early period and improved spray characteristics of the fuel. Dual operation with diesel-alcohol, formaldehyde emissions decreased, when compared with vegetable oil-alcohol operation in both versions of the engine. Diesel has got low viscosity, having high calorific value and moderate duration of combustion and hence chances of forming intermediate compounds like formaldehyde and fuel deposits were less with diesel fuel.

Table 5 followed the similar trend with Table 4. LHR engine decreased acetaldehyde emissions in comparison with CE with the same amount of alcohol induction. This was due to improved combustion in LHR engine because of high evaporation rate with the hot environment provided with LHR engine leading to reduce fuel deposits.

Table V. Comparative data on Acetaldehyde emissions at peak load operation

IT	Test Fuel/ Engine Version	Alcohol induction on mass basis	Acetaldehyde emissions at peak load operation (% concentration)					
			Methanol			Ethanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
	CJO							
27	CE	0%	9	8	6.9	9	8	6.9
	LHR	0%	8	7	5.7	8	7	5.7
	CE	35%	18.3	16.4	14.7	28.3	26.5	24.5
		40%	--	--	16.5	--	--	26.7
	LHR	60%	24.3	22.7	20.5	30.2	28.6	26.6
32	LHR	55%	13	11.4	9.4	20.2	18.3	16.4
33	CE	35%	15.5	13.7	11.5	25.5	23.5	21.5
	Diesel							
	CE	0%	7	6	4.9	7	6	4.9

27	LHR	0%	6	5	4.1	6	5	4.1
	CE	35%	16.3	14.4	12.5	24.4	22.5	20.4
		40%	--	--	14.4	--	--	24.4
	LHR	60%	22.6	20.4	18.5	28.5	26.6	24.4
32	LHR	55%	11	10	8.7	18.4	16.6	14.5
33	CE	35%	13.4	11.7	10.5	23.3	21.4	19.5

Acetaldehyde emissions decreased with the advanced injection timing and increase of injection pressure in both versions of the engine at various percentages of alcohol induction. Diesel-alcohol combustion decreased acetaldehyde emissions marginally when compared with vegetable oil-alcohol. This was due to low viscous nature and moderate ignition delay of the diesel fuel in comparison with vegetable oil, which improved combustion so as to not to form intermediate fuel deposits like acetaldehyde compounds. From the Table, it is noticed that, acetaldehyde emissions were higher with ethanol operation in comparison with methanol operation in both versions of the engine at various percentage induction of alcohol. This was due to nature of the fuel.

IV. CONCLUSIONS

Smoke intensity at peak load decreased by 47%, NOx levels at peak load decreased by 38%, PP at peak load increased by 46%, TOPP was found to be lower and MRPR was observed to be higher with methanol operation on LHR engine at its optimum injection timing of 32^{o}bTDC in comparison with pure diesel operation on CE at 27^{o}bTDC. Aldehyde emissions decreased in LHR engine when compared with CE at their optimum injection timings with alcohol operation.

Ethanol operation followed similar trends with methanol operation. CE with ethanol operation showed improved performance over the same configuration of the engine with methanol operation. LHR engine with methanol operation showed improved performance over the same configuration of the engine with ethanol operation. However, exhaust emissions of smoke and NOx at peak load operation on LHR engine with methanol operation decreased by 25% and 16% respectively in comparison with ethanol operation on same version of the engine. Methanol operation increased formaldehyde emissions marginally while ethanol operation slightly increased acetaldehyde emissions on both versions of the engine at recommended and optimized injection timings.

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