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Performance Evaluation of a Low Heat Rejection Diesel Engine with Mohr Oil Based Biodiesel

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Authors' contributions

This work was carried out in collaboration between all authors. TRR managed the literature searches. MVSMK and PVKM designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. CKR managed the analyses of the study. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

Aim: Investigations were carried out to evaluate the performance of a high grade low heat rejection (LHR) diesel engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head (ceramic coating of thickness 500 microns was done on inside portion of cylinder head] with different operating conditions (normal temperature and pre-heated temperature) of Mohr oil based bio-diesel (MOBD) with varied injection pressure and injection timing.
Study Design: Performance parameters of brake thermal efficiency, exhaust gas temperature and volumetric efficiency were determined at various values of brake mean effective pressure (BMEP).
Methodology: Exhaust emissions of smoke and oxides of nitrogen (NOx) were recorded at different values of BMEP. Combustion characteristics at peak load operation of the engine were measured with TDC (top dead centre) encoder, pressure transducer, console and

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special pressure-crank angle software package.
Results: Conventional engine (CE) showed deteriorated performance with biodiesel operation, while LHR engine showed improved performance at recommended injection timing and pressure of 27°bTDC (before top dead centre) and 190 bar respectively. 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°bTDC for CE while it was 30°bTDC for LHR engine using biodiesel operation. It was also observed that peak brake thermal efficiency increased by 14%, volumetric efficiency decreased by 8%, smoke levels decreased by 6% and NOx levels increased by 47% with MOBD operation on LHR engine at its optimum injection timing, when compared with pure diesel operation on CE at 27°bTDC.

Keywords: Mohr oil; esterification; LHR engine; fuel performance, emissions; combustion characteristics.

1. INTRODUCTION

It has been found that the vegetable oils are promising substitute, because of their properties are similar to that of diesel fuel and it is a renewable and can be easily produced. Rudolph Diesel, (Cummins and Lyle, 1993) the inventor of the diesel engine that bears his name, experimented with fuels ranging from powdered coal to peanut oil. Several researchers (Bari et al., 2002; Pramanik et al., 2003; Ramadhas et al., 2004; Pugazhvadivu et al., 2005; Agarwal et al., 2007; Surendra et al., 2008; Misra et al., 2010) 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. The presence of the fatty acid components greatly affects the viscosity of the oil. The increase in viscosity and crystal formation of fatty acids below cloud point hinders the operation of the injector. Increase saturated hydro carbon content increases the cloud point of the oil. The limitation of unsaturated fatty acids is necessary due to the fact heating higher unsaturated fatty acids results in polymerization of glycerides. This can leads to formation of deposits or to deterioration of lubricating oil. The different fatty acids present in the vegetable oil are palmic, steric, lingoceric, oleic, linoleic and fatty acids. These fatty acids increase smoke emissions and also lead to incomplete combustion due to improper air-fuel mixing. These problems can be solved, if neat vegetable oils are chemically modified to bio-diesel.

The process of chemical modification is not only used to reduce viscosity, but to increase the cloud and pour points. The higher viscosity of the oil affects the spray pattern, spray angle, droplet size and droplet distribution. Bio-diesels derived from vegetable oils present a very promising alternative to diesel fuel since biodiesels have numerous advantages compared to fossil fuels as they are renewable, biodegradable, provide energy security and foreign exchange savings besides addressing environmental concerns and socio-economic issues. Experiments were carried out (Canakei et al., 2005; Jiwak Suryawanshi et al., 2006; Raheman et al., 2007; Radhwan et al., 2007; Banapurmath et al., 2008; Magin et al., 2008; Murugesan et al., 2009; Sahoo et al., 2009; Mustafa et al., 2009; Jindal et al., 2010; Venkatramn et al., 2010) with bio-diesel on CE and reported performance was compatible with pure diesel operation on CE. 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. Hence grading of LHR engines is done as per the degree of insulation. Low grade engines are ceramic coated engines, medium grade LHR engines are air gap insulated engines and high grade LHR engines are the combination of low and medium grade LHR engines Several methods adopted for achieving LHR to the coolant are i) using ceramic coatings on piston, liner and cylinder head ii) creating air gap in the piston and other components with low-thermal conductivity materials like superni (an alloy of nickel whose thermal conductivity is one sixteenth of that of aluminum alloy), cast iron and mild steel etc.. Ceramic coatings provided adequate insulation and improved brake specific fuel consumption (BSFC) which was reported by various researchers. However previous studies (Parlak et al., 2005; Ekrem et al., 2006; Ciniviz, et al., 2006; Hanbey Hazar et al., 2009; Modi et al., 2010 Rajendra Prasath et al., 2010) 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. Air gap was created (Rama Mohan et al., 1999) in the nimonic piston crown and experiments were conducted with pure diesel and reported that BSFC increased by 7% with varied injection timings. Investigations were carried (Murali Krishna, 2004) with air gap insulated piston with superni crown and air gap insulated liner with superni insert with varied injection pressures and injection timings with alternate fuels of alcohols and vegetable oils and reported LHR engine improved efficiency and decreased pollution levels.

Since interest is beginning to build up in the area of bio-diesel, the present paper attempted to evaluate the performance of LHR engine, which contained an air gap insulated piston air gap insulated liner and ceramic coated cylinder head with different operating conditions of MOBD with varying engine parameters of change of injection pressure and timing and compared with CE at recommended injection timing and injection pressure.

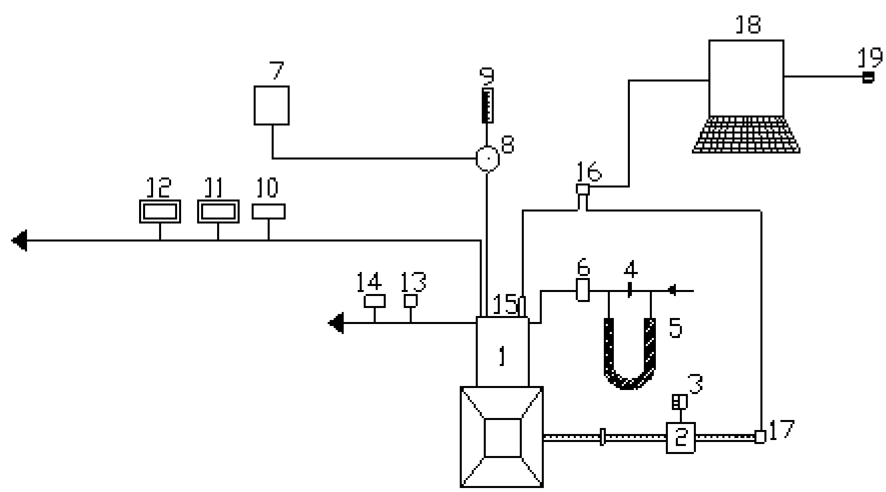
2. MATERIALS AND METHODS

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 of converting the oil into methyl esters was carried out by heating the oil with the methanol in the presence of the catalyst (Sodium hydroxide). In the present case, 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 is 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. The properties of the vegetable oil ester and the diesel used in this work are presented in Table-1. 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 (Magin et al., 2008) 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. Partially stabilized zirconium (PSZ) of thickness 500 microns was coated on inside portion of cylinder head.

Table 1. Properties of test fuels

Test Fuel	Viscosity at 25°C (Centi-poise)	Density at 25°C	Cetane number	Calorific value (kJ/kg)
Diesel	12.5	0.84	55	42000
Mohr oil (esterified)	53	0.87	55	37500

The experimental setup used for the investigations of LHR diesel engine with MOBD is 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 rate 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 brake power of the engine. 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.



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

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 bars due to practical difficulties involved. Exhaust gas temperature (EGT) was measured with thermocouples made of iron and iron-constantan. Pollution levels of smoke and NO_x were recorded by AVL smoke meter and Netel Chromatograph NOx analyzer respectively at the peak load operation 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.

3. RESULTS AND DISCUSSION

3.1 Performance Parameters

From Fig. 2, the use of biodiesel on the CE showed compatible performance for the for entire load range when compared with the pure diesel operation on CE at recommended injection timing. BTE increased up to 80% of the full load and later it decreased in CE with biodiesel operation. 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 biodiesel provided a possible explanation for the compatible performance with biodiesel operation. 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.

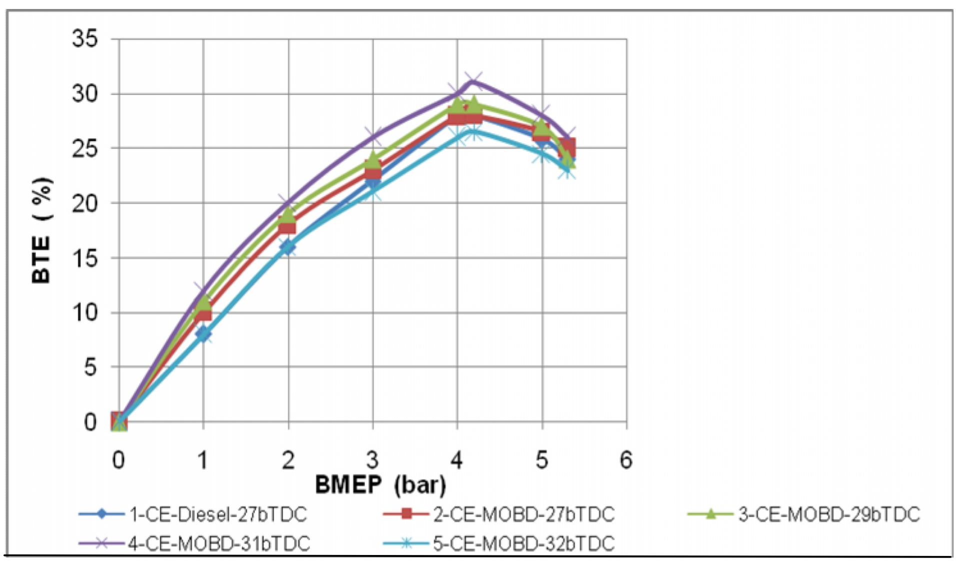


Fig. 2. Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in conventional engine (CE) at different injection timings with mohr oil based bio diesel (MOBD) oil operation

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 oil and reduced the impingement of the fuel spray on combustion chamber walls, causing efficient combustion thus improving BTE.

Curves from Fig. 3 indicate that the LHR version of engine showed improvement in the performance for the entire load range compared with CE using pure diesel. 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. This was due to increase of fuel conversion efficiency up to 80% of the full load operation and increase of friction power beyond that load. 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.

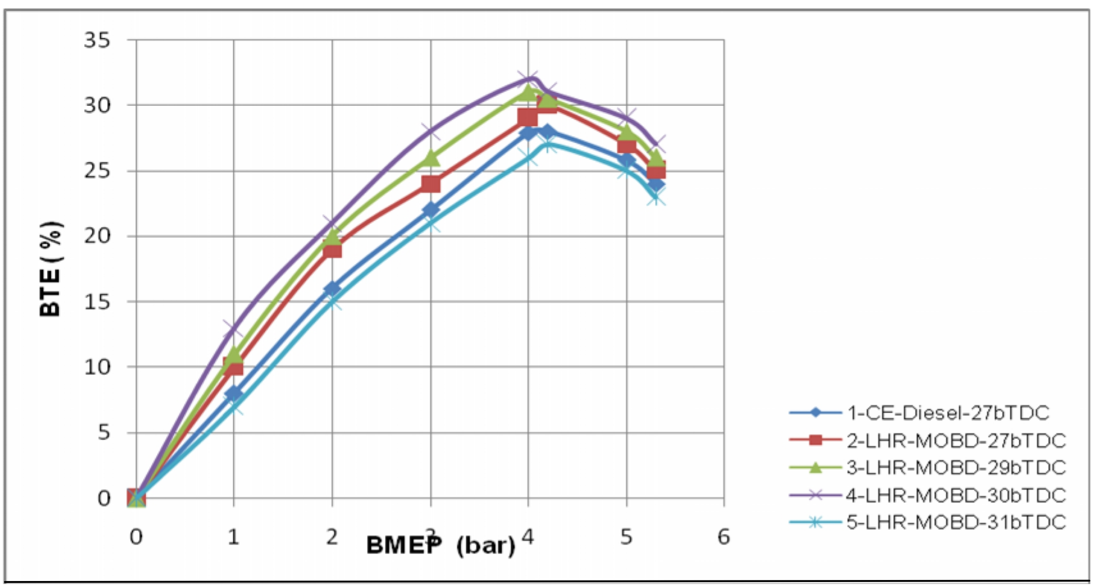


Fig. 3. Variation of BTE with BMEP in LHR engine at different injection timings with MOBD operation

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 30°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 biodiesel operation.

Fig. 4 indicates that at optimum injection timing, BTE with LHR engine at its optimum injection timing was higher than CE. Decrease of combustion duration and better evaporation rates would help in increasing the efficiency of LHR engine.

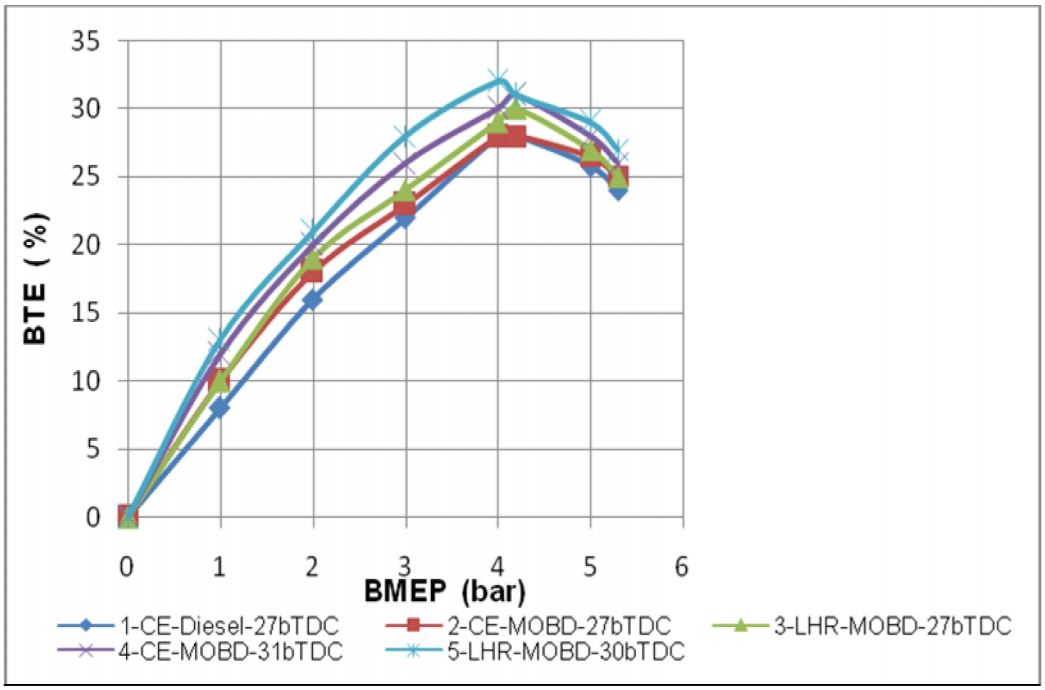


Fig. 4. Variation of BTE with BMEP in different versions of the engine at the recommended injection timing and optimum injection timing at an injection pressure of 190 bar

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 could be noticed that 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 2. 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	--
	MOBD	28	29	29	30	30	31	30	31	31	32	32	33
29	DF	28.5	--	29.5	--	30.2		29.5	--	30.5	--	31	--
	MOBD	29	30	30	31	31	32	31	32	32	33	33	34
30	DF	29	---	30	--	30.5	--	29	--	30	--	30.5	--
	MOBD	30	31	31	32	30.5	31.5	32	33	33	34	34	35
31	DF	29.5	--	30	--	31	--	--	--	--	--	--	--
	MOBD	31	32	30.5	31.5	30	31	31	31.5	31.5	32	32.5	33
32	DF	30		30.5		30.5							
	MOBD	30	31	29	30	30	31	--	--	--	--	--	--
33	DF	31		31		30	---	--	--	--	--	--	-

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

From the Fig. 5, it could be observed 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. 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 was improved with LHR engine over CE with biodiesel operation. The value of exhaust gas temperature 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 value of EGT, compared with normal biodiesel in both versions of the engine.

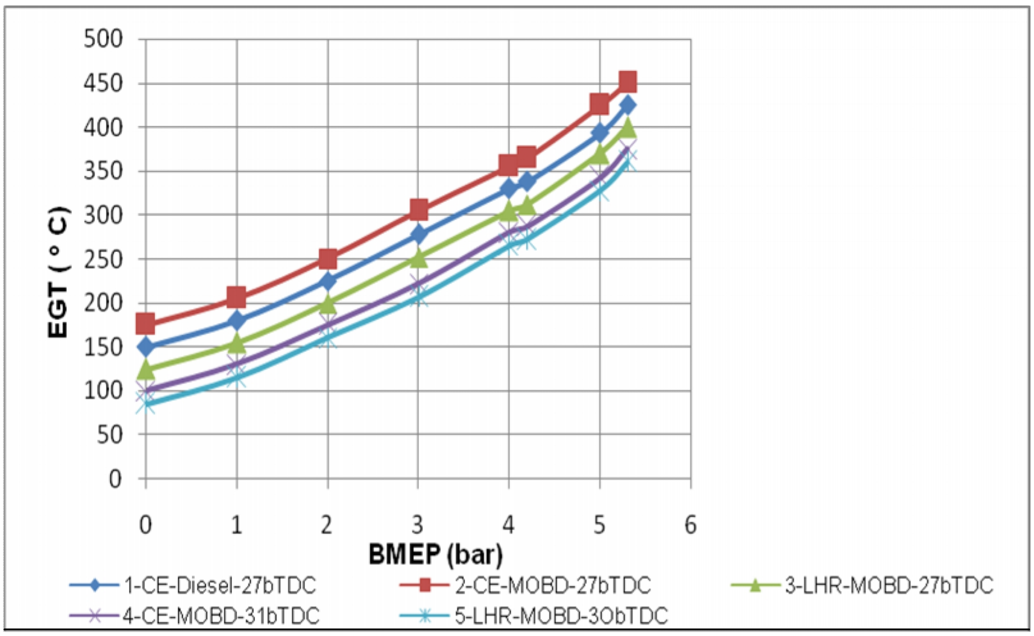


Fig. 5. Variation of exhaust gas temperature (EGT) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with MOBD operation

From the Table-3, it could be 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 3. Data of EGT at peak load operation

Injection timing (°b TDC)	Test Fuel	EGT at the peak load (°C)											
		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
	DF	425	--	410	---	395	--	460	---	450	--	440	--
27	MOBD	450	425	425	400	400	375	400	375	375	350	350	325
29	DF							440		430		420	
	MOBD	425	400	400	375	375	350	380	360	360	340	340	320
	DF	410	---	400	--	385	---	460	---	450	--	440	--
30	MOBD	400	375	375	350	400	375	360	340	340	320	320	300
	DF	400	---	390	--	375	---	450	---	445	---	440	---
31	MOBD	375	350	400	375	425	400	400	380	380	360	360	340
32	DF	390		380		380							--
	MOBD	430	410	410	390	390	370	-------	---	---	----	---	-
33	DF	375	---	375	---	400	--	--	--	--	---	--	--

It can be observed in Fig. 6 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 is 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.

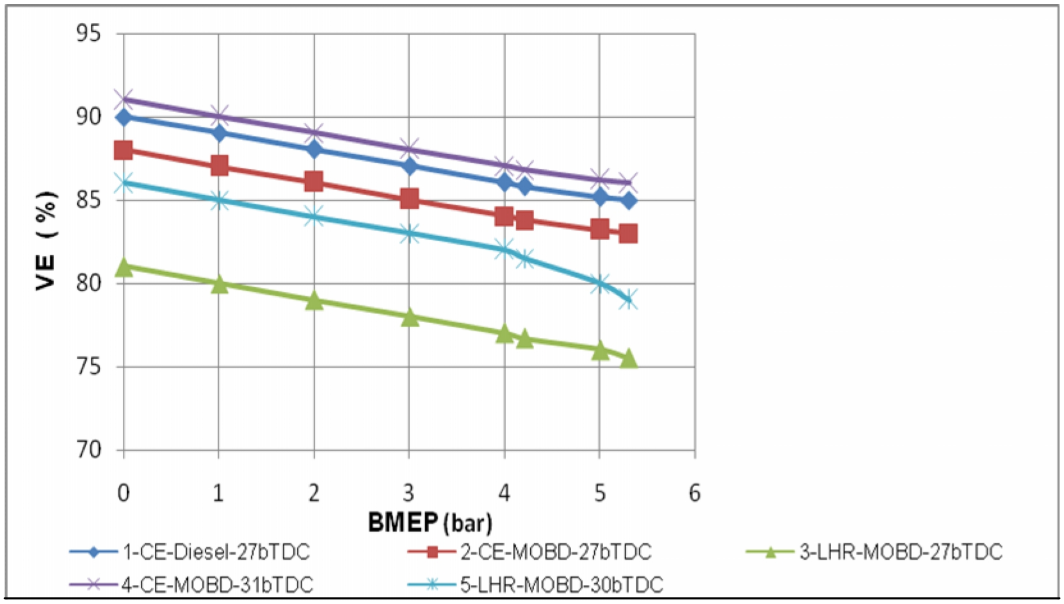


Fig. 6. Variation of volumetric efficiency (VE) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with MOBD operation

VE increased marginally in CE and LHR engine at optimized injection timings when compared with recommended injection timing 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.

Table-4 shows data of volumetric efficiency at peak load operation with varied injection timing and injection pressure with MOBD operation.

VE increased with increase of injection pressure and with advanced injection timing in both versions of the engine. 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 biodiesel.

Table 4. Data of volumetric efficiency at peak load operation

Injection timing (° bTDC)	Test Fuel	Volumetric efficiency (%)											
		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
	DF	85	--	86	--	87	--	78	--	80	--	82	--
27	MOBD	83	84	84	85	85	86	75.5	76.5	76.5	77.5	77.5	78.5
29	DF	86		87		88		78.5		80.5		82.5	
	MOBD	84	85	85	86	86	87	77	77.5	78.5	79.5	79.5	80.5
	DF	86	--	87	--	88	---	76	--	77	--	78	--
30	MOBD	85	86	86	87	85	86	78	78.5	78.5	79	79	79.5
31	DF	87	--	87.5	--	89	--						
	MOBD	86	87	85	86	84	85	77	78	78	78.5	78.5	79
32	DF	87.5	--	88	--	87	--	-	--	-	--	--	-
	MOBD	80	81	81	82	82	83	--	--	--	--	--	--
33	MOBD	89	--	89	--	86	--	--	--	--	--	--	--

3.2 Exhaust Emissions

The accuracy of the instruments for measuring smoke levels and NOx levels is 99.99%. Fig. 7 indicates that the magnitude of smoke intensity increased from no load to full load in both versions of the engine with test fuels. During the first part, the smoke level was more or less constant, as there was always excess air present. However, in the higher load range there was an abrupt rise in smoke levels due to less available oxygen, causing the decrease of air-fuel ratio, leading to incomplete combustion, producing more soot density. The variation of smoke levels with the brake power 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.

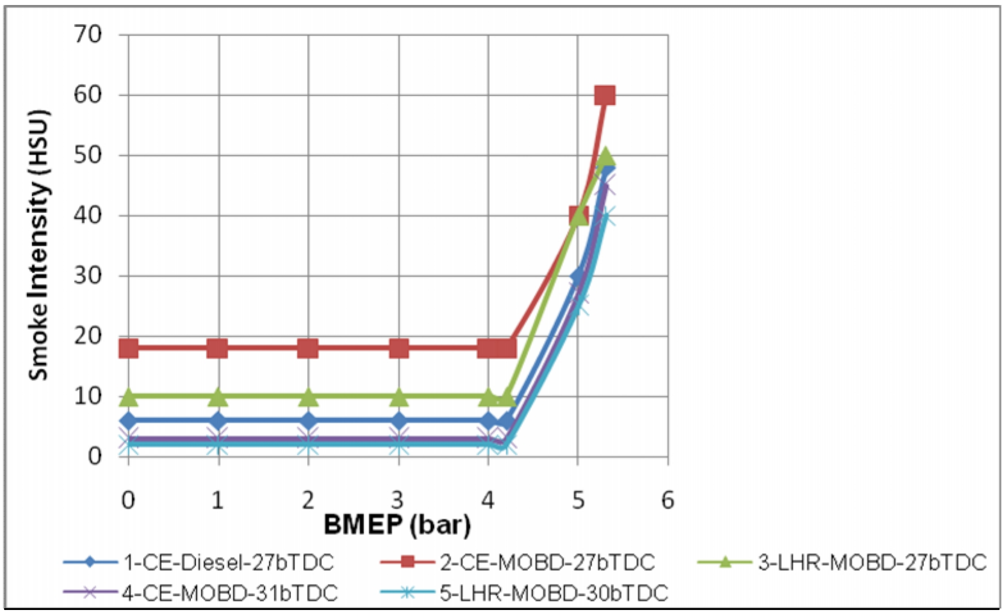


Fig. 7. Variation of smoke intensity in hartridge smoke unit (HSU) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with MOBD

Drastic increase of smoke levels at peak load operation in CE with biodiesel was observed compared with pure diesel operation on CE. This was due to the higher value of 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. Since biodiesel has higher density compared to diesel fuels, smoke levels are higher with biodiesel. 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. Smoke levels suddenly increased at nearly 80% of the full load in all versions of the engine with different test fuels. A rich fuel–air mixture results in higher smoke because of the availability of oxygen is less. The magnitude of smoke intensity increased from no load to full load in both versions of the engine. During the first part, the smoke level is more or less constant, as there is always excess air present. However, in the higher load range there is an abrupt rise in smoke levels due to less available oxygen, causing the decrease of air-fuel ratio, leading to incomplete combustion, producing more soot density. The variation of smoke levels with the brake power typically shows a U-shaped behavior due to the predominance of hydrocarbons in their composition at light load and of carbon at high load. The magnitude of smoke levels was less for entire load range in both versions of the engine, at their respective optimum injection timings, when compared to the CE with pure diesel operation at the recommended injection timing.

This was due to increase of air fuel ratios, causing effective combustion in both versions of the engine at their respective optimum injection timings. Preheating of the biodiesel 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 biodiesel, 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.

The data from Table- 5 shows a decrease in smoke levels with increase of injection timing and the injection pressure in both versions of the engine, with different operating conditions of the biodiesel. 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. The reason for reduction of smoke levels in the LHR engine was reduction of gas temperatures, with the availability of more of oxygen.

Table 5. Data of smoke levels in hartridge smoke unit 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	50	45	45	40	40	35
29	DF	40	--	36	--	34							
	MOBD	55	50	50	45	45	40	45	40	40	35	35	30
	DF	36	--	34	--	32	--	45	--	42	--	41	--
30	MOBD	50	45	45	40	50	45	40	35	35	30	30	25
	DF	33	---	32	--	30	--	43	--	41	--	40	--
31	MOBD	45	40	50	45	55	50	45	40	40	35	35	30
	DF	32	--	31	--	32	--	--	--	--	---	--	--
32	MOBD	50	45	45	40	45	40	--	--	--	--	---	-
33	DF	30	---	30	--	35	--	-	--	--	--	--	--

This was confirmed by the observation of improved air fuel ratios with the increase of injection pressure and with the advancing of the injection timing with both versions of the engine.

Fig. 8 indicates for both versions of the engine, NOx concentrations raised steadily as the fuel/air ratio increased with increasing BP/BMEP, at constant injection timing. At part load, NOx concentrations were less in both versions of the engine. This was due to the availability of excess oxygen. At remaining loads, NOx concentrations steadily increased with the load in both versions of the engine. This was because, local NOx concentrations raised from the residual gas value following the start of combustion, to a peak at the point where the local burned gas equivalence ratio changed from lean to rich.

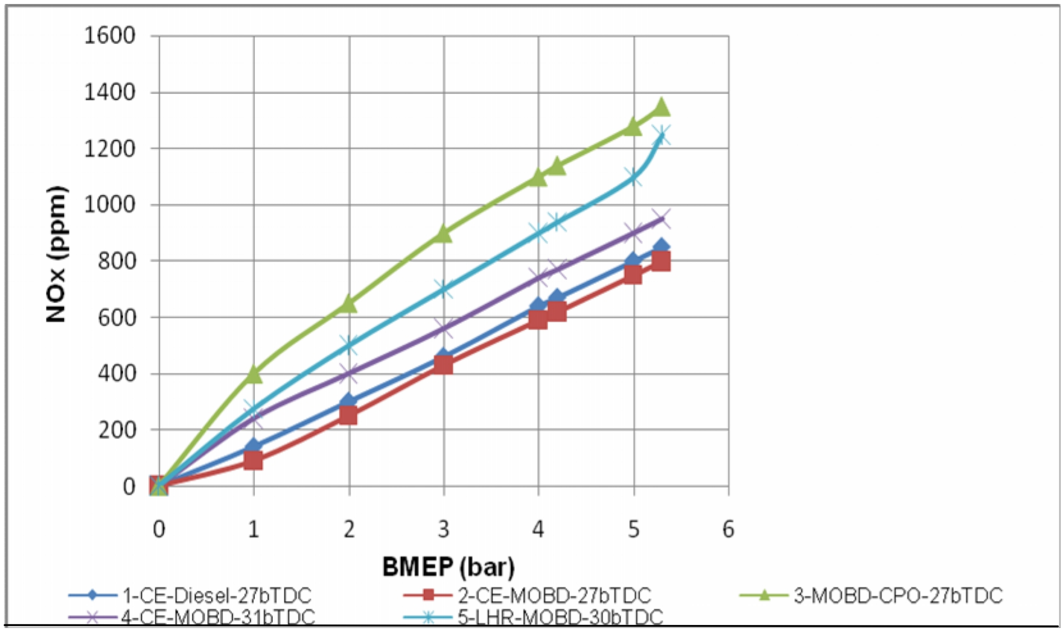


Fig. 8. Variation of NOx levels with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with MOBD operation

At peak load, with higher peak pressures, and hence temperatures, and larger regions of close-to-stoichiometric burned gas, NOx levels increased in both versions of the engine. Though amount of fuel injected decreased proportionally as the overall equivalence ratio was decreased, much of the fuel still burns close to stoichiometric. Thus NOx emissions should be roughly proportional to the mass of fuel injected (provided burned gas pressures and temperature do not change greatly). It could be 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 LHR engine.

The data in Table-6 shows that, NOx levels increased with the advancing of the injection timing in CE with different operating conditions of biodiesel.

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.

3.3 Combustion Characteristics

From Table-7, it could be observed 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 biodiesel. TOPP was more with different operating conditions of biodiesel 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. This trend of increase of MRPR and decrease of TOMRPR indicated better and faster energy substitution and utilization by biodiesel, which could replace 100% diesel fuel. However, these combustion characters were within the limits hence the biodiesel could be effectively substituted for diesel fuel.

Table 6. 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	1350	1300	1300	1250	1250	1200
29	DF	900	--	860	--	820	--						
	MOBD	850	800	800	750	750	700	1300	1250	1250	1200	1200	1150
30	DF	935	---	900	---	860	--	1225	--	1205	--	1185	--
	MOBD	900	850	850	800	800	750	1250	1200	1200	1150	1150	1100
	DF	1020	---	980	---	940	---	1150	--	1130	--	1110	--
31	MOBD	950	900	900	850	850	800	1300	1250	1250	1200	1200	1150
	DF	1105	----	1060	---	1020	---	--	--	--	--	--	--
32	MOBD	1000	950	950	900	900	850	--	-	--	--	--	-
33	DF	1190	----	1150	---	1110	---	--	--	--	--	--	-

Table 7. 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	59.8	60.7	63.1	64.8	3.3	3.4	3.5	3.5	10	9	9	8	1	1	1	1
30/MOBD	LHR	62.5	63.8	65.1	65.8	3.7	3.9	3.9	4.0	9	8	8	8	0	0	0	0
32/MOBD	CE	53.3	54.6			3.5	3.7			10	9			0	0		

4. CONCLUSIONS

BTE increased up to 80% of the full load operation and beyond this load it decreased in all versions of the engine with test fuels. At all loads, biodiesel operation at 27°bTDC on CE showed the compatible performance, while LHR engine showed improvement in the performance, when compared with pure diesel operation on CE. Peak BTE increased by 7% and EGT decreased by 25°C with LHR engine with biodiesel operation in comparison with pure diesel operation on CE. 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 at 30°bTDC at an injection pressure of 190 bar. At the recommended injection timing and pressure, VE decreased by 11% with LHR engine with biodiesel operation, in comparison with pure diesel operation on CE. At the recommended injection timing and pressure, biodiesel operation on CE increased smoke levels by 25%, decreased NOx levels by 6%, while LHR engine increased smoke levels by 5% and NOx levels by 59% when compared with pure diesel operation on CE. With biodiesel operation on CE, preheated biodiesel decreased smoke levels by 8% and NOx levels by 6% when compared with normal condition of biodiesel. In LHR version of the engine, preheated biodiesel decreased smoke levels by 10% and NOx levels by 3% in comparison with normal biodiesel. 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. At recommend injection timing and pressure, lower peak pressures and higher TOPP were observed with normal biodiesel in CE in comparison with pure diesel operation on CE. With biodiesel operation, LHR engine increased PP and decreased TOPP when compared with CE. Preheating increased PP and decreased TOPP when compared with normal biodiesel on both versions of the engine. With advanced injection timing and increase of injection pressure, combustion parameters improved in both versions of the engine with different operating conditions of the biodiesel.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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