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Performance Evaluation of Mohr Oil Based Biodiesel in Low Grade Low Heat Rejection Diesel Engine

T. Ratna Reddy[1], M.V.S. Murali Krishna[2], Ch. Kesava Reddy[3] and P.V.K.Murthy[4]

Research Scholar, Mechanical Engineering, Rayalaseema University, Karnool, Andhra Pradesh, India[1, 3]

Mechanical Engineering, Chaitanya Bharathi Institute of Technology, Gandipet, Hyderabad, Andhra Pradesh, India[2]

Vivekananda Institute of Science and Information Technology, Shadnagar, Mahabubnagar, Andhra Pradesh, India[4]

Abstract: Investigations were carried out to evaluate the performance of a low grade low heat rejection (LHR) diesel engine with ceramic coated cylinder head with 3-mm air gap with different operating conditions [normal temperature and pre-heated temperature] of mohr oil based biodiesel (MOBD) with varied injection pressure and injection timing. Performance parameters of brake thermal efficiency, exhaust gas temperature, volumetric efficiency and sound intensity were determined at various values of brake mean effective pressure (BMEP).Exhaust emissions of smoke and oxides of nitrogen (NOx) were recorded at the various values of BMEP. Combustion characteristics at peak load operation of the engine were measured with TDC (top dead centre) encoder, pressure transducer, console and special pressure-crank angle software package. Conventional engine (CE) showed compatible performance, while LHR engine showed marginally increased performance with MOBD operation at recommended injection timing and pressure. 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 33^{o}bTDC for CE while it was 29.5^{o}bTDC with LHR engine with MOBD operation. Peak brake thermal efficiency increased by 13%, at peak load operation- brake specific energy consumption (BSEC), coolant load, volumetric efficiency, smoke levels and sound intensity decreased by 4%, 15%, 7%, 27%, 24% respectively while NOx levels increased by 47% with MOBD operation on LHR engine at its optimum injection timing when compared with diesel operation on CE at manufacturer's recommended injection timing of 27^{o}bTDC. (Before top dead centre)

Keywords: Mohr oil, Bio-diesel, CE, LHR engine, Fuel Performance, Exhaust Emissions, Sound Intensity, Combustion Characteristics.

I. INTRODUCTION

The search for alternate fuels has become pertinent, as fossil fuels are depleting, the pollution levels with fossil fuels are increasing and also there is increase of burden on economy sector of Govt. of India. Vegetable oils and alcohols are promising substitutes of fossil diesel fuels as they are renewable in nature. Alcohols have low cetane number and engine modification is necessary for use in diesel engines. That too, most of the alcohols produced are diverted to Petro-chemical industries in India. On the other hand, the properties of the vegetable oils are similar to those of diesel fuel and they can be easily produced. Rudolph diesel, the inventor of the engine that bears his name, experimented with fuels ranging from powdered coal to peanut oil.

Several researchers [1-5] experimented the use of vegetable oils as fuel on conventional engines (CE) and reported that the performance was poor, citing the problems of high viscosity, low volatility and their polyunsaturated character. Not only that, the common problems of crude vegetable oils in diesel engines are formation of carbon deposits, oil ring sticking, thickening and gelling of lubricating oil as a result of contamination by the vegetable oils.

These problems can be solved, if neat vegetable oils were chemically modified to bio-diesel [6]. The process of converting the oil into methyl esters or biodiesel was carried out [6] by heating the crude oil at around 60-70^{o}C with the methanol in the presence of the 0.5% of catalyst (Sodium hydroxide) 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 vegetable oil esters. These biodiesels have low viscosity and low molecular weight compared to crude vegetable oil. Investigations were carried out

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[7-14] on biodiesel in CE and reported compatible performance with biodiesel in comparison with pure diesel operation on CE. The drawbacks of crude vegetable oil and biodiesel call for LHR engine.

The concept of LHR engine is to minimize heat loss to the coolant by providing thermal insulation in the path of the heat flow to the coolant. LHR engines were classified depending on degree of insulation as low grade LHR engines, medium grade LHR engines and high grade LHR engines. Low grade LHR engines consisted of thermal coatings on piston, liner and cylinder head with low thermal conductivity materials, medium grade LHR engines provide an air gap in the piston and other engine components with superni (an alloy of nickel), cast iron and mild steel etc., while high grade LHR engine was the combination of low and medium grade LHR engines.

Ceramic coatings provided adequate insulation, improved brake specific fuel consumption (BSFC) as reported by various researchers. However previous studies with pure diesel in LHR engine with ceramic coated components revealed that the thermal efficiency variation of LHR engine not only depended on the heat recovery system, but also depended on the engine configuration, operating condition and physical properties of the insulation material. Experiments were conducted with pure diesel on LHR engine with ceramic coating. Experiments were conducted on LHR engine [15] with cylinder head, valves and pistons of the engine coated with plasma spray zirconium with the thickness of 0.5 mm and it was reported that In comparison to CE, SFC was decreased by 6 %, and BTE was increased by 2%. The available exhaust gas energy of the LHR engine was 3–27% higher for the LHR engine compared to the standard (STD) Diesel engine. Tests were performed [16] on a six cylinder, direct injection, turbocharged diesel engine whose pistons were coated with a 350 microns thickness of $MgZrO_3$ over a 150 micron thickness of NiCrAl bond coat. $CaZrO_3$ was employed as the coating material for the cylinder head and valves. The results showed that 1–8% reduction in BSFC could be achieved by the combined effect of the thermal barrier coating (TBC) and injection timing. On the other hand, NOx emissions were obtained below those of the base engine by 11% for 18^{o}bTDC injection timing. It was [17] explained that compared with CE, LHR engine with ceramic coating on piston crown and inner side of cylinder head with pure diesel operation, the engine power was increased by 2%, the engine torque was increased by 1.5–2.5 %, and SFC was decreased by 4.5–9 %.

Crude vegetable oil was used [18] in LHR engine with ceramic coated cylinder head and reported that marginal improvement in thermal efficiency and it increased with advanced injection timing and with increase of injection pressure.

Biodiesel was used as fuel in LHR engine with ceramic coating on engine components.

Experiments were conducted [19] on turbo charged diesel engine converted as low heat rejection diesel with ceramic coating on cylinder head with sunflower oil based bio-diesel and reported that LHR engine improved thermal efficiency and exhaust gas temperature before the turbine inlet was increased for both fuels in the LHR engine. Experiments were conducted [20] on LHR diesel engine with ceramic coated material MgO–ZrO2 on cylinder head, exhaust, and inlet valves while the piston surface was coated with ZrO2 with canola methyl and reported that increase in engine power and decrease in specific fuel consumption, as well as significant improvements in exhaust gas emissions and smoke density with LHR engine when compared with conventional engine. Experiments were conducted [21] on LHR engine with ceramic coated piston crown, liner and inner surface of cylinder head with palm oil based bio-diesel and reported that LHR engine reduced smoke and marginally increased NOx emissions and thermal efficiency. Experiments were conducted [22] on LHR engine with ceramic coating (thickness- 500 microns) on piston crown, cylinder head, valves and cylinder liner with jatropha oil based bio-diesel and reported improvement in the efficiency and pollution levels except NOx emissions. In this study, for the first time, fly ash was used [23] as a thermal barrier coating material for engine combustion chamber elements such as cylinder head, cylinder liner, valves and piston crown face to a thickness of 200 μm by using plasma spray coating method and experiments were carried out on LHR diesel engine fueled by methyl ester of rice bran, pongamia oil and its blend (20% by volume) with diesel. An increase in engine power and decrease in specific fuel consumption, as well as significant improvements in exhaust gas emissions (except NOx) were observed for all test fuels used in LHR engine when compared with that of the CE. Experiments were conducted [24] on LHR engine with Y_2O_3-ZrO_2 (yttria-stabilized zirconia) layer of 0.35 mm thickness over a NiCrAl bond coat of 0.15 mm thickness over the cylinder head and valves of the test engine with sunflower oil based bio-diesel and reported that brake-specific fuel consumption (BSFC) and brake thermal efficiency were improved with biodiesel. Experiments were conducted [25] with pongamia oil and jatropha oil based biodiesel in high grade LHR engines and reported performance improved with LHR engine.

The present paper attempted to evaluate the performance of LHR engine, which contained ceramic coated cylinder head with different operating conditions of MOBD with varying engine parameters of change of injection pressure and timing and compared with pure diesel with CE at recommended injection timing and injection pressure.

II. METHODOLOGY

The properties of MOBD and diesel fuel were presented in Table 1.

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TABLE I

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
Mohr oil (esterified) (MOBD)	53	0.87	55	37500

Partially stabilized zirconium (PSZ) of thickness 500 microns was coated on inside portion of cylinder head. Experimental setup used for the investigations of LHR diesel engine with MOBD is shown in Figure 1.

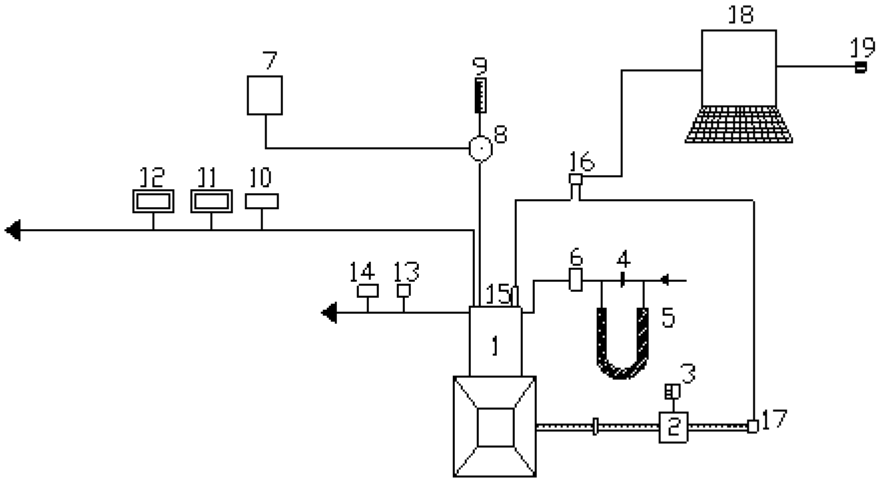

Fig.1 Experimental Set-up

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.

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 finding fuel consumption of the engine. 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°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. Emission levels of smoke and NO_x were recorded by AVL smoke meter and Netel Chromatograph NOx analyzer respectively at various values of BMEP. Sound intensity was measured with Sound analyzer at different values of BMEP. Piezo electric transducer, fitted on the cylinder head to measure pressure in the combustion chamber was connected to a console, which in turn was connected to Pentium personal computer. TDC encoder provided at the extended shaft of the dynamometer was connected to the console to measure the crank angle of the engine. A special P-θ software package evaluated the combustion characteristics such as peak pressure (PP), time of occurrence of peak pressure (TOPP), maximum rate of pressure rise (MRPR) and time of occurrence of maximum rate of

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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 used was 0.1%.

III. RESULTS AND DISCUSSION

A. Performance Parameters

Figure 2 indicates that CE with MOBD showed compatible performance for entire load range when compared with the pure diesel operation on CE at recommended injection timing. Although carbon accumulations on the nozzle tip might play a partial role for the general trends observed, the difference of viscosity between the diesel and MOBD provided a possible explanation for the compatible performance of the engine with MOBD operation. In addition, less air entrainment by the fuel spay suggested that the fuel spray penetration might increase and resulted in more fuel reaching the combustion chamber walls. Furthermore droplet mean diameters (expressed as Sauter mean) were larger for MOBD leading to reduce the rate of heat release as compared with diesel fuel. This also, contributed the higher ignition (chemical) delay of the MOBD due to lower cetane number.

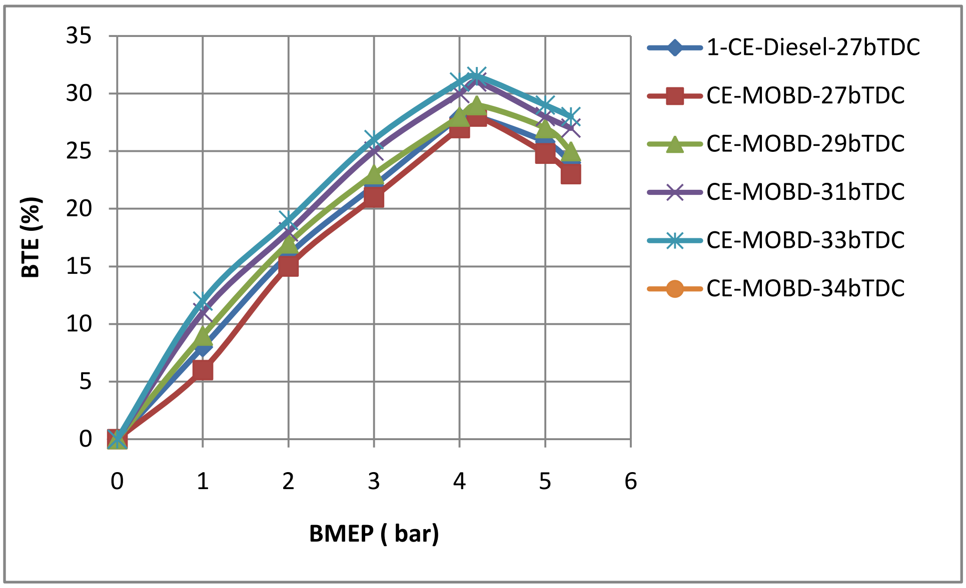

Fig.2. Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in conventional engine (CE) at different injection timings with mohr oil based bio-diesel (MOBD) operation.

According to the qualitative image of the combustion under the MOBD operation with CE, the lower BTE was attributed to the relatively retarded and lower heat release rates. BTE increased with the advancing of the injection timing in CE with the MOBD 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 33^{o}bTDC in the CE at the normal temperature of MOBD. The increase of BTE at optimum injection timing over the recommended injection timing with MOBD 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 33^{o}bTDC in CE, at the preheated temperature of MOBD. The performance improved further in CE with the preheated MOBD for entire load range when compared with normal MOBD. Preheating of the MOBD reduced the viscosity, which improved the spray characteristics of the oil and reduced the impingement of the fuel spray on combustion chamber walls, causing efficient combustion thus improving BTE.
Curves from Figure 3 indicate that LHR version of the engine showed improvement in the performance for entire load range compared with CE with pure diesel operation.

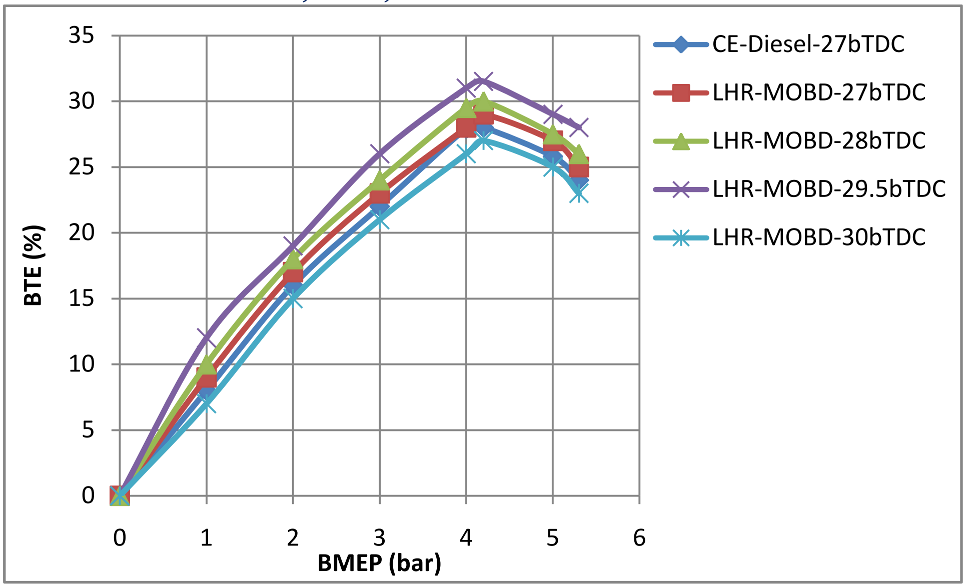

Fig.3. Variation of BTE with BMEP in LHR engine at different injection timings with MOBD operation.

High cylinder temperatures helped in better evaporation and faster combustion of the fuel injected into the combustion chamber. Reduction of ignition delay of the MOBD oil in the hot environment of the LHR engine improved heat release rates and efficient energy utilization. Preheating of MOBD improved performance further in LHR version of the engine. The optimum injection timing was found to be 29.5^{o}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 MOBD operation.
It could be noticed from Figure 4, at optimum injection timing, BTE with LHR engine was higher than that of CE. Decrease of combustion duration and better evaporation rates would help in increasing the efficiency of LHR engine.

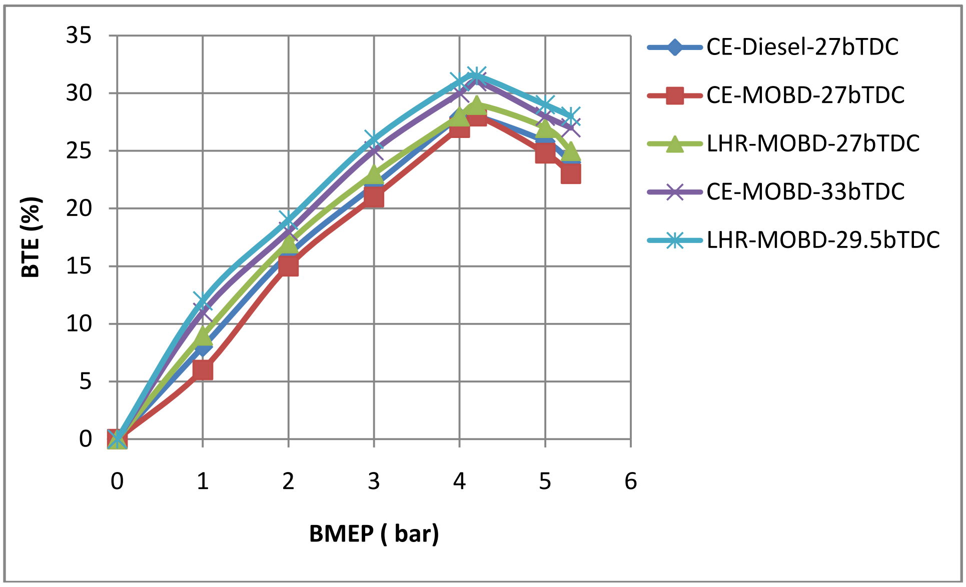

Fig.4.Variation of BTE with BMEP in different versions of the engine at the recommended injection timing and optimum injection timing at an injection pressure of 190 bar with MOBD.

Injection pressure was varied from 190 bars to 270 bars to improve the spray characteristics and atomization of the MOBD and injection timing was advanced from 27 to 34^{o}bTDC for CE and LHR engine. From Table-2, it was evident that BTE increased

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with increase in injection pressure in both versions of the engine at different operating conditions of the MOBD. 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 33°bTDC at 190 bar, 32°bTDC at 230 bar and 31°bTDC at 270 bar for CE. The optimum injection timing for LHR engine was 29.5°bTDC irrespective of injection pressure. Peak BTE was higher in LHR engine when compared with CE with different operating conditions of the MOBD.

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	30	30	31	31	32
29.5	DF	28.5	--	29.5	--	30.2		29.5	--	30.5	--	31	--
	MOBD	29	30	30	30.5	30.5	31	31.5	32	32	32.5	32.5	33
30	DF	29	---	30	--	30.5	--	29	--	30	--	30.5	--
	MOBD	29.5	30	30	30.5	30.5	31	27	28	27.5	28	27.6	28
31	DF	29.5	--	30	--	31	--	--	--	--	--	--	--
	MOBD	30	30.5	30.5	31	31	31.5	27					
32	DF	30		30.5		30.5							
	MOBD	30.5	31	31	31.5	29.5	30	--	--	--	--	--	--
33	DF	31		31		30	---	--	--	--	--	--	-
	MOBD	31	31.5	30	30.5	29.5	30	--	--	--	--	--	--

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

From Table-3 it is evident that BSEC at peak load reduced with the increase of injection pressure and with the advancing of the injection timing at different operating conditions of the bio-diesel.

TABLE III
DATA OF BSEC AT PEAK LOAD OPERATION

Injection Timing (° bTDC)	Test Fuel	BSEC (kW/ kW)											
		CE						LHR Engine					
		Injection Pressure (Bars)						Injection Pressure (Bars)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	4.00	--	3.92	--	3.84	--	4.16	---	4.08	--	4.00	--
	MOBD	4.80	4.60	4.60	4.55	4.55	4.50	3.84	3.80	3.80	3.76	3.76	3.72
29.5	D	3.92	---	3.88	--	3.84	--	4.08	--	4.00	--	3.90	--
	MOBD	4.60	4.55	4.55	4.50	4.50	4.45	3.82	3.78	3.78	3.74	3.74	3.70
31	DF	3.84	--	3.80	--	3.77	--	3.86		3.85		3.84	
	MOBD	4.35	4.30	4.30	4.25	3.84	3.80						
32	DF	3.82	---	3.78	--	3.79	--	--	--	--	--	--	--
	MOBD	3.88	3.84	3.84	3.80	3.92	3.88	---	---	--	---	--	--
33	DF	3.77	--	3.77	--	3.84	---	--	----	----	----	---	---
	MOBD	3.84	3.80	3.88	3.84	4.15	4.05	-	---	--	--	-	----

Esterification reduced the viscosity and increased the cetane number. Preheating of the vegetable oils improved the performance in both versions of the engine compared to the bio-diesel at normal temperature. Preheating reduced the viscosity of the bio-diesel, which reduced the impingement of the fuel spray on combustion chamber walls, causing efficient combustion thus improving BSEC.

Figure 5 indicates that CE with MOBD at the recommended injection timing recorded 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

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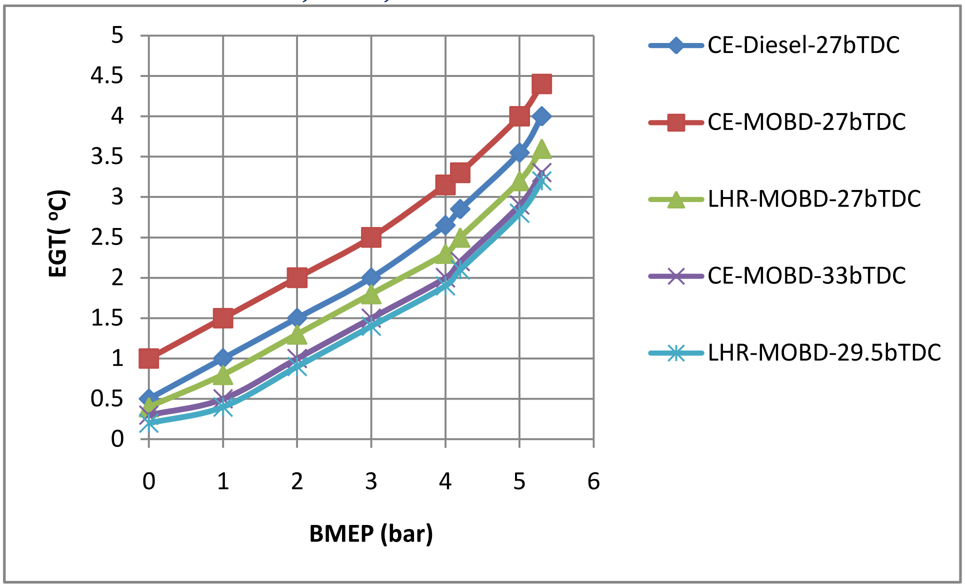

Fig.5 Variation of exhaust gas temperature (EGT) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with MOBD operation.

Ignition delay in the CE with different operating conditions of MOBD increased the duration of the burning phase. LHR engine recorded lower value of EGT when compared with CE with MOBD 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 MOBD 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 MOBD. Preheating of MOBD further reduced the magnitude of EGT, compared with normal MOBD in both versions of the engine. From the Table-4, it is evident 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 MOBD decreased EGT in both versions of the engine

TABLE IV
DATA OF EGT AT PEAK LOAD OPERATION

Curves from Figure 6 indicate that that coolant load (CL) increased with BMEP in both versions of the engine with test fuels.

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	430	430	410	410	390	440	420	420	400	400	380
29.5	DF	415	--	405	--	395	--	440	--	430	--	420	
	MOBD	430	410	410	390	370	350	420	400	400	380	380	360
30	DF	410	---	400	--	385	---	460	---	450	--	440	--
	MOBD	410	390	390	370	370	350	450	430	430	410	410	390
31	DF	400	---	390	--	375	---	450	---	445	---	440	---
	MOBD	390	370	370	350	380	360	-	-	-	-	-	-
32	DF	390		380		380							--
	MOBD	370	350	390	370	380	360	-	---	---	----	---	-
33	DF	375	---	375	---	400	--	--	--	--	---	--	--
	MOBD	360	340	380	360	370	360						

However, CL reduced with LHR version of the engine with biodiesel operation when compared with CE with pure diesel operation.

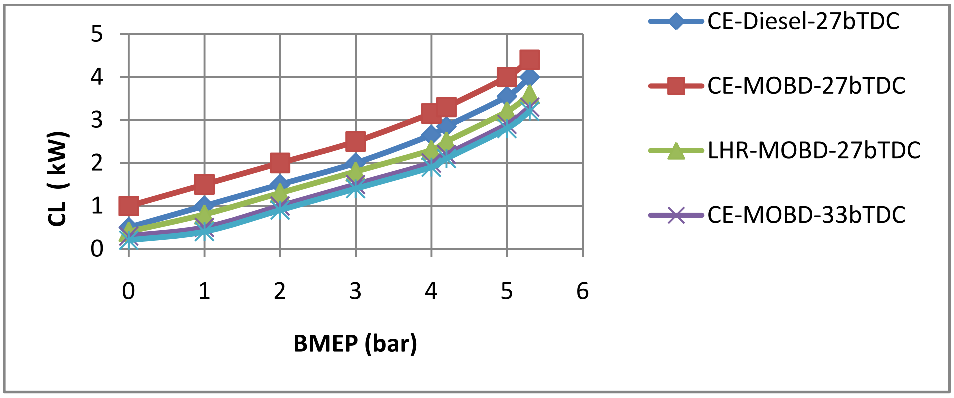

Fig.6 Variation of Coolant load (CL) with BMEP in both versions of the engine at recommended and optimized injection timings with mohr oil based bio-diesel (MOBD) operation at an injection pressure of 190 bar.

Heat output was properly utilized and hence efficiency increased and heat loss to coolant decreased with effective thermal insulation with LHR engine. However, CL increased with CE with bio-diesel operation in comparison with pure diesel operation on CE. This was due to concentration of fuel at the walls of combustion chamber. CL decreased with advanced injection timing with both versions of the engine with test fuels. This was due to improved air fuel ratios. From Table.5, it is noticed that CL decreased with advanced injection timing and with increase of injection pressure.

TABLE V
DATA OF CL AT PEAK LOAD OPERATION

Injection timing (°bTDC)	Test Fuel	Coolant Load (kW)											
		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	4.4	4.2	4.3	4.1	4.2	4.0	3.6	3.4	3.4	3.2	3.2	3.0
29.5	DF	3.8	--	3.6	---	3.4	--	4.3	--	4.1	--	3.9	--
	MOBD	4.0	3.8	3.8	3.6	3.6	3.4	3.2	3.0	3.0	2.8	2.8	2.6
	DF	3.6	--	3.4	--	3.2	---	4.1	--	3.9	---	3.7	--
30	MOBD	3.8	3.6	3.6	3.4	3.4	3.2						
31	DF	3.4	---	3.2	---	3.0	--						
	MOBD	3.6	3.4	3.4	3.2	3.3	3.1						
32	DF	3.2	---	3.0	---	3.2	---						
	MOBD	3.4	3.2	3.3	3.1	3.8	3.6						
33	DF	3.0	---	3.2	---	3.4	---						
	MOBD	3.3	3.1	3.4	3.2	3.5	3.3						

This was because of improved combustion and proper utilization of heat energy with reduction of gas temperatures. CL decreased with preheated bio-diesel in comparison with normal bio-diesel in both versions of the engine. This was because of improved spray characteristics. From Figure 7, it is noticed that volumetric efficiency (VE) decreased with an increase of BMEP in both versions of the engine. 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 MOBD operation decreased at all loads when compared with CE with pure diesel operation. 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 timings with MOBD. 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.

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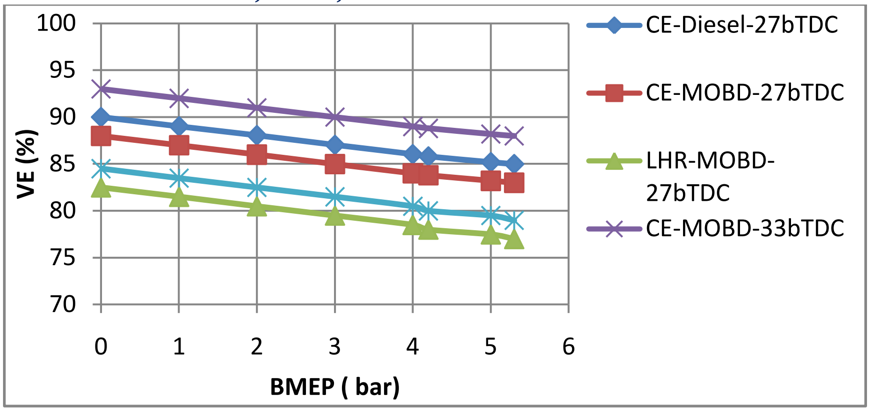

Fig.7 Variation of volumetric efficiency (VE) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with mohr oil based bio-diesel (MOBD) operation.

From the Table-6, it could be observed that VE increased marginally with the advancing of the injection timing and with the increase of injection pressure in both versions of the engine. This was 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.Table-4 showed the variation of VE with injection pressure and injection timing at different operating conditions of MOBD with different configurations of the engine. Preheating of the MOBD 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 bio-diesel.

TABLE VI
DATA OF VOLUMETRIC EFFICIENCY 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	77	78	78	79	79	80
29.5	DF	85.5		86.5		87.5		78.5		80.5		82.5	
	MOBD	84	84	84	85	85	86	79	80	80	81	81	82
30	DF	86	--	87	--	88	---	76	--	77	--	78	--
	MOBD	85	85	85	86	86	87	78	79	79	80	80	81
31	DF	87	--	87.5	--	89	--	77		78	--	79	--
	MOBD	86	86	86	87	88	89	--	--	--	--	--	--
32	DF	87.5	--	88	--	87	--	-	--	-	--	--	-
	MOBD	87	87	88	89	84	85	--	--	--	--	--	--
33	DF	89	--	89	--	86	--	--	--	--	--	--	--
	MOBD	88	89	87	88	86	87						

B. Exhaust Emissions

Figure 8 indicates that the value of smoke intensity increased from no load to full load in both versions of the engine. During the first part, the smoke level was more or less constant, as there was always excess air present. However, in the higher load range there was an abrupt rise in smoke levels due to less available oxygen, causing the decrease of air-fuel ratio, leading to

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incomplete combustion, producing more soot density. The variation of smoke levels with BMEP, typically showed a U-shaped behavior due to the pre-dominance of hydrocarbons in their composition at light load and of carbon at high load. Drastic increase of smoke levels was observed at the peak load operation in CE at different operating conditions of the MOBD, compared with pure diesel operation on CE. This was due to the higher magnitude of the ratio of C/H of biodiesel (0.7) when compared with pure diesel (0.45). The increase of smoke levels was also due to decrease of air-fuel ratios and VE with MOBD compared with pure diesel operation. Smoke levels were related to the density of the bio-diesel. Since MOBD has higher density compared to diesel fuels, smoke levels are higher with MOBD. 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 MOBD compared with the CE. Density influences the fuel injection system.

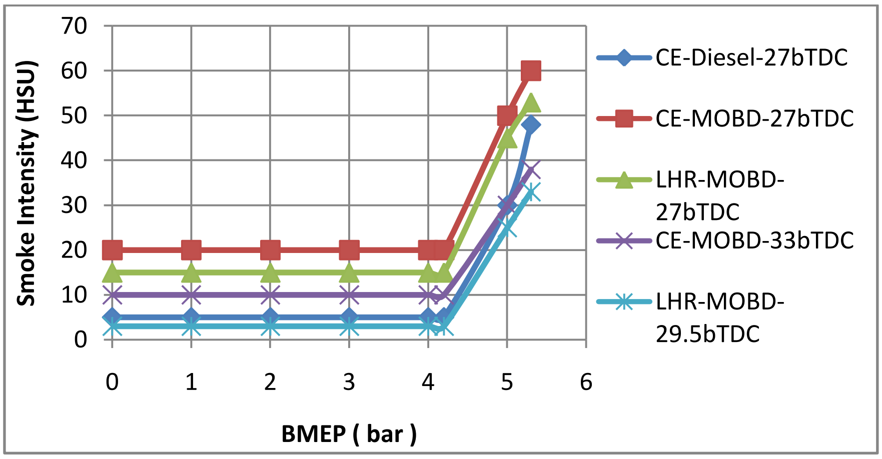

Fig.7 Variation of smoke intensity in Hartridge Smoke Unit (HSU) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with MOBD

Decreasing the fuel density tends to increase spray dispersion and spray penetration. Preheating of the MOBD reduced smoke levels in both versions of the engine, when compared with normal temperature of the MOBD. This was due to i) the reduction of density of the MOBD, as density was directly proportional to smoke levels, ii) the reduction of the diffusion combustion proportion in CE with the preheated MOBD, iii) the reduction of the viscosity of the MOBD, with which the fuel spray does not impinge on the combustion chamber walls of lower temperatures rather than it directed into the combustion chamber.

From Table-7, it is evident 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 MOBD. 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.

TABLE VII
DATA OF SMOKE LEVELS IN HARTRIDGE SMOKE UNIT (HSU) 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	53	45	45	37	37	30
29.5	DF	40	--	36	--	34		52		48		43	
	MOBD	55	50	50	45	45	40	35	25	28	26	26	22
30	DF	36	--	34	--	32	--	45	--	42	--	41	--
	MOBD	50	45	45	40	39	36	50	45	45	40	40	35
31	DF	33	---	32	--	30	--	43	--	41	--	40	--
	MOBD	45	40	40	38	38	33	--	--	--	--	--	-
32	DF	32	--	31	--	32	--	--	--	--	---	--	--
	MOBD	40	35	38	33	40	35	--	--	--	--	---	-
33	DF	30	---	30	--	35	--	-	--	--	--	--	--
	MOBD	38	33	42	37	46	42						

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Figure 9 shows that NOx levels were lower in CE while they were higher in LHR engine at different operating conditions of the MOBD 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 MOBD 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 MOBD decreased NOx levels in both versions of the engine when compared with the normal MOBD. 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.

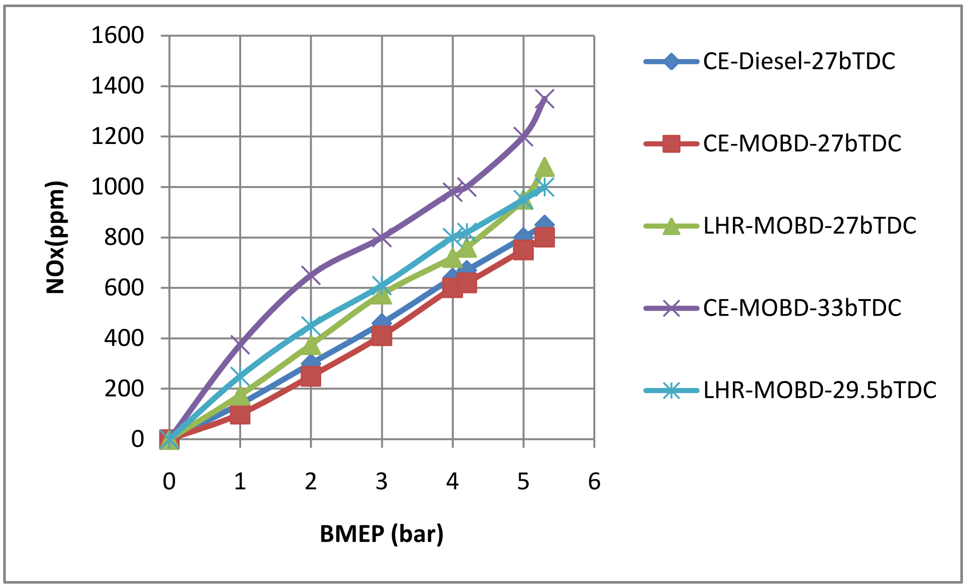

Fig.9 Variation of NOx levels with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with MOBD operation.

From Table-8, it is noticed that NOx levels increased with the advancing of the injection timing in CE with different operating conditions of MOBD.

TABLE VIII
DATA OF NOX LEVELS AT PEAK LOAD OPERATION

Injection timing (° b TDC)	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	1080	1000	1030	950	980	900
29.5	DF	900	--	860	--	820	--						
	MOBD	1000	950	950	900	900	850	1000	920	920	840	840	760
30	DF	935	---	900	---	860	--	1225	--	1205	--	1185	--
	MOBD	1050	1000	1000	900	900	850	1000	950	950	900	900	850
31	DF	1020	---	980	---	940	---	1150	--	1130	--	1110	--
	MOBD	1150	1100	1100	1050	950	900	--	--	--	--	--	--
32	DF	1105	----	1060	---	1020	---	--	--	--	--	--	--
	MOBD	1250	1200	1200	1150	1000	950	--	-	--	--	--	-
33	DF	1190	----	1150	---	1110	---	--	--	--	--	--	-
	MOBD	1350	1300	1400	1350	1350	1300						

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Residence time and availability of oxygen had increased, when the injection timing was advanced with the MOBD 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. Sound Intensity

Figure 10 indicates at recommended injection timing, sound intensities drastically increased in CE with MOBD operation in comparison with CE with pure diesel operation. This was due to deterioration in the performance of MOBD operation on CE. High viscosity, poor volatility and high duration of combustion caused improper combustion of MOBD 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 MOBD. When injection timings were advanced to optimum, sound intensities were reduced for both versions of the engine, due to early initiation of combustion.

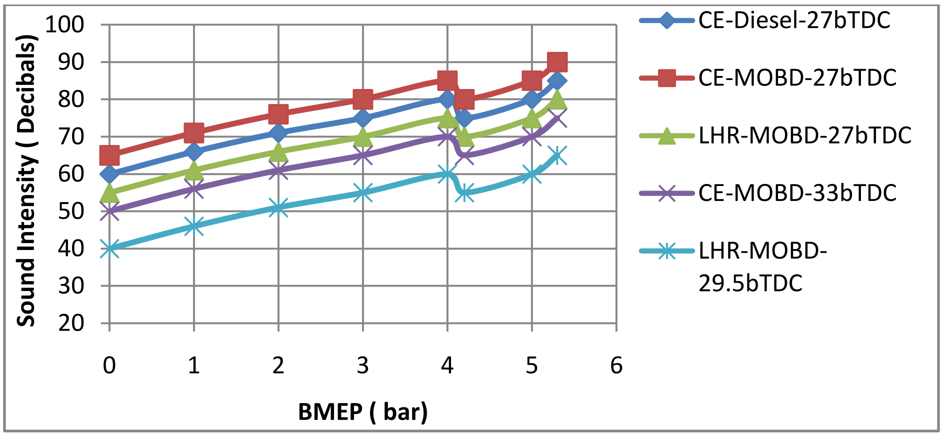

Fig.10 Variation of sound intensity with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with MOBD

Table 9 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.

TABLE IX
DATA OF SOUND INTENSITY 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	85		80		95		95		90		85	
	MOBD	90	85	88	83	86	81	80	75	75	70	70	65
29.5	DF	83		81		79		90		85		80	
	MOBD	87	82	82	77	81	76	65	60	60	55	55	50
30	DF	80		78		77		87		82		77	
	MOBD	84	79	82	77	80	75	75	70	70	65	65	60
31	DF	78		77		75		84		79		74	
	MOBD	82	77	80	75	75	70	--	--	--	--	--	--
32	DF	76		75		76		80		75		70	
	MOBD	80	75	75	70	80	75						
33	DF	75		76		77							
	MOBD	75	70	80	75	82	77						

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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.

At recommended injection timing, MOBD operation on CE produced high levels of sound intensity as combustion was deteriorated due to high viscosity and poor volatility of the fuel and high duration of combustion. However, LHR engine with MOBD operation produced low levels of sound intensity due to the efficient combustion in the hot environment provided by LHR engine. However, when injection timing was advanced to the respective optimum injection timing, combustion improved in both versions of the engine leading to generate low levels of sound. Preheated MOBD reduced sound levels as preheated oil reduced viscosity and improved atomization characteristics of the fuel.

D. Combustion Characteristics

From Table-10, it could be observed peak pressures were lower in CE while they were higher in LHR engine at the recommended injection timing and pressure, when compared with pure diesel operation on CE. This was due to increase of ignition delay, as MOBD 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 MOBD 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 MOBD 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 MOBD. TOPP was more with different operating conditions of MOBD in CE, when compared with pure diesel operation on CE. This was due to higher ignition delay with the MOBD when compared with pure diesel fuel. This once again established the fact by observing lower peak pressures and higher TOPP, that CE with MOBD operation showed the deterioration in the performance when compared with pure diesel operation on CE. Preheating of the MOBD showed lower TOPP, compared with MOBD 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 MOBD compared with the normal MOBD.

TABLE X
DATA OF PP, MRPR, TOPP AND TOMRPR AT PEAK LOAD OPERATION

Injection timing (^{o}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	46.5	47.8	49.9	50.6	2.6	2.7	2.8	2.9	11	10	11	10	1	1	1	1
	LHR	57.5	58.6	60.6	61.8	3.3	3.4	3.6	3.7	10	9	10	9	1	1	1	1
29.5/MOBD	LHR	61.75	62.88	63.1	64.88	3.55	3.6	3.67	3.78	8	8	8	8	0	0	0	0
33/MOBD	CE	54.3	55.4			3.4	3.5			9	9			0	0		

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

IV. CONCLUSIONS

MOBD operation at 27^{o}bTDC on CE showed the deterioration in the performance, while LHR engine showed compatible performance, when compared with pure diesel operation on CE. Preheating of the MOBD improved performance when compared with normal MOBD 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 MOBD operation on both versions of the engine. CE with MOBD operation showed the optimum injection timing at 33^{o}bTDC, while the optimum injection for LHR engine was at 29.5^{o}bTDC at an injection pressure of 190 bars. At the recommended injection timing and pressure, MOBD operation on CE showed compatible BTE, increased BSEC by 20%, increased CL by 10%, decreased VE by 2%, increased smoke levels by 25%, decreased NOx levels by 6%, increased sound intensity by 6% in comparison with pure diesel operation on CE. At recommended injection timing and pressure, MOBD operation on LHR engine increased peak BTE by 4%, decreased BSEC by 16%, decreased CL by 10%, decreased VE by 9%, increased smoke levels by 10%, increased NOx levels by 27%, decreased sound intensity by 6% when compared with pure diesel operation on CE. Preheating of the MOBD decreased smoke levels and NOx levels slightly in both versions of the engine. CE with MOBD 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. Performance parameters and exhaust emissions improved with advanced injection timing and increase of injection pressure with both versions of the engine at different operating conditions of the MOBD operation. Lower peak pressures and more TOPP were observed with normal MOBD in CE. LHR engine with MOBD operation increased PP and decreased TOPP when compared with CE. Preheating increased PP and decreased TOPP when compared with normal MOBD operation on both versions of the engine. Lower peak pressures were observed in CE, while higher peak pressures in the LHR engine with MOBD operation at the recommended injection timing and pressure.

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Biography

T.Ratana Reddy received his B.Tech degree in Mechanical Engineering and the M.Tech. Degree in Production Engineering and CAD/CAM.. He was a teaching assistant, assistant professor, and presently working as Assistant professor with Department of Mechanical Engineering, CBIT affiliated to Osmania University, Hyderabad. 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 5 papers in national and International journals and attended several national and international conferences.

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.

Ch. Kesava Reddy received his B.Tech degree in Mechanical Engineering and the M.Tech. Degree in Thermal Engineering.. He was a teaching assistant, assistant professor, and presently working as Assistant professor with Department of Mechanical Engineering, MGIT affiliated to JNT University, Hyderabad. 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 5 papers in national and International journals and attended several national and international conferences.

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 Principal Vivekananda Institute of Science & Information Technology, Shadnagar, 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 60 papers in various International and National Journals. He attended various International and National conferences.