Comparative Performance Evaluation of 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 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, air gap insulated liner with superni insert and ceramic coated cylinder head with normal temperature condition of jatropha oil and carbureted alcohol (ethanol and methanol) with varied injection timing and injection pressure and compared with methanol operation over ethanol operation. Performance parameters were determined at various values of bake mean effective pressure (BMEP) with varied injection timing and injection pressure.Pollution levels of smoke and oxides of nitrogen (NOx) were recorded at different values of BMEP. Aldehydes were measured by dinitrophenyl hydrazine (DNPH) method. Combustion characteristics of the engine were measured with TDC (top dead centre) encoder, pressure transducer, console and special pressure-crank angle software package. Conventional engine (CE) and LHR engine showed improved performance at recommended injection timing of 27^{o}bTDC and recommend injection pressure of 190 bar, when compared with CE with pure diesel operation. Peak brake thermal efficiency increased by 21%, smoke levels decreased by 58% and NOx levels decreased by 47% with LHR engine at its optimum injection timing with maximum induction of methanol when compared with pure diesel operation on CE at manufacturer's recommended injection timing.

Keywords- Crude Vegetable Oil, Methanol, Ethanol, LHR engine, Fuel Performance, Emissions and Combustion Characteristics

1. Introduction

Following fuel crisis and vehicular population growth, search for renewable fuels has become pertinent for the engine manufacturers, users and researchers involved in the combustion research. It has becomes very important to search renewable alternate fuels which are environment friendly such as vegetable oils and alcohols. Vegetable oils 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.

According to a Report [1], The U.S. Department of Energy has stated that, "Raw or refined vegetable oil, or recycled greases that have not been processed into biodiesel, and should be avoided. The use of raw, unprocessed vegetable oils or animal fats in diesel engines - regardless of blend level - can have significant adverse effects and should not be used as fuel in diesel engines. Raw or refined vegetable oil, or recycled greases have significantly different and widely varying properties that are not acceptable for use in modern diesel engines". For example, the higher viscosity and chemical composition of unprocessed oils and fats have been shown 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. The significantly higher viscosity of raw vegetable oils (27 - 54 mm^2/s) compared to petroleum diesel fuel (2.6 mm^2/s) alters fuel injector spray patterns and spray duration, adds stress on fuel injection systems, and results in incomplete combustion and high dilution of the engine lubricating oil. In turn, fuel injector spray pattern, duration, etc. affect the combustion process and the resulting engine performance and emissions levels.

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 [3-8] 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 [9] 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 [10-14] 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 is inducted through a variable jet carburetor, installed in inlet manifold and diesel is injected in conventional manner. Investigations were carried out [15-18] with carbureted alcohol and diesel on CE and reported performance improved with dual fuel engine and decreased exhaust emissions of smoke and oxides of nitrogen (NOx) in comparison with pure diesel operation on CE. However, alcohols have low Cetane number. Hence engine modification is necessary if alcohol is 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 are classified depending on degree of insulation, such as low grade, medium grade and high grade engines. Low grade LHR engines are using ceramic coatings on piston, liner and cylinder head while in medium grade LHR engines, air gap is created in the piston and other components with low-thermal conductivity materials like superni, cast iron and mild steel etc. High grade LHR engines are the combination of low grade and medium grade.

Investigations were carried out by various researchers [19-21] on low grade LHR ceramic coated diesel engines with pure diesel operation and reported brake specific fuel consumption (BSFC) was improved in the range 5-9% and pollution levels of smoke decreased with ceramic coated engine. Experiments were carried out [22-25] with biodiesel in low grade LHR diesel engine and reported performance improved, decreased smoke levels and increased NOx levels.

Creating an air gap in the piston involved the complications of joining two different metals like bolted and welded design adopted by researchers [26] in fixing the crown of the piston to the body of the piston could not withstand more than 78 hours. Later it [27] was 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. It was reported from these investigations that BSFC decreased by 3.5% at advanced injection timing of 29.5^{o}bTDC.

In order to increase the degree of the insulation, air gap is not only created in the piston but also in the liner. It was studied [28] the performance of a diesel engine by insulating engine parts employing 2-mm air gap in the nimonic piston studded with the body of the piston and mild steel sleeve, provided with 2-mm air gap was fitted with the total length of the liner. It was reported the deterioration in the performance of the engine at all loads, when compared to pure diesel operation on CE. This was due to higher exhaust gas temperatures. Experiments were conducted [9] 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 different alternate fuels like alcohols and non-edible vegetable oil and reported improved performance with LHR engine.

Investigations were carried out [29] with high grade LHR engine with pure diesel operation. The piston with nimonic crown with 2 mm air gap was fitted with the body of the piston by stud design. Mild steel sleeve was provided with 2 mm air gap and it was fitted with the 50 mm length of the liner. The performance was deteriorated with this engine with pure diesel operation, at recommended injection timing. Hence the injection timing was retarded to achieve better performance and pollution levels.

Experiments were carried out [30] with high grade LHR engine, which consisted of air gap insulated piston, air gap insulated liner and ceramic coated cylinder head with crude jatropha oil and pongamia oil based bio-diesel and reported performance was deteriorated with CE and improved with LHR engine.

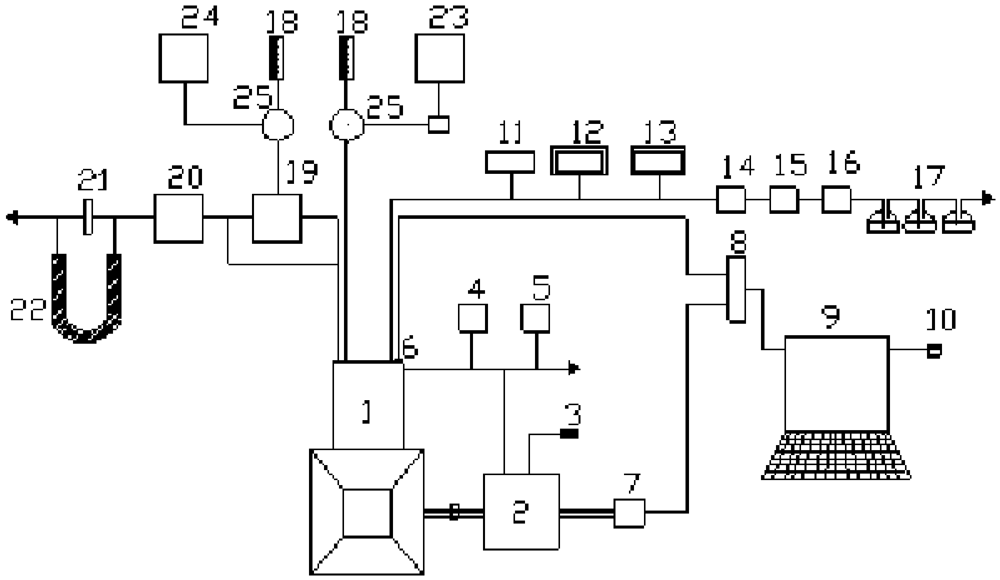
Alcohols, both ethanol and methanol were used [31-35] in LHR engine and reported that performance was improved with LHR engine and the effect of higher heat generated in the combustion space due to adiabatic conditions improved alcohol combustion with varying pilot quantities of diesel. It was reported [9] that optimum induction of alcohol was 35% with CE and 50% with LHR engine with air gap insulated piston and air gap insulated liner. 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 have to be used in LHR engine.

The present paper attempted to evaluate the performance of LHR engine, which contained air gap piston, air gap liner and ceramic coated cylinder head with crude jatropha oil (CJO) with carbureted alcohol (ethanol and methanol) with varied injection pressure and injection timing and compared with methanol operation with ethanol operation on both versions of the engine.

2. Materials and Methods

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 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 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 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.



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. The Experimental Set-up

The fuel injector had 3 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. 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 gas temperature (EGT) was measured with thermocouples made of iron and iron-constantan.

Exhaust emissions of smoke and NOx 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 [9] 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.

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-q software package evaluated the combustion characteristics such as peak pressure (PP), time of occurrence of peak pressure (TOPP), maximum rate of pressure rise (MRPR) and time of occurrence of maximum rate of pressure rise (TOMRPR) from the signals of pressure and crank angle at the peak load operation of the engine. The properties of the diesel, vegetable oil, ethanol and methanol used in this work are presented in Table-1. The accuracy of the instrumentation used in the experimentation is 0.1%.

Table 1. 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
Crude Jatropha oil (CJO)	125	0.90	45	36000
Ethanol	--	0.79	08	26880
Methanol	--	0.81	03	19740

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 [9] 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.

3. Results and Discussions

3.1. 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.

Figure 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.

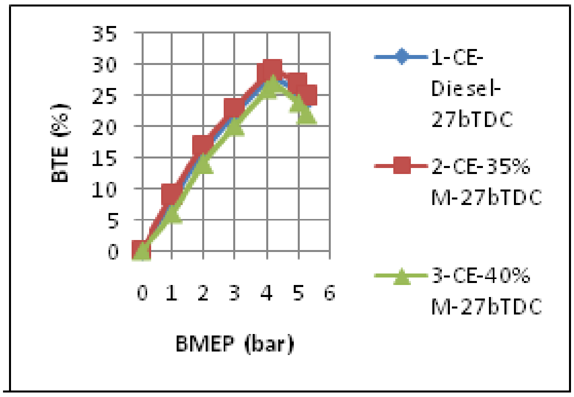


Fig. 2. Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in conventional engine (CE) at different percentages of methanol (M) induction

Curves from Figure 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. 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.

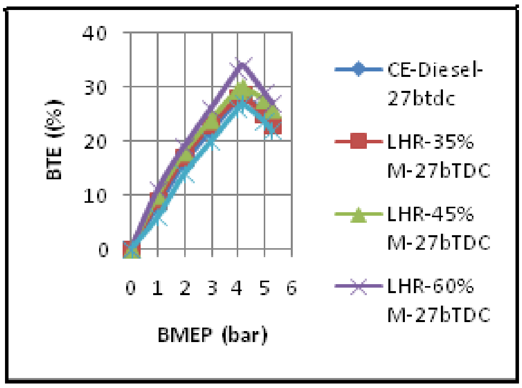


Fig. 3. Variation of BTE with BMEP in LHR engine at different percentages of methanol (M) induction

The optimum injection timings were at 33°bTDC for CE, and at 32°bTDC for LHR engine with pure diesel operation [33]. 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°bTDC against 60% induction at 27°bTDC, while maximum induction of methanol remained the same in CE at 33°bTDC as in the case of 27°bTDC.

From Figure 4, it is noticed that LHR engine with 55% methanol induction at its optimum injection timing showed improved performance at all loads when compared with other versions of the engine. This was due to higher amount of methanol substitution and improved combustion at advanced injection timing caused better evaporation leading to produce higher BTE.

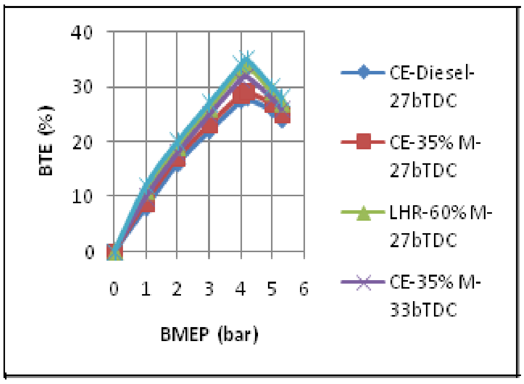


Fig. 4. Variation of BTE with BMEP with maximum percentage of methanol (M) induction in CE and LHR engine at recommended and optimum injection timings

There is a limitation to use methanol due to low cetane number and having higher self-ignition temperature than vegetable oil to use in CE without increasing injection pressure because as percentage of methanol increased, more heat was utilized to evaporate alcohol fuels and less heat was available to evaporate vegetable oil. Therefore a major quantity of alcohol which burned late in the expansion stroke, would not be fully utilized. In order to avert this, injection pressure was increased, which reduced fuel droplet size, increased surface to volume ratio and required comparatively less heat to evaporate vegetable oil droplet.

The trend exhibited by both versions of the engine with dual fuel operation at higher injection pressure of 270 bar was similar to the corresponding to the injection pressure of 190 bars. However, the maximum induction of alcohol was 40% in CE at an injection pressure of 270 bar against 35% at 190 bar, while maximum alcohol induction remained same with LHR engine at 270 bar as in the case of 190 bars. From Table 2, it is noticed that peak BTE was higher with CE with ethanol operation in comparison with methanol operation. This was due to higher calorific value of ethanol when compared with methanol. However, methanol operation on LHR engine improved the performance when compared with ethanol operation on same version of the engine. This was because of higher evaporation characteristics of methanol in the hot environment provided by LHR engine, which lead to higher energy supplied by methanol as energy supplied to the engine was the product of mass of fuel burned and calorific value of the fuel. Peak BTE increased with increase of injection pressure in both versions of the engine with alcohol operation. This was due to improved spray characteristics of the fuel with increased injection pressure.

Table 2. Comparative data on Peak Brake thermal efficiency

IT	Engine Version	Alcohol induction on mass basis	Peak Brake Thermal Efficiency (%)					
			Methanol			Ethanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
		0%	28	29	30	28	29	30
27	CE	35%	29	30	31	29.5	30	30.5
		40%	--	--	32	--	---	32.2
	LHR	60%	34	35.5	36	33	33.5	34
32	LHR	55%	35	36	36.5	34	34.5	35
33	CE	35%	32	32.5	33	32.2	32.5	33

From Table 3, it is evident that brake specific energy consumption (BSEC) at peak load operation decreased with the increase of methanol induction, as higher amount of alcohol substitution caused better evaporation and produced lower BSEC in both versions of the engine. BSEC was lower in LHR engine at its optimum injection timing, which shows the suitability of the engine for alternate fuels. It also decreased with the increase of injection pressure and advanced injection timing in both versions of the engine. This was due to early initiation of combustion with improved fuel spray characteristics. BSEC was lower with CE, while it was higher with LHR engine with ethanol operation when compared with methanol operation. This was due to good evaporating characteristics with methanol operation.

Table 3. Comparative data on Brake specific energy consumption at peak load operation

IT	Engine Version	Alcohol induction on mass basis	Brake specific energy consumption (kW/kW)					
			Methanol			Ethanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
		0%	4.0	3.92	3.84	4.0	3.92	3.84
27	CE	35%	3.98	3.96	3.94	3.88	3.86	3.84
		40%	--	---	3.88	--	---	3.76
	LHR	60%	3.72	3.70	3.68	3.74	3.72	3.70
32	LHR	55%	3.64	3.62	3.60	3.68	3.66	3.64
33	CE	35%	3.76	3.74	3.72	3.75	3.73	3.71

Figure 5 indicates that the value of EGT decreased with the increase of percentage of methanol induction in both versions of the engine. At the recommended injection timing, the magnitude of EGT was lower in CE with 35% induction of methanol induction at all loads when compared with standard diesel engine. Lower exhaust gas temperatures were observed in the LHR engine with 60% methanol induction when compared with CE with 35% methanol induction. This showed that the performance of the LHR engine improved with 60% methanol induction over CE with 35% methanol induction. EGT further decreased, when the injection timings were advanced in both versions of the engine. This was due to increase of thermal efficiency and decrease of gas temperatures.

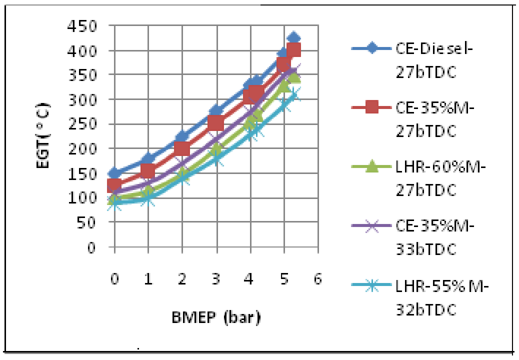


Fig. 5. Variation of EGT with BMEP with maximum percentage of methanol (M) induction in CE and LHR engine at recommended and optimum injection timings

Table 4. Comparative data on Exhaust gas temperature (EGT) at peak load operation

IT	Engine Version	Alcohol induction on mass basis	Exhaust gas temperature at peak load operation (^{o}C)					
			Methanol			Ethanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
		0%	425	410	395	425	410	395
27	CE	35%	400	375	350	375	350	325
		40%	--	--	320	--	--	300
	LHR	60%	350	325	300	360	340	320
32	LHR	55%	310	290	270	320	300	280
33	CE	35%	360	340	320	340	320	300

From Table 4, it is observed that the value of EGT is higher in CE while it is lower in LHR engine with methanol operation in comparison with ethanol operation at peak load. This is due to improved air fuel ratios with which gas temperatures decreased. This once again established the fact that the performance of CE improved with ethanol operation and methanol operation improved the performance of LHR engine. The value of EGT decreased marginally with increase of injection pressure in both versions of the engine. This is due to improved air fuel ratios with increase of injection pressure.

From Figure 6, it is observed that Coolant load increased with increase of BMEP in both versions of the engine at recommended and optimized injection timings. This is due to increase of gas temperatures. Coolant load was less in both versions of the engine at different percentages of methanol induction at all loads when compared with pure diesel operation on CE. This was due to the reduction of gas temperatures with methanol induction. Cooling load was less in the LHR engine with 60% methanol induction when compared with CE with 35% methanol induction at all loads. This was due to the insulation provided in LHR engine.

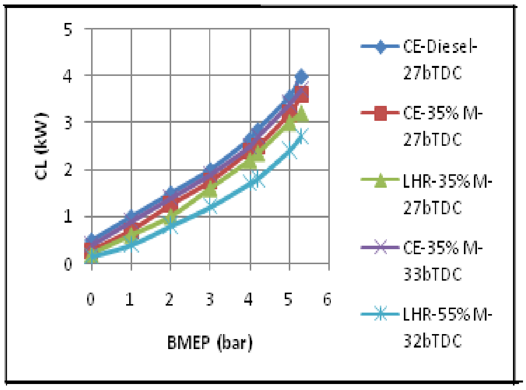


Fig. 6. Variation of CL with BMEP with maximum percentage of methanol (M) induction in CE and LHR engine at recommended and optimum injection timings

Cooling load decreased in both version of the engine with the advancing of injection timing and increase of injection pressure. This was due to decrease of gas temperatures.

From Table 5, it is noticed that coolant load is marginally higher with ethanol operation in comparison with methanol operation in both versions of the engine. Methanol has high latent heat of evaporation and hence it absorbs temperature from surroundings leading to decrease gas temperature and hence coolant decreases for methanol operation. Coolant load decreased marginally with increase of injection pressure in both versions of the engine with alcohol operation. This is due to improved air fuel ratios with which gas temperatures decreased and hence coolant load.

Table 5. Comparative data on Coolant Load (CL) at peak load operation

IT	Engine Version	Alcohol induction on mass basis	Coolant Load (CL) at peak load operation					
			Methanol			Ethanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
		0%	4.0	3.8	3.6	4.0	3.8	3.6
27	CE	35%	3.6	3.4	3.2	3.7	3.5	3.3
		40%	--	--	3.0	--	--	3.1
	LHR	60%	3.2	3.0	2.8	3.4	3.2	3.0
32	LHR	55%	2.7	2.5	2.3	2.9	2.7	2.5
33	CE	35%	3.7	3.5	3.3	3.9	3.7	3.5

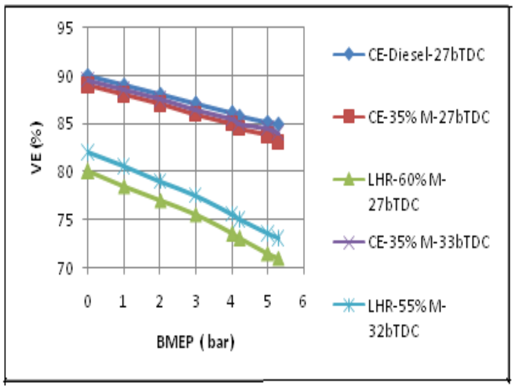


Fig. 7. Variation of VE with BMEP with maximum percentage of methanol (M) induction in CE and LHR engine at recommended and optimum injection timings

However, CE with different percentage of methanol induction showed higher volumetric efficiency when compared with LHR engine. This was because of increase of temperatures of insulated components in LHR engine, which heat the incoming charge to high temperatures and consequently the mass of air inducted in each cycle was lower. VE increased marginally with the increase of injection pressure in both versions of the engine. This was due to improvement of air utilization and combustion with the increase of injection pressure. However, these variations were very small. From Table 6, it is evident that VE was higher with methanol operation in comparison with ethanol operation in both versions of the engine. This was due to decrease of gas temperatures because of high latent heat of evaporation of methanol. VE increased marginally with increase of injection pressure in both versions of the engine with alcohol operation. This was due to improved spray characteristics and reduction of deposits.

Table 6. Comparative data on Volumetric efficiency (VE) at peak load operation

IT	Engine Version	Alcohol induction on mass basis	Volumetric efficiency (VE) at peak load operation (%)					
			Methanol			Ethanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
		0%	85	86	87	85	86	87
27	CE	35%	83	84	85	82	83	84
		40%	--	--	84	--	--	83
	LHR	60%	71	72	73	70	71	72
32	LHR	55%	73	74	75	72	73	74
33	CE	35%	84	85	86	83	84	85

3.2. Exhaust Emissions

Figure 8 indicates that for the same load, the smoke density decreased with induction of alcohol.

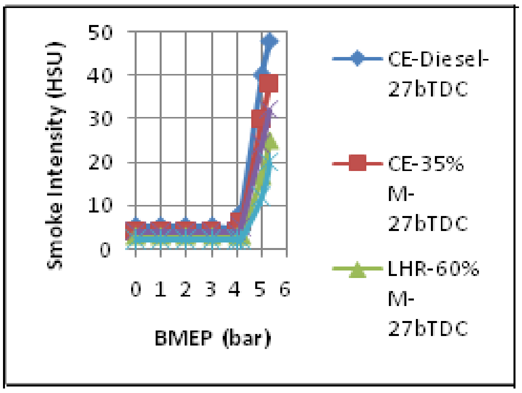


Fig. 8. Variation of smoke intensity in Hartridge smoke unit (HSU) with BMEP with maximum percentage of methanol (M) induction in CE and LHR engine at recommended and optimum injection timings

The combustion of injected fuel in case of pure vegetable oil operation is predominantly one of oxidation of products of destructive decomposition. In this case, there are greater chances of fuel cracking and forming carbon particles. On the other hand, the combustion of alcohol is predominantly a process of hydroxylation and the chances of fuel cracking are negligible. 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 is 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 magnitudes 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 7, 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.

Table 7. Comparative data on Smoke levels at peak load operation

IT	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
		0%	48	38	34	48	38	34
27	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

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).

From Figure 9 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 temperatures.

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.

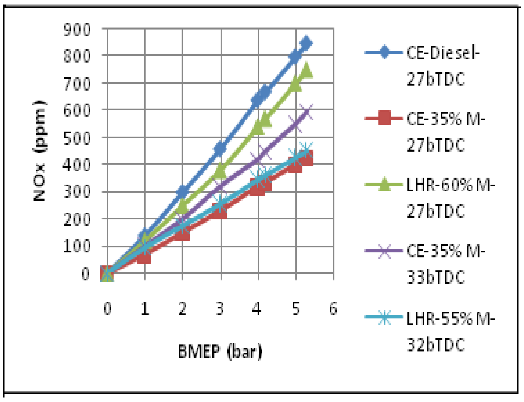


Fig. 9. Variation of NOx levels with BMEP with maximum percentage of methanol (M) induction in CE and LHR engine at recommended and optimum injection timings

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 8. 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.

Table 8. Comparative data on NOx levels at peak load operation

IT	Engine Version	Alcohol induction on mass basis	NOx levels at peak load operation (ppm)					
			Methanol			Ethanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
		0%	850	800	750	850	800	750
27	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

These 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 9, that formaldehyde emissions were low with pure diesel operation in both CE and LHR engine.

Table 9. Comparative data on Formaldehyde (% concentration) at peak load operation

IT	Engine Version	Alcohol induction on mass basis	Formaldehyde (% concentration) at peak load operation					
			Methanol			Ethanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
		0%	9.0	8.1	6.9	9.0	8.1	6.9
27	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

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. 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 performance in LHR engine by reducing the intermediate compounds like formaldehydes. Table 10 followed the similar trend with Table 9. However, acetaldehyde emissions were higher with ethanol operation in comparison with methanol operation.

Table 10. Comparative data on Acetaldehyde (% concentration) at peak load operation

IT	Engine Version	Alcohol induction on mass basis	Acetaldehyde (% concentration) at peak load operation					
			Methanol			Ethanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
		0%	7	6	4.9	7	6	4.9
27	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

3.3. Combustion Characteristics

From Table 11, it is noticed that the magnitude of PP increased with increase of methanol induction in both versions of the engine. The magnitude of PP increased with advancing of the injection timing in both versions of the engine, with methanol induction. With maximum induction of methanol, LHR engine at 32°bTDC produced higher PP compared with CE at 33°bTDC.

Table 11. Comparative data on Peak Pressure at peak load operation

IT	Engine Version	Alcohol induction on mass basis	Peak Pressure (bar)at peak load operation					
			Methanol			Ethanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
		0%	50.4	51.7	53.5	50.4	51.7	53.5
27	CE	35%	52.6	53.7	54.8	53.6	54.7	55.8
		40%	--	--	56.4	--	--	57.6
	LHR	60%	72.2	73.5	74.6	70.2	71.3	72.4
32	LHR	55%	78.4	79.7	80.1	75.6	76.3	77.5
33	CE	35%	60.2	61.2	62.2	64	65.1	66.2

PP was lower with methanol induction in CE, while it was higher in LHR engine in comparison with ethanol induction. This once again proved that CE with ethanol induction improved the performance while LHR engine with methanol induction showed higher performance. PP increased with increase of injection pressure in both versions of the engine with alcohol operation. This was due to improved air fuel ratios.

From the Table 12, it is observed that the value of TOPP decreased with the increase of methanol induction with both versions of the engine. When the methanol induction is increased to 60% in LHR engine, the magnitude of TOPP is lower (shifted towards TDC) when compared with CE with 35% methanol induction. This was once again confirmed by the observation of higher PP and lower TOPP in LHR engine with dual fuel mode, that the performance of LHR engine with 60% methanol induction was improved over CE with 35% methanol induction. The value of TOPP decreased with advancing of the injection timing with both versions of the engine. Similar trends were observed with ethanol operation. TOPP decreased with increase of injection pressure in both versions of the engine with alcohol induction. This was due to improved air fuel ratios.

Table 12. Comparative data on Time of Occurrence of Peak Pressure (TOPP) at peak load operation

IT	Engine Version	Alcohol induction on mass basis	TOPP (deg)at peak load operation					
			Methanol			Ethanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
		0%	9	9	8	9	9	8
27	CE	35%	8	8	7	8	7	6
		40%	--	--	7	--	--	6
	LHR	60%	7	7	6	7	7	6
32	LHR	55%	6	6	6	6	6	6
33	CE	35%	7	7	7	7	7	7

From the Table 13, it is evident that MRPR increased with increase of methanol induction. This was due to increase of ignition delay. MRPR followed the similar trends of PP. These combustion characteristics improved with increase of injection pressure.

Table 13. Comparative data on Maximum Rate of Pressure Rise (MRPR) at peak load operation

IT	Engine Version	Alcohol induction on mass basis	MRPR (bar/deg) at peak load operation					
			Methanol			Ethanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
		0%	3.1	3.3	3.4	3.1	3.3	3.4
27	CE	35%	3.8	4.0	4.2	4.0	4.2	4.4
		40%			4.6			4.8
	LHR	60%	4.8	4.8	5.1	4.6	4.8	5.0
32	LHR	55%	5.4	5.6	5.8	4.9	5.1	5.3
33	CE	35%	4.2	4.4	4.6	4.4	4.6	4.8

4. Conclusion

Maximum induction of alcohol was 35% on mass basis with best possible efficiency at all loads in CE while it was 60% in the LHR engine. LHR engine with 60% methanol induction showed improved performance when compared to CE with 35% methanol induction. Increase of injection pressure from 190 bar to 270 bar increased the amount of alcohol induction in CE from 35% to 40% while methanol induction remained same in the LHR engine. The maximum induction of alcohol was 35% in CE at 33^{o}bTDC, while it was 55% in LHR engine at 32^{o}bTDC. BTE increased in both versions of the engine with maximum induction of methanol when the injection timings were advanced and with the increase of injection pressure. Volumetric efficiency decreased with the induction of methanol in both versions of the engine, when compared to the pure diesel operation on the CE. LHR engine showed lower volumetric efficiency when compared with CE with methanol operation. Volumetric efficiencies increased marginally in both versions of the engine, when the injection timings were advanced and injection pressures increased. Smoke levels decreased with methanol induction when compared with pure diesel operation on CE. 35% induction of methanol in CE showed the reduction of 21% smoke levels while the LHR engine with 60% methanol induction recorded 48% reduction of smoke levels when compared with pure diesel operation on CE. Smoke levels decreased in CE and LHR engines with maximum induction of alcohol when the injection timings were advanced to 33^{o}bTDC with CE and 32^{o}bTDC with the LHR engine at increased injection pressure. NOx levels decreased with methanol induction in both versions of the engine. CE with 35% methanol induction showed 50% reduction of NOx levels, while LHR engine with 60% methanol induction recorded 12% reduction of NOx levels when compared with pure diesel operation on CE. With maximum methanol induction at 190 bars, NOx levels decreased by 30% in CE while they decreased by 47% in LHR engine when the injection timings were advanced to 33^{o}bTDC with CE and 32^{o}bTDC with LHR engine, when compared to same configurations of the engine at 27^{o}bTDC. Aldehyde emissions increased with the induction of methanol in both versions of the engine. Aldehyde emissions decreased with increase of injection pressure and with advanced injection timings with CE and LHR engine. All combustion characteristics are within the limits for alcohol induction in both versions of the engine. Increase of peak pressures, decrease of TOPP and marginal increase of MRPR are observed with the methanol induction in both versions of the engine. All combustion characteristics were improved with the increase of injection pressure and at the advanced injection timings in both versions of the engine.

Ethanol operation followed similar trends with methanol operation. However, CE with ethanol operation and LHR engine with methanol operation showed improved performance. Methanol operation on both versions of the engine decreased pollution levels of smoke and NOx levels higher than ethanol operation.

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