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

Abstract*—Experiments were carried out to evaluate the performance of a mohr oil based biodiesel (MOBD) 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. 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^{o}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 when compared with CE with pure diesel operation. The optimum injection timing was 31^{o}bTDC for CE while it was 30^{o}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^{o}bTDC.

***Index Terms*—Mohr oil, Esterification, LHR engine, Performance, Emissions, Combustion characteristics.**

I. INTRODUCTION

In the context of depletion of fossil fuels, ever increase of pollution levels with fossil fuels and increase of economic burden on developing countries like India in importing crude petroleum, the search for alternate and renewable fuels has become pertinent. Alcohol and vegetable oils are promising substitutes for diesel fuel. Through 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.

***First Author: T.Ratna Reddy**,Mechanical Engineering, , Research Scholar, Rayalaseema University. Kurnool, Andhra Pradesh, India, Mobile No +91* 9985666778.
***Second Author:**M.V.S.Murali Krishna, Mechanical Engineerug Department* chaitanya bharathi institute of technology Gandipet, Hyderabad - 500 075 *Mobile No+91* 9885517936
***Third Author** , Ch.Keseva Reddy, Mechanical Engineering Department, Mahatma Gandhi Institute of Technology, Gandipet, Andhra Pradesh, India, Phone/ Mobile No.,*+ 9177383838,*).*
***Fourth Author:** P.V.K.Murthy, Mechanical engineering Department, Jaya Prakash narayan Educational Society Group of Institutions, Mahabubnagar, Andhra Pradesh, India, And Mobile No: +919490116544,*

The U.S. Department of Energy [7] has stated that, "Raw or refined vegetable oil, or recycled greases that have not been processed into biodiesel, are not 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 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 [19-21] 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 biodiesel operation and reported that LHR engine improved the performance and decreased smoke levels and increased NOx levels. Studies were made [22-24] on LHR engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head with biodiesel 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 monr oil based biodiesel.

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 biodiesel with varied injection timing and injection pressure and compared 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^{o}C with 0.5% of NaOH based on weight of the oil, for about 3 hours. At the end of the reaction, excess methanol was removed by distillation and glycerol, which 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 biodiesel were given in Table I along with diesel fuel. 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 [18] 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.

Table I. Properties of the Test Fuels

Test Fuel	Viscosity at 25^{o}C (Centi-poise)	Density at 25^{o}C	Cetane number	Calorific value (kJ/kg)
Diesel	12.5	0.84	55	42000
Bio-diesel (MOBD)	53	0.87	55	37500

Experimental setup used for the investigations of LHR diesel engine with biodiesel was shown in Fig.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. 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

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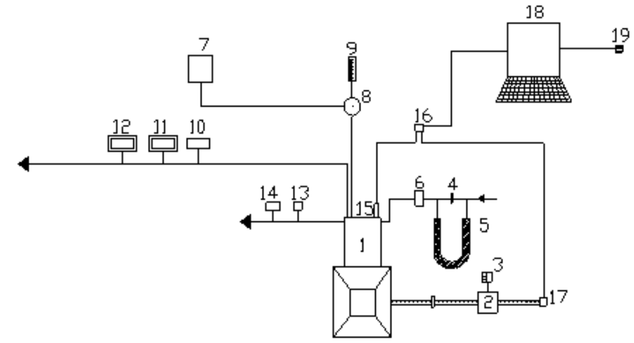
method was used for determining fuel consumption of the engine. Air-consumption of the engine was measured by air-box method.



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°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 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.

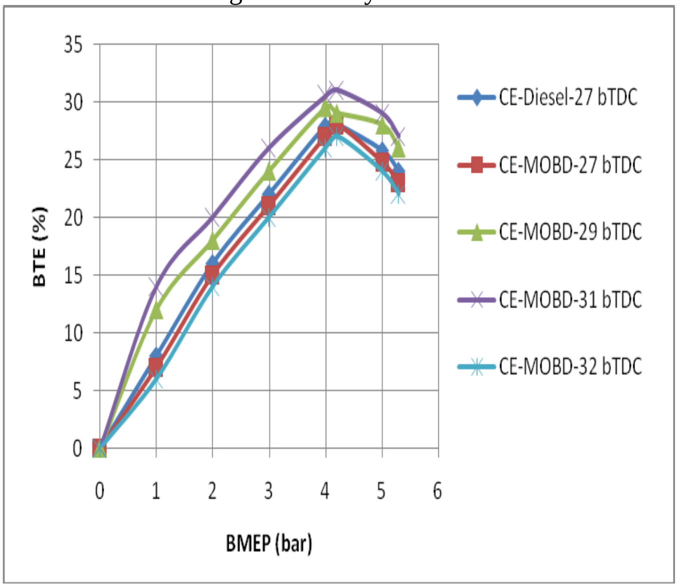


Fig.2 Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in conventional engine (CE) at different injection timings with Mohr oil based biodiesel (MOBD) oil operation at an injection pressure of 190 bar.

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.

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From the Fig. 3, 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.

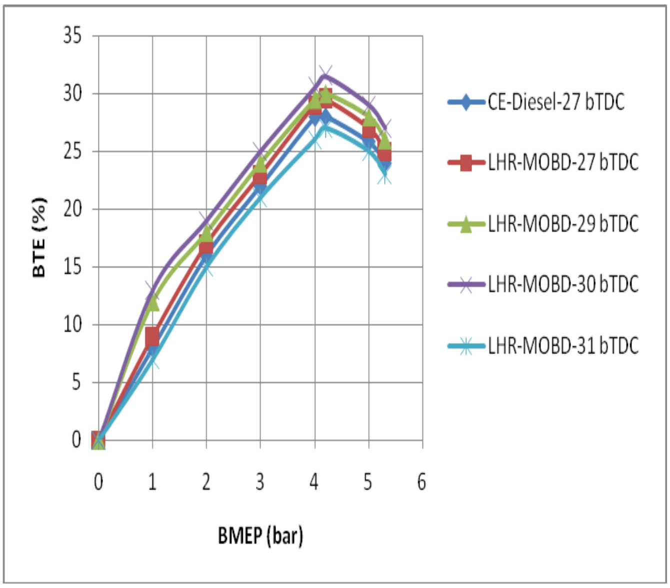

Fig.3 Variation of BTE with BMEP in LHR engine at different injection timings with biodiesel (MOBD) operation.

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.

From Fig. 4, it was observed that at optimum injection timing, BTE with LHR engine at its optimum injection timing was higher than that of CE. Decrease of combustion duration and better evaporation rates would help in increasing the efficiency of LHR engine. The advantage of LHR engine was obvious for burning high viscous biodiesel.

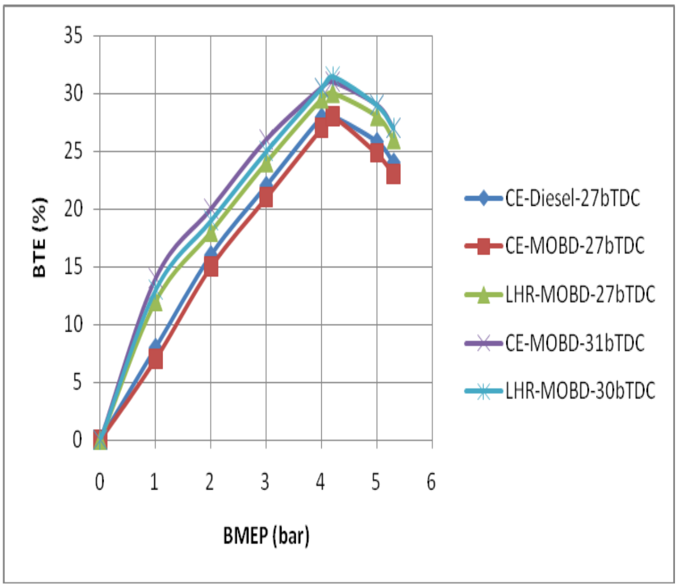

Fig.4 Variation of BTE with BMEP in different versions of the engine at the recommended injection timing and optimum injection timing at an injection pressure of 190 bar.

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.

Table II. Data of peak BTE

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	--
	MOBD	28	29	29	30	30	31	29.5	30	30	30.5	30.5	31
30	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, MOBD- Mohr oil based bio-diesel, NT- Normal or Room Temperature , PT- Preheat Temperature

From Table III, 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.

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
30	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.5 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.

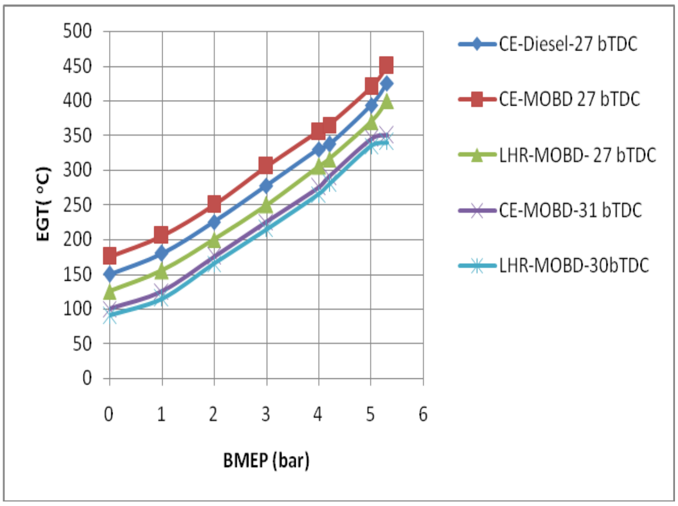

Fig.5 Variation of exhaust gas temperature (EGT) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel (MOBD) operation.

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 IV, 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.

Table IV. Data of EGT at peak load operation

Injection timing (° b TDC)	Test Fuel	EGT at the peak load (°C)											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	425	--	410	---	395	--	460	---	450	--	440	--
	MOBD	450	425	425	400	400	375	400	375	375	350	350	325
30	MOBD	400	375	375	350	400	375	340	320	320	300	300	280
31	MOBD	350	325	360	340	370	350	--	--	--	--	--	--

From Fig. 6, 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.

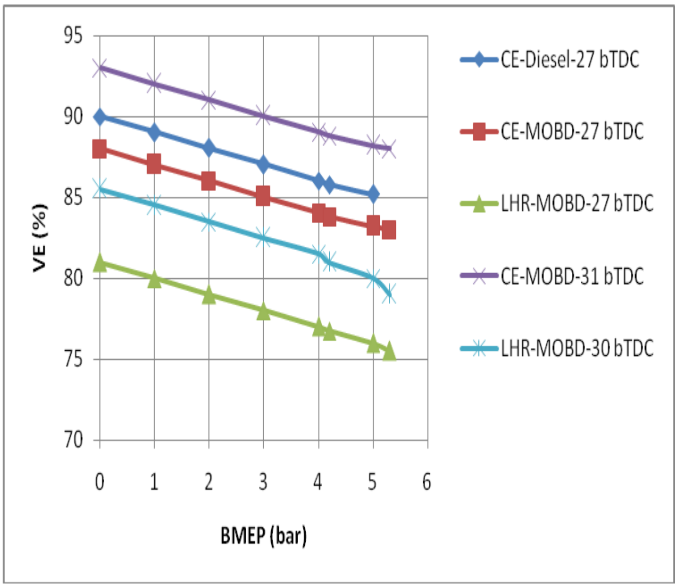

Fig.6 Variation of volumetric efficiency (VE) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel (MOBD) operation at an injection pressure of 190 bar.

From Table V, it was clear that VE increased with increase of injection pressure and with advanced injection timing in both versions of the engine.

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	--
	MOBD	83	84	84	85	85	86	75.5	76.5	76.5	77.5	77.5	78.5
30	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	76	--	77	--	78	--

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 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.

Curves from Fig.7 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.

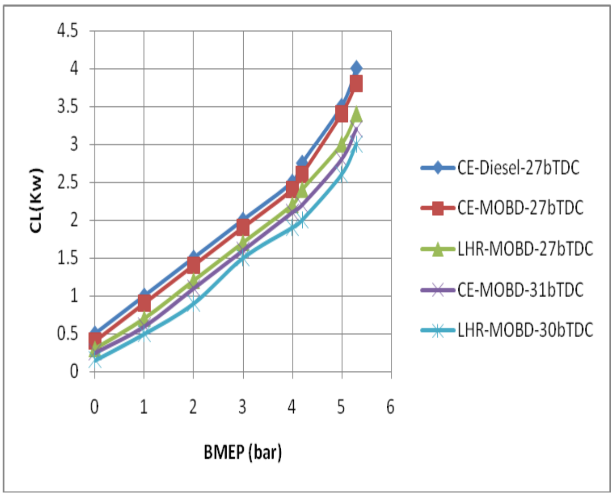

Fig.7 Variation of coolant load (CL) with BMEP in both versions of the engine at recommended and optimized injection timings with MOBD operation at an injection pressure of 190 bar

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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 IV, 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

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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
	DF	4.0	---	3.8	--	3.6	---	4.5	---	4.3	--	4.1	---
27	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
30	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 biodiesel in comparison with normal biodiesel in both versions of the engine. This was because of improved spray characteristics.

Fig.8 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.

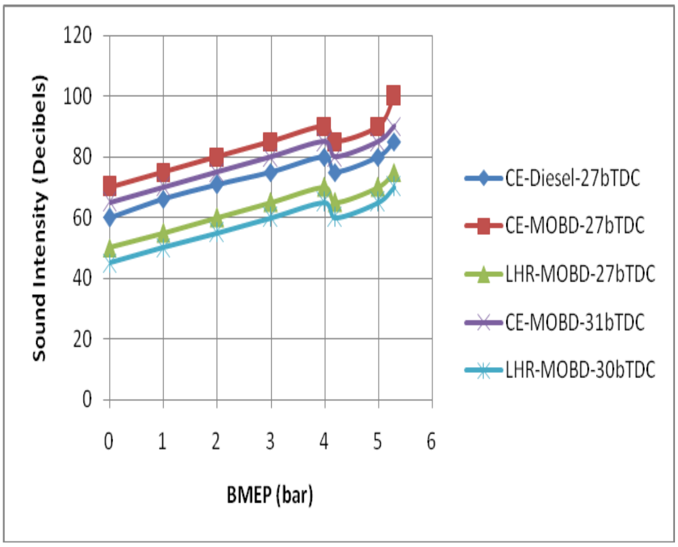

Fig.8 Variation of sound intensity with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel (MOBD) operation.

Table VII 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 biodiesel when compared with their normal condition. This was due to improved spray characteristics, decrease of density and reduction of viscosity of the fuel.

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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	--
	MOBD	100	95	98	93	96	91	75	70	70	65	65	60
30	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. 8, 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.

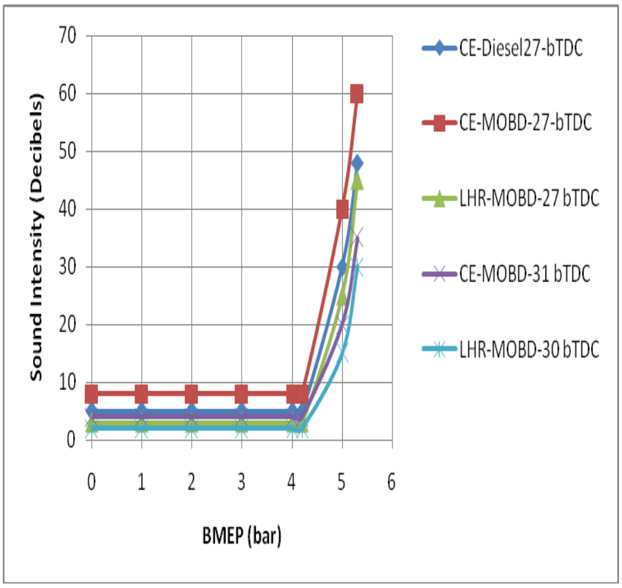

Fig.8 Variation of smoke intensity in Hartridge Smoke Unit (HSU) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel (MOBD) at an injection pressure of 190 bar.

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 VIII, 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	--
	MOBD	60	55	55	50	50	45	45	40	40	35	35	30
30	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.

From Figure 9, 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.

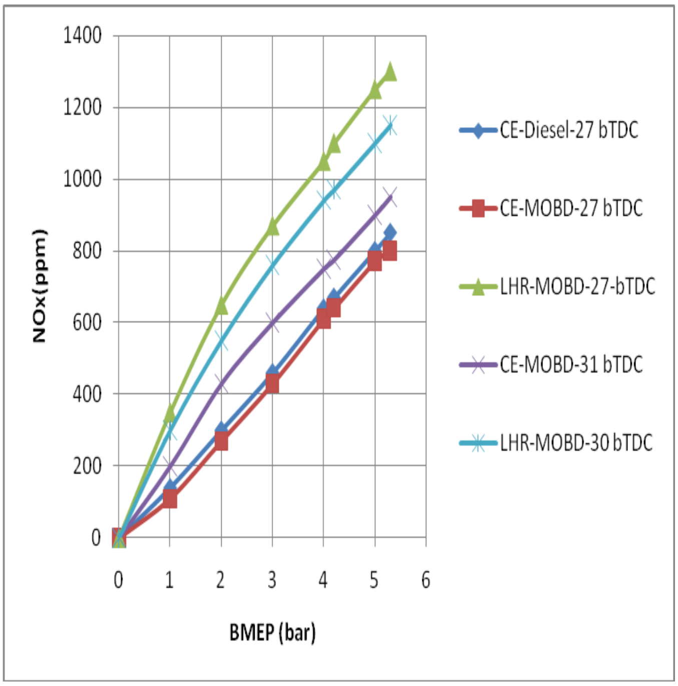

Fig.9 Variation of NOx levels with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel (MOBD) operation at an injection pressure of 190 bar.

From Table IX it was observed that that NOx levels increased with the advancing of the injection timing in CE with different operating conditions of 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	--
	MOBD	800	750	750	700	700	650	1300	1250	1250	1200	1200	1150
30	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 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.

C. Combustion Characteristics

From Table X, 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.

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

Injection timing (°bTDC)/ Test fuel	Engine version	PP(bar)				MRPR (Bar/deg)				TOPP (Deg)				TOMRPR (Deg)			
		Injection pressure (Bar)				Injection pressure (Bar)				Injection pressure (Bar)				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/ 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
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			3.5	3.7			10	9			0	0		

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

CONCLUSIONS

Biodiesel operation at 27°bTDC on CE showed the compatible performance, while LHR engine showed improved performance, when compared with pure diesel operation on CE. Preheating of the biodiesel improved performance when compared with normal biodiesel 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 biodiesel operation 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. 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 biodiesel decreased smoke levels and

NOx levels slightly in both versions of the engine. CE with biodiesel operation decreased smoke levels and increased NOx levels, while LHR engine decreased smoke and NOx levels with the advancing of the injection timing. With increase in injection pressure, smoke and NOx levels decreased in both versions of the engine. Lower peak pressures and more TOPP were observed with normal biodiesel in CE. LHR engine with biodiesel operation increased PP and decreased TOPP when compared with CE. Preheating increased PP and decreased TOPP when compared with normal biodiesel 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.

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First Author: T.Rana Reddy received his B.Tech, and M.Tech, From Osmonia University, Hyderabad, Andhra Pradesh, His Specilization is Cad/Cam and Heat Traansfer. Presently he is working as Associate Professor in Chaitanya Bharathi Institute of Technology, Andhra Pradesh. He is doing his Ph.D in Alternative Fuels, form Rayalaseema University, kurnppl, Andhra Pradesh. He published 8 papers in national and internaitonal journals and attended several national and international conferences.

Second Author: M.V.S.Murali Krishna received his B.Tech degree in Mechanical Engineering from K.L.C of Engineering, India, in 1985, the M.E. degree in Production Engineering from College of Engineering Osmania University, Hyderabad, India in 1992, and the Ph.D. degree in Thermal engineering from JNT University Hyderabad, Andhra Pradesh, India, in 2006. He was a teaching assistant, assistant professor, associate professor, and presently working as professor with Department of Mechanical Engineering, CBIT affiliated to Osmania University. His research interests include IC Engines, Alternative fuels, Combustion and renewable energy. At present, He is engaged in alternative fuels research work. He published more than 90 papers in national and

International journals and attended several national and international conferences.

Third Author: Ch. Keseva Reddy received his B,Tech and M.Tch from Osmonia University. His specilization is Thermal Engineerig. Presently he is working asAssistant Professor in Mahatma Gandhi Institute of Technology, Gandipet, Ranga Reddy Dist. Andhra Pradesh. He published more than 10 papers in National and International Journals. He attended several National and International Conferences.

Fourth Author: P..V.Krishna murthy received his AMIE degree in Mechanical Engineering from Institute of Engineers (India), India, in 1983, the M.Tech. degree in Production Engineering from JNT University, Hyderabad, India in 1988 and the Ph.D. degree in Thermal Engineering from JNT University, Hyderabad, Andhra Pradesh, India, in 2010. He Worked 13 years in different capacities from ASSISTANT PROFESSOR to PROFESSOR, Presently working as Director/Principal Jaya Prakash Narayan Educational Society Group of Institutions Mahabubnagar Dist., Andhra Pradesh, India. Previously he worked 20 years in various positions in Hindustan Machine Tools (HMT Ltd) a Public Sector Company and took VRS in December 2000. His research interests include IC Engines, Alternative fuels, Combustion and renewable energy. At present, He is engaged in alternative fuels research work. He published more than 80 papers in various International and National Journals. He attended various International and National conferences.