Performance, Exhaust Emissions and Combustion Characteristics of Mohr Oil in Crude Form and Biodiesel Form in A Medium Grade Low Heat Rejection Diesel Engine

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Abstract:-Investigations were carried out to evaluate the performance of mohr oil in crude form and biodiesel form at different operating conditions [normal temperature and pre-heated temperature] in a medium grade low heat rejection (LHR) diesel engine with air gap insulated piston with superni (an alloy of nickel) crown and air gap insulated liner with superni insert with varied injection pressure and injection timing. **Study Design**: Performance parameters and exhaust emissions of smoke and oxides of nitrogen (NOx) were determined at different values of brake mean effective pressure (BMEP). Combustion characteristics were recorded at peak load operation of the engine. Combustion parameters were measured with TDC (top dead centre) encoder, pressure transducer, console and special pressure-crank angle software package. Conventional engine (CE) showed compatible performance with biodiesel operation, while LHR engine showed improved performance at recommended injection timing of 27°bTDC (before top dead centre) and recommended injection pressure of 190 bar. The performance of both version of the engine improved with advanced injection timing and at higher injection pressure with crude vegetable oil and biodiesel when compared with CE with pure diesel operation. The optimum injection timing was 31°bTDC for CE while it was 30°bTDC with LHR engine with biodiesel operation. Peak brake thermal efficiency increased by 12.5%, smoke levels decreased by 38% and NOx levels increased by 35% with biodiesel operation on LHR engine at its optimum injection timing, when compared with pure diesel operation on CE at 27°bTDC.

Key words: Crude Mohr oil, Esterification, LHR engine, Performance, Emissions, Combustion characteristics.

I. INTRODUCTION

The search for alternate fuels for internal combustion engines like petrol engine and diesel engine is necessary as these fossil fuels are depleting and also pollution levels with these fuels are increasing. Usage of diesel is heavy as it is being consumed in agricultural and transport sector and hence substitution of alternate fuel calls for immediate attention. Alcohol and vegetable oils are probable substitutes for diesel fuel. Although alcohol has good volatility, it has low cetane number and hence engine modification is necessary if alcohol is used as fuel in diesel engine. That too, most of the alcohol produced in India is diverted for Petro-chemical industries. On the other hand, vegetable oil is a renewable and can be easily produced. It has properties similar to those of diesel fuel. When Rudolf Diesel [1] first invented the diesel engine, about a century ago, he demonstrated the principle by employing peanut oil and hinted that vegetable oil would be the future fuel in diesel engine. Several researchers [2-6] experimented the use of vegetable oils as fuels on conventional engines (CE) and reported that the performance was poor, citing the problems of high viscosity and low volatility. Higher viscosity and chemical composition of unprocessed oils and fats have been shown [7] 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 above problems can be solved once vegetable oil is converted into biodiesel. Biodiesels 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 [8-11] with biodiesel on CE and reported performance was compatible with pure diesel operation on CE. The internal combustion engines that presently depend on fossil fuels need to be redesigned and optimized for greater efficiencies and lower emissions. The drawbacks of the biodiesel call for hot combustion chamber provided by low heat rejection (LHR) diesel engine. The concept of LHR engine is to provide thermal insulation in the path of heat flow to the coolant and increase thermal efficiency of the engine. LHR engines are classified into low grade, medium grade and high grade engines depending on degree of insulation. Low grade engines consist of thermal coatings on piston, liner, cylinder head and other engine components, medium grade engines provide an air gap in the piston and other components with low-thermal conductivity materials like superni, cast iron and mild steel etc and high grade engines are combination of low and medium grade engines. Ceramic coatings provided adequate insulation and improved marginally thermal efficiency with pure diesel operation [12-14] and biodiesel operation [15-17]. However, peeling of coating was reported by these researchers. Investigations were carried out [18] on LHR engine with air gap insulated piston with superni crown with varied injection timing with pure diesel operation and reported improvement in brake specific fuel consumption with advanced injection timing. Experiments were conducted on medium grade LHR engine with air gap insulated piston with superni crown and air gap insulated liner with superni insert with varied injection timing and injection pressure with vegetable oil operation [19-21] and biodiesel operation [22] and reported that LHR engine improved the performance and decreased smoke levels and increased NOx levels. Studies were made on LHR engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head with vegetable oils [23-25] and biodiesel [26] with varied injection timing and pressure and reported high grade LHR engine improved thermal efficiency and decreased pollution levels.

Little literature was available in evaluating the performance of LHR engine with air gap insulated piston and air gap insulated liner with varying engine parameters at different operating conditions of the Mohr oil in crude form and biodiesel form.

The present paper attempted to evaluate the performance of LHR engine, which contained an air gap insulated piston and air gap insulated liner at different operating conditions of crude Mohr oil and Mohr oil based biodiesel with varied injection timing and injection pressure and compared with one over the another and also with CE with pure diesel operation at recommended injection timing and injection pressure.

## II.   MATERIALS AND METHODS

The term esterification means conversion of one ester into the other. In the present case glycerol was replaced with methyl alcohol, the fatty acids remaining the same. The chemical conversion reduced viscosity four fold. As it is evident glycerol was the byproduct of the reaction and a valuable commercial commodity. The process[19] of converting the oil into methyl esters was carried out by heating the crude vegetable oil with the methanol in the presence of the catalyst (Sodium hydroxide). In the present case, crude vegetable oil (Mohr oil) was stirred with methanol at around   60-70°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 separates 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 biodiesel esters. The esters were used in present study. The properties of crude vegetable oil, biodiesel were given in Table-1 along with diesel fuel.

Table.I: Properties of the 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 mohr oil (CMO)	120	0.91	45	38000
Bio-diesel (MOBD)	53	0.87	55	37500

The LHR diesel engine contained a two-part piston - the top crown made of low thermal conductivity material, superni-90 was 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 for better 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 was maintained between the insert and the liner body. Experimental setup used for the investigations of LHR diesel engine with crude vegetable oil and biodiesel was shown in Figure .1. CE had an aluminum alloy piston with a bore of 80-mm and a stroke of 110-mm. The rated output of the engine was 3.68 kW at a speed of 1500 rpm. The compression ratio was 16:1 and manufacturer's recommended injection timing and injection pressures were 27°bTDC and 190 bar respectively.

The fuel injector had 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. Burette method was used for determining fuel consumption of the engine. Air-consumption of the engine was measured by air-box method.
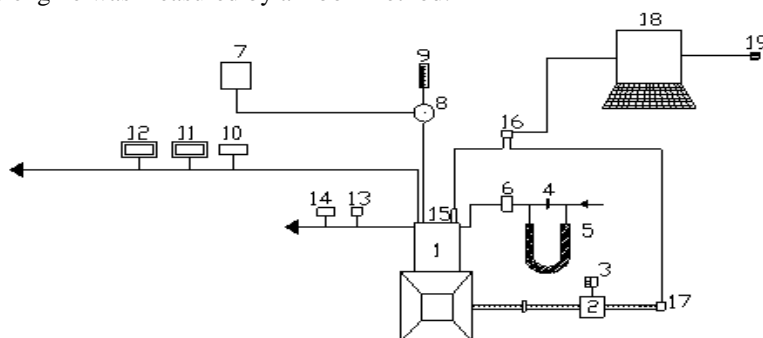
1.Engine, 2.Electical Dynamo meter, 3.Load Box, 4.Orifice meter, 5.U-tube water manometer, 6.Air box, 7.Fuel tank, 8, Pre-heater, 9.Burette, 10. Exhaust gas temperature indicator, 11.AVL Smoke meter, 12.Netel Chromatograph NOx Analyzer, 13.Outlet jacket water temperature indicator, 14. Outlet-jacket 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. 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. The exhaust emissions of smoke and NO_x were recorded by AVL smoke meter and Netel Chromatograph NOx analyzer respectively at various values of BMEP 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-θ 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. Pressure-crank angle diagram was obtained on the screen of the personal computer. The accuracy of the instrumentation was 0.1%. Biodiesel was heated to a temperature (Pre-heated temperature) where its viscosity was matched to that of diesel fuel. The test fuels used in the experimentation were pure diesel, crude vegetable oil and mohr oil based biodiesel. The various configurations used in the experimentation were CE and LHR. The different operating conditions of biodiesel were normal temperature (NT) and preheated temperature (PT).

III.   RESULTS AND DISCUSSION

A. *Performance Parameters*

From the Fig. 2, it was noticed that CE with biodiesel showed compatible performance for entire load range when compared with the pure diesel operation on CE at recommended injection timing. This was due to lower calorific value and higher viscosity of the biodiesel.
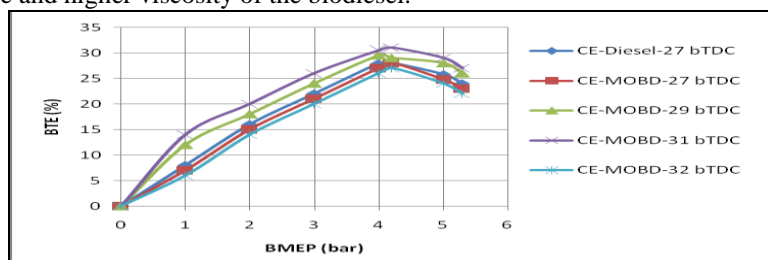

Fig.2: Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in conventional engine (CE) at different injection timings with Mohr oil based biodiesel (MOBD) oil operation at an injection pressure of 190 bar.

BTE increased with the advancing of the injection timing in CE with the biodiesel at all loads, when compared with CE at the recommended injection timing and pressure. This was due to initiation of combustion at earlier period and efficient combustion with increase of air entrainment in fuel spray giving higher BTE. BTE increased at all loads when the injection timing was advanced to 31°bTDC in the CE at the normal temperature of biodiesel. The increase of BTE at optimum injection timing over the recommended injection timing with biodiesel with CE could be attributed to its longer ignition delay and combustion duration. BTE increased at all loads when the injection timing was advanced to 31°bTDC in CE, at the preheated temperature of MOBD. The performance improved further in CE with the preheated biodiesel for entire load range when compared with normal biodiesel. Preheating of the biodiesel reduced the viscosity, which improved the spray characteristics of the biodiesel and reduced the impingement of the fuel spray on combustion chamber walls, causing efficient combustion thus improving BTE.

Curves from Fig.3 indicate that CE operated with crude Mohr oil (CMO) showed deteriorated performance for the for entire load range when compared with the pure diesel operation on CE at recommended injection timing. This was due to higher viscosity and accumulation of carbon on nozzle tip with CMO. BTE increased with the advancing of the injection timing with CE with crude vegetable oil at all loads, when compared with CE at the recommended injection timing and pressure. Crude vegetable oil has loner duration of combustion and longer ignition delay. Hence advancing of injection timing helped the initiation of combustion, when the piston was at TDC. BTE increased at all loads when the injection timing was advanced to 30°bTDC in the CE at the normal temperature of CMO.
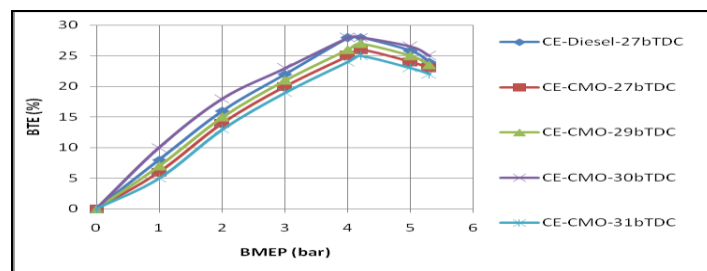

Fig.3: Variation of BTE with BMEP in CE at different injection timings with crude vegetable oil (CMO) operation

From the Fig. 4, it was observed that LHR version of the engine showed improvement in the performance for entire load range compared with CE with pure diesel operation.
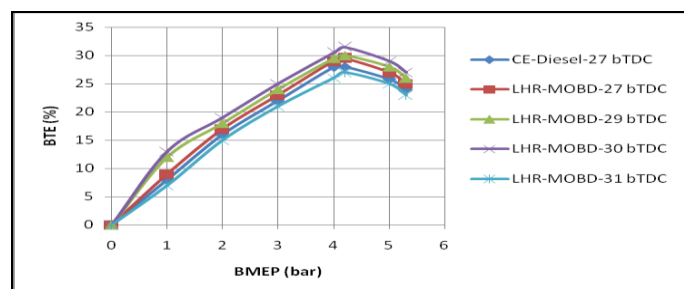

Fig.4: Variation of BTE with BMEP in LHR engine at different injection timings with biodiesel (MOBD) operation.

High cylinder temperatures helped in better evaporation and faster combustion of the fuel injected into the combustion chamber. Reduction of ignition delay of the biodiesel in the hot environment of the LHR engine improved heat release rates and efficient energy utilization. Preheating of biodiesel improved performance further in LHR version of the engine. The optimum injection timing was found to be 30°bTDC with LHR engine with normal MOBD. Since the hot combustion chamber of LHR engine reduced ignition delay and combustion duration and hence the optimum injection timing was obtained earlier with LHR engine when compared with CE with the biodiesel operation.

Curves from Fig. 5 indicate that the BTE increased up to 80% of the full load and beyond that load it decreased in LHR version of the engine at different injection timings as it was noticed with CE. This was due to conversion of fuel efficiency up to 80% of peak load and beyond this load the performance deteriorated due to increase of friction power. LHR version of engine with crude vegetable oil operation at recommended injection

timing showed improvement in the performance for the entire load range compared with CE with pure diesel. High cylinder temperatures helped in better evaporation and faster combustion of the fuel injected into the combustion chamber. Reduction of ignition delay of the crude vegetable oil in the hot environment of the LHR engine improved heat release rates and efficient energy utilization. The optimum injection timing was found to be 29°bTDC with LHR engine with crude vegetable oil. Further advancing of the injection timing resulted in decrease in thermal efficiency due to longer ignition delay. Hence it was concluded that the optimized performance of the LHR engine was achieved at an injection timing of 29°bTDC.Since the hot combustion chamber of LHR engine reduced ignition delay and combustion duration and hence the optimum injection timing was obtained earlier with LHR engine when compared with CE with the crude vegetable oil operation.
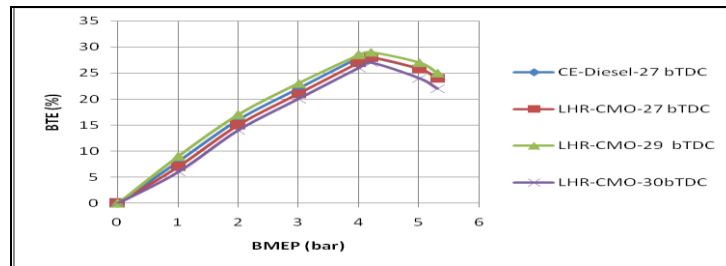

Fig. 5:.Variation of BTE with BMEP in LHR engine at different injection timings with crude vegetable oil (CMO) operation.

Injection pressure was varied from 190 bars to 270 bars to improve the spray characteristics and atomization of the biodiesel and injection timing was advanced from 27 to 34°bTDC for CE and LHR engine. From Table-2, it was evident that peak BTE increased with increase in injection pressure in both versions of the engine at different operating conditions of the biodiesel. The improvement in BTE at higher injection pressure was due to improved fuel spray characteristics. However, the optimum injection timing was not varied even at higher injection pressure with LHR engine, unlike the CE. Hence it was concluded that the optimum injection timing was 31°bTDC at 190 bar, 30°bTDC at 230 bar and 29°bTDC at 270 bar for CE. The optimum injection timing for LHR engine was 30°bTDC irrespective of injection pressure. Peak BTE was higher in LHR engine when compared with CE with different operating conditions of the biodiesel. Similar trends were observed with crude vegetable oil also. Optimum injection timing was 30°bTDC at 190 bar, 29°bTDC at 230 bar and 28°bTDC at 270 bar for CE with crude vegetable oil operation. The optimum injection timing for LHR engine was 29°bTDC irrespective of injection pressure with crude vegetable oil operation. Since cetane number was higher with biodiesel, it permitted more injection advance than crude vegetable oil operation. Peak BTE was higher with biodiesel operation on both versions of the engine at different operating conditions than crude vegetable oil operation. This was due to efficient combustion with improved cetane rating of biodiesel.

Table.II: Data of peak BTE

Injection Timing (°bTDC)	Test Fuel	Peak BTE (%) Conventional Engine (CE) Injection Pressure (Bar)						LHR Engine Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	28	--	29	---	30	--	29	--	30	--	30.5	--
	CMO	26	27	27	28	28	29	28	29	29	30	30	31
	MOBD	28	29	29	30	30	31	29.5	30	30	30.5	30.5	31
29	CMO	27	28	28	29	27	28	29	30	30	31	31	32
30	CMO	28	29	27	28	26	27	--	--	--	--	--	--
	MOBD	29.5	30	30	30.5	30.5	31	31.5	32	32	32.5	32.5	33
31	MOBD	31	31.5	31.5	32	32	32.5	--	--	--	--	--	--

DF-Diesel Fuel, CMO-Crude mohr oil, MOBD- Mohr oil based bio-diesel, NT- Normal or Room Temperature , PT- Preheat Temperature

From Table 3, it was noticed that the performance improved in both versions of the engine with the preheated biodiesel at peak load operation when compared with normal biodiesel. Preheating of the biodiesel reduced the viscosity, which improved the spray characteristics of the oil. Brake specific energy consumption (BSEC) at peak load operation decreased with the advanced injection timing and increase of injection pressure with both versions of the engine with different operating conditions of crude vegetable oil and biodiesel. This was due to initiation of combustion at earlier period and efficient combustion with the increase of air entrainment in fuel spray giving lower BSEC. BSEC was found to be lower with biodiesel operation on both versions of the engine

in comparison with crude vegetable oil at different operating conditions. This was increase of mass flow rate of fuel with biodiesel operation which gave lower BSEC.

Table III: Data of BSEC at peak load operation

Injection Timing (° bTDC)	Test Fuel	Brake Specific Energy (BSEC) at peak load operation (kW/kW)											
		Conventional Engine (CE)						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	4.0	--	3.96	--	3.92	--	4.1	--	3.8	--	3.7	--
	CMO	4.62	4.2	4.2	3.98	3.98	3.94	3.96	3.92	3.92	3.88	3.88	3.84
	MOBD	3.96	3.92	3.92	3.88	3.88	3.84	3.88	3.84	3.84	3.80	3.80	3.76
29	CMO	4.4	4.0	4.0	3.96	3.96	3.92	3.90	3.86	3.86	3.82	3.82	3.78
30	CMO	4.0	3.96	4.2	3.98	3.98	3.94	-	--	--	--	--	--
	MOBD	3.84	3.80	3.80	3.76	3.82	3.78	3.78	3.74	3.74	3.70	3.70	3.66
31	MOBD	3.80	3.76	3.82	3.78	3.84	3.80	--	--	--	--	--	--

From the Fig. 6, it was noticed that CE with MOBD at the recommended injection timing recorded marginally higher EGT at all loads compared with CE with pure diesel operation. Lower heat release rates and retarded heat release associated with high specific energy consumption caused increase in EGT in CE. Ignition delay in the CE with different operating conditions of biodiesel increased the duration of the burning phase.
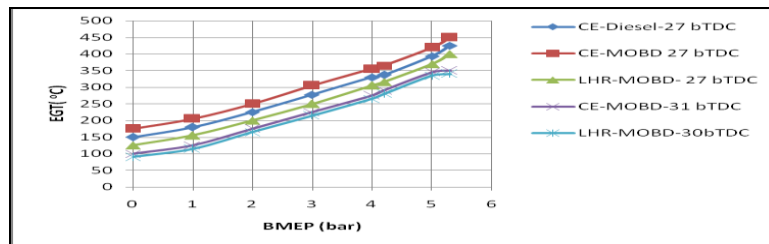

Fig.6: Variation of exhaust gas temperature (EGT) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel (MOBD) operation.

LHR engine recorded lower value of EGT when compared with CE with biodiesel operation. This was due to reduction of ignition delay in the hot environment with the provision of the insulation in the LHR engine, which caused the gases expanded in the cylinder giving higher work output and lower heat rejection. This showed that the performance improved with LHR engine over CE with biodiesel operation. The magnitude of EGT at peak load decreased with advancing of injection timing and with increase of injection pressure in both versions of the engine with biodiesel. Preheating of the biodiesel further reduced the magnitude of EGT, compared with normal biodiesel in both versions of the engine.

From the Table-4 it was noticed that EGT decreased with increase in injection pressure and injection timing with both versions of the engine, which confirmed that performance increased with increase of injection pressure. Preheating of biodiesel decreased EGT in both versions of the engine. Similar trends were observed with crude vegetable oil operation. However, crude vegetable oil gave higher EGT than biodiesel operation on both versions of the engine at different operating conditions. This was due to more heat rejection as thermal efficiency with crude vegetable oil was lower than biodiesel operation.

Table.IV: Data of EGT at peak load operation

Injection Timing (° bTDC)	Test Fuel	Peak BTE (%)											
		Conventional Engine (CE)						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	28	--	29	---	30	--	29	--	30	--	30.5	--
	CMO	26	27	27	28	28	29	28	29	29	30	30	31
	MOBD	28	29	29	30	30	31	29.5	30	30	30.5	30.5	31
29	CMO	27	28	28	29	27	28	29	30	30	31	31	32
30	CMO	28	29	27	28	26	27	--	--	--	--	--	--
	MOBD	29.5	30	30	30.5	30.5	31	31.5	32	32	32.5	32.5	33
31	MOBD	31	31.5	31.5	32	32	32.5	--	--	--	--	--	--

From Fig.7, it was noticed that volumetric efficiency (VE) decreased with an increase of BMEP in both versions of the engine with test fuels. This was due to increase of gas temperature with the load. At the recommended

injection timing, VE in the both versions of the engine with biodiesel operation decreased at all loads when compared with CE with pure diesel operation. This was due to increase of deposits with biodiesel operation with CE. With LHR engine, this was due increase of temperature of incoming charge in the hot environment created with the provision of insulation, causing reduction in the density and hence the quantity of air with LHR engine.VE increased marginally in CE and LHR engine at optimized injection timings when compared with recommended injection timing with biodiesel. This was due to decrease of un-burnt fuel fraction in the cylinder leading to increase in VE in CE and reduction of gas temperatures with LHR engine. VE decreased relatively by 6.5% with LHR engine at its optimized injection timing when compared with pure diesel operation on CE.
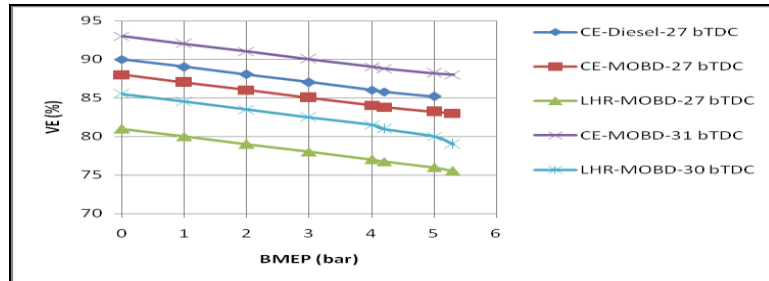

Fig.7: Variation of volumetric efficiency (VE) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel (MOBD) operation at an injection pressure of 190 bar.

From Table 5, it was clear that VE increased with increase of injection pressure and with advanced injection timing in both versions of the engine with crude vegetable oil and biodiesel.

Table.V: Data of VE at peak load operation

Injection timing (bTDC)	Test Fuel	Volumetric efficiency (%)											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	85	--	86	--	87	--	78	--	80	--	82	--
	CMO	81	82	82	83	83	84	75	76	76	77	77	78
	MOBD	83	84	84	85	85	86	75.5	76.5	76.5	77.5	77.5	78.5
29	CMO	82	83	83	84	82	81	76	77	77	78	78	79
30	CMO	83	84	82	83	81	82	--	--	-	--	--	--
	MOBD	85	86	86	87	85	86	79	79.5	79.5	80	80	81
31	MOBD	88	89	88	89	88.5	89.5	--	-	--	--	--	--

This was also due to better fuel spray characteristics and evaporation at higher injection pressures leading to marginal increase of VE. This was also due to the reduction of residual fraction of the fuel, with the increase of injection pressure. Preheating of the crude vegetable oil and biodiesel marginally improved VE in both versions of the engine, because of reduction of un-burnt fuel concentration with efficient combustion, when compared with the normal temperature of oil. Biodiesel gave marginally higher values of VE than crude vegetable oil in both versions of the engine at different operating conditions. This was due to efficient combustion with biodiesel which eliminated the accumulation of carbon deposits.

Curves from Fig. 8 indicate that that coolant load (CL) increased with BMEP in both versions of the engine with test fuels. However, CL reduced with LHR version of the engine with biodiesel operation when compared with CE with pure diesel operation.
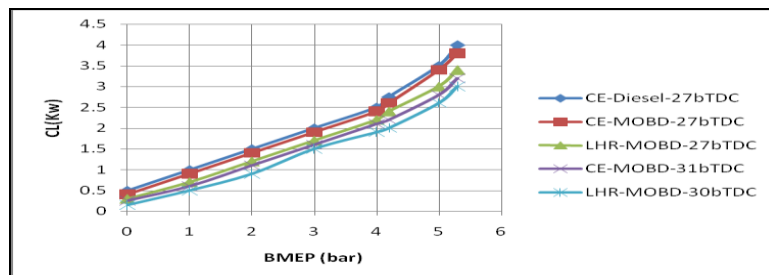

Fig.8: Variation of coolant load (CL) with BMEP in both versions of the engine at recommended and optimized injection timings with MOBD operation at an injection pressure of 190 bar.

Heat output was properly utilized and hence thermal efficiency increased and heat loss to coolant decreased with effective thermal insulation with LHR engine. However, CL increased with CE with biodiesel operation in comparison with pure diesel operation on CE. This was due to concentration of un-burnt fuel at the walls of combustion chamber. CL decreased with advanced injection timing with both versions of the engine with biodiesel operation. This was due to improved air fuel ratios and reduction of gas temperatures. From Table.6, it is noticed that CL decreased with advanced injection timing and with increase of injection pressure with test fuels.

Table VI: Data of CL at peak load operation

Injection timing (°bTDC)	Test Fuel	Coolant Load (kW) at peak load operation											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	4.0	---	3.8	--	3.6	---	4.5	---	4.3	--	4.1	---
	CMO	4.4	4.2	4.0	3.8	3.8	3.6	3.8	3.6	3.6	3.4	3.4	3.2
	MOBD	3.8	3.6	3.6	3.4	3.4	3.2	3.4	3.2	3.2	3.0	3.0	2.8
29	CMO	4.2	4.0	3.7	3.5	3.9	3.7	3.6	3.4	3.4	3.2	3.2	3.0
30	CMO	3.7	3.5	3.9	3.7	4.1	3.9	--	--	--	--	--	--
	MOBD	3.4	3.2	3.2	3.0	3.4	3.2	3.0	2.8	2.8	2.6	2.6	2.4
31	MOBD	3.2	3.0	3.4	3.2	3.6	3.4	--	--	--	--	--	--

This was because of improved combustion and proper utilization of heat energy with reduction of gas temperatures. CL decreased with preheated condition of vegetable oils in comparison with normal vegetable oils in both versions of the engine. This was because of improved spray characteristics. CL was lower with biodiesel operation than crude vegetable oil in both versions of the engine at different operating conditions. Heat rejection was lower with biodiesel operation as more amount of heat output was converted into thermal efficiency. Fig. 9 indicates at recommended injection timing, sound intensities drastically increased in CE with biodiesel operation in comparison with CE with pure diesel operation. This was due to compatible performance of biodiesel operation on CE. Moderate viscosity, poor volatility and moderate duration of combustion caused moderate combustion of biodiesel leading to generate high sound levels. LHR engine decreased sound intensity when compared with pure diesel operation on CE. This was because of hot environment in LHR engine improved combustion of biodiesel. When injection timings were advanced to optimum, sound intensities were reduced for both versions of the engine, due to early initiation of combustion.
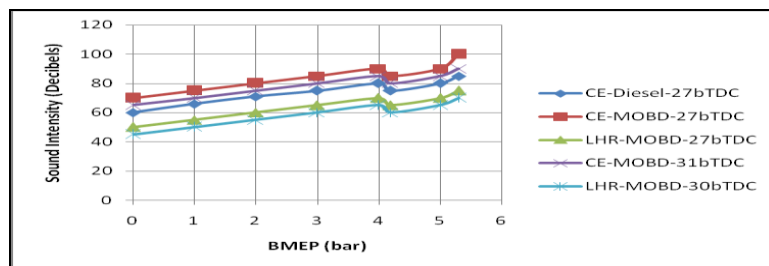

Fig.9: Variation of sound intensity with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel (MOBD) operation.

Table 7 denotes that the Sound intensity decreased with increase of injection pressure for both versions of the engine with the test fuels. This was due to improved spray characteristic of the fuel, with which there was no impingement of the fuel on the walls of the combustion chamber leading to produce efficient combustion. Sound intensities were lower at preheated condition of vegetable oils when compared with their normal condition. This was due to improved spray characteristics, decrease of density and reduction of viscosity of the fuel. Biodiesel recorded lower sound intensities than crude vegetable oil. This showed that combustion was efficient with biodiesel operation and hence lower sound intensities were produced with biodiesel operation.

Table VII: Data of sound intensity at peak load operation

Injection timing (° bTDC)	Test Fuel	Sound Intensity (Decibels) at peak load operation											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	85	--	80	--	95	--	95	--	90	--	85	--
	CMO	110	105	105	103	100	95	85	80	80	75	75	70
	MOBD	100	95	98	93	96	91	75	70	70	65	65	60
29	CMO	104	100	102	97	110	105	80	75	75	70	70	65
30	CMO	102	97	105	100	110	105	--	--	--	--	--	--
	MOBD	92	87	90	85	93	87	70	65	65	60	60	55
31	MOBD	90	85	93	88	95	88	--	--	--	--	--	-

B Exhaust Emissions

From Fig.10, it was noticed that that drastic increase of smoke levels was observed at the peak load operation in CE at different operating conditions of the biodiesel, compared with pure diesel operation on CE.
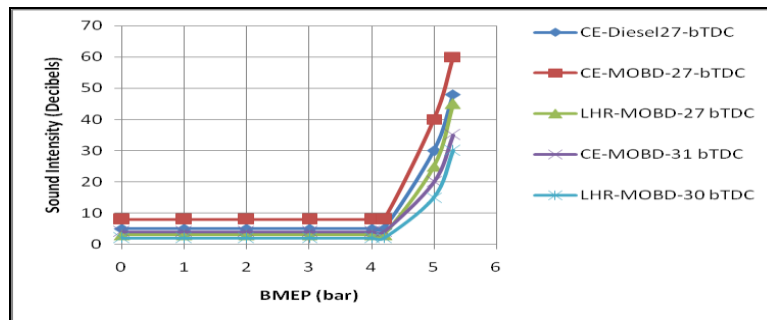

Fig.10: Variation of smoke intensity in Hartridge Smoke Unit (HSU) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel (MOBD) at an injection pressure of 190 bar.

This was due to the higher magnitude of the ratio of C/H of MOBD (0.78) when compared with pure diesel (0.45). The increase of smoke levels was also due to decrease of air-fuel ratios and VE with biodiesel compared with pure diesel operation. Smoke levels were related to the density of the fuel. Smoke levels are higher with biodiesel due to its high density. 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 biodiesel compared with the CE. Density influences the fuel injection system. Decreasing the fuel density tends to increase spray dispersion and spray penetration.

From Table-8, it was noticed that smoke levels decreased with increase of injection timings and with increase of injection pressure, in both versions of the engine, with different operating conditions of the biodiesel. Preheating of the biodiesels reduced smoke levels in both versions of the engine, when compared with normal temperature of the biodiesel. This was due to i) the reduction of density of the biodiesels, as density was directly proportional to smoke levels, ii) the reduction of the diffusion combustion proportion in CE with the preheated biodiesel, iii) the reduction of the viscosity of the biodiesel, with which the fuel spray does not impinge on the combustion chamber walls of lower temperatures rather than it directed into the combustion chamber.

Table VIII: Data of smoke levels at peak load operation

Injection timing (° bTDC)	Test Fuel	Smoke intensity (HSU)											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	48	--	38	--	34	--	55	--	50	--	45	--
	CMO	70	65	65	60	60	55	65	60	60	55	55	50
	MOBD	60	55	55	50	50	45	45	40	40	35	35	30
29	CMO	60	55	55	50	60	55	55	50	50	45	45	40
30	CMO	55	50	60	55	65	60	--	--	--	--	---	--
	MOBD	50	45	45	40	50	45	30	25	25	20	20	18
31	MOBD	35	32	40	35	42	37	-	--	--	--	--	--

This was due to improvement in the fuel spray characteristics at higher injection pressures and increase of air entrainment, at the advanced injection timings, causing lower smoke levels. Smoke levels were lower with biodiesel operation than crude vegetable oil due to its lower value of C/H, less denser, less viscous, lower molecular weight.

From Figure 11, it was noticed that NOx levels were lower in CE while they were higher in LHR engine at different operating conditions of the biodiesel at the peak load when compared with diesel operation. This was due to lower heat release rate because of high duration of combustion causing lower gas temperatures with the biodiesel operation on CE, which reduced NOx levels. Increase of combustion temperatures with the faster combustion and improved heat release rates in LHR engine caused higher NOx levels. As expected, preheating of the biodiesel decreased NOx levels in both versions of the engine when compared with the normal biodiesel. This was due to improved air fuel ratios and decrease of combustion temperatures leading to decrease NOx emissions in the CE and decrease of combustion temperatures in the LHR engine with the improvement in air-fuel ratios leading to decrease NOx levels in LHR engine.
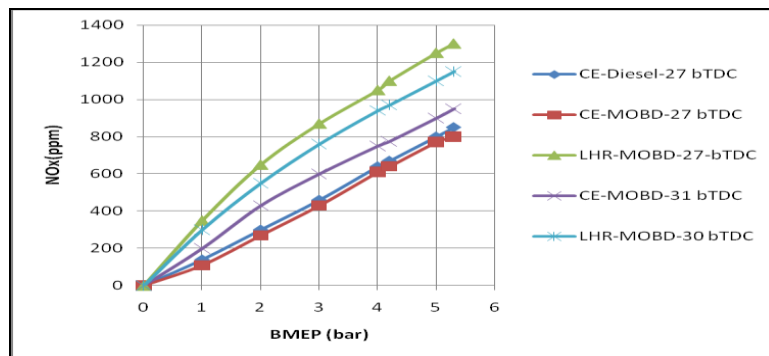

Fig.11: Variation of NOx levels with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel (MOBD) operation at an injection pressure of 190 bar.

From Table 9, it was observed that that NOx levels increased with the advancing of the injection timing in CE with different operating conditions of vegetable oil and biodiesel.

Table IX: Data of NOx levels at peak load operation

Injection timing (° bTDC)	Test Fuel	NOx levels (ppm)											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	850	----	810	----	770	---	1300	--	1280	--	1260	--
	CMO	750	700	700	650	650	600	1200	1125	1125	1050	1050	975
	MOBD	800	750	750	700	700	650	1300	1250	1250	1200	1200	1150
29	CMO	800	750	750	700	700	650	1150	1075	1075	1000	1000	925
30	CMO	850	800	800	750	750	700	--	--	--	--	--	--
	MOBD	900	850	850	800	800	750	1150	1100	1100	1050	1050	1000
31	MOBD	950	900	900	850	850	800	-	--	--	--	--	--

Residence time and availability of oxygen had increased, when the injection timing was advanced with the biodiesel operation, which caused higher NOx levels in CE. However, NOx levels decreased with increase of injection pressure in CE with vegetable oils. 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 which caused decrease of gas temperatures marginally thus leading to decrease in NOx levels. Marginal decrease of NOx levels was observed in LHR engine, due to decrease of combustion temperatures, which was evident from the fact that thermal efficiency was increased in LHR engine due to the reason sensible gas energy was converted into actual work in LHR engine, when the injection timing was advanced and with increase of injection pressure with vegetable oils. Biodiesel recorded higher NOx levels than crude vegetable oil in both versions of the engine at different operating conditions. This was due to efficient combustion with biodiesel operation causing higher combustion temperatures leading to produce higher NOx levels.

C Combustion Characteristics

From Table 10, it was observed that peak pressures were compatible in CE while they were higher in LHR engine at the recommended injection timing and pressure with biodiesel operation, when compared with pure diesel operation on CE. This was due to increase of ignition delay, as biodiesels 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 biodiesel 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 the biodiesel operation. Higher injection pressure produced smaller fuel particles with low surface to volume ratio, giving rise to higher PP. 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 produces 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 magnitude 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 biodiesels. TOPP was more with different operating conditions of biodiesels in CE, when compared with pure diesel operation on CE. This was due to higher ignition delay with the biodiesel when compared with pure diesel fuel. This once again established the fact by observing lower peak pressures and higher TOPP, that CE with biodiesel operation showed the deterioration in the performance when compared with pure diesel operation on CE. Preheating of the biodiesel showed lower TOPP, compared with biodiesel 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 biodiesel compared with the normal biodiesel. Similar observations were made with crude vegetable oil operation on both versions of the engine at different operating conditions. However, PP was higher, TOPP was lower with biodiesel operation which confirmed that performance improved with biodiesel operation than crude vegetable oil operation.

Table.10: Data of PP, MRPR, TOPP and TOMRPR at peak load operation

Injection timing (°bTDC)/ Test fuel	Engine version	PP(bar) Injection pressure (Bar)				MRPR (Bar/deg) Injection pressure (Bar)				TOPP (Deg) Injection pressure (Bar)				TOMRPR (Deg) Injection pressure (Bar)			
		190		270		190		270		190		270		190		270	
		NT	PT	NT	PT	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	--	0	0	0	0
	LHR	48.1	--	53.0	--	2.9	--	3.1	--	10	--	9	--	0	0	0	0
27/CMO	CE	46.3	47.3	48.5	49.4	2.0	2.1	2.7	2.8	11	10	11	9	1	1	1	1
	LHR	53.5	55.5	56.6	57.6	2.9	3.0	3.2	3.3	10	9	9	8	0	0	0	0
27/ MOBD	CE	48.9	50.9	51.1	52.4	2.2	2.3	2.9	3.0	11	10	11	9	1	1	1	1
	LHR	58.8	59.7	62.1	63.8	3.2	3.3	3.4	3.4	10	9	9	8	1	1	1	1
29/CMO	LHR	58.2	59.4	61.5	62.6	3.3	3.4	3.5	3.6	9	8	8	8	0	0	0	0
30/CMO	CE	49.4	50.6	52.5	53.5	3.2	3.3	3.4	3.5	10	9	--	--	1	1	1	1
30/MOBD	LHR	61.5	62.8	64.1	64.8	3.6	3.8	3.8	3.9	9	8	8	8	0	0	0	0
31/MOBD	CE	53.3	54.6	56.4	57.5	3.5	3.7	3.6	3.8	10	9	8	8	0	0	0	0

This trend of increase of MRPR and decrease of TOMRPR indicated better and faster energy substitution and utilization by vegetable oils and biodiesels, which could replace 100% diesel fuel. However, these combustion characters were within the limits hence the vegetable oils can be effectively substituted for diesel fuel.

IV.   CONCLUSIONS

Biodiesel operation at 27°bTDC on CE showed the compatible performance while crude vegetable oil showed deteriorated performance when compared with pure diesel operation on CE. LHR engine showed improved performance with biodiesel and crude vegetable oil operation when compared with pure diesel operation on CE. Preheating of the vegetable oils improved performance when compared with normal vegetable oils in both versions of the engine. Improvement in the performance was observed with the advancing of the injection timing and with the increase of injection pressure with the vegetable oils on both versions of the engine. CE with biodiesel operation showed the optimum injection timing at 31°bTDC, while the LHR engine showed the optimum injection at 30°bTDC at an injection pressure of 190 bars. CE with crude vegetable oil operation showed the optimum injection timing at 30°bTDC, while the LHR engine showed the optimum injection at 29°bTDC at an injection pressure of 190 bars. At the recommended injection timing and pressure,

biodiesel operation on CE increased smoke levels, decreased NOx levels, while LHR engine decreased smoke levels and increased NOx levels when compared with pure diesel operation on CE. Preheating of the vegetable oils decreased smoke levels and NOx levels slightly in both versions of the engine. With increase in injection pressure, smoke and NOx levels decreased in both versions of the engine with vegetable oils operation. Lower peak pressures and higher TOPP were observed with normal vegetable oils in CE. LHR engine with vegetable oils increased PP and decreased TOPP when compared with CE. Preheating increased PP and decreased TOPP when compared with normal vegetable oils operation on both versions of the engine. Compatible peak pressures were observed in CE, while higher peak pressures in the LHR engine with biodiesel operation at the recommended injection timing and pressure.

Acknowledgments

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