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Performance, Emissions and Combustion Characteristics of Waste Fried Vegetable Oil in Based Biodiesel in High Grade Low Heat Rejection Diesel Engine

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Authors' contributions

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

Research Article

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ABSTRACT

Aims: Aim: Experiments were conducted to evaluate the performance of a 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 waste fried vegetable oil based biodiesel with varied injection pressure and injection timing and compared the performance with pure diesel operation on CE.
Study Design: Performance parameters of BTE, BSEC, EGT, VE, CL, Sound intensity were determined at various values of BMEP of the engine.
Methodology: Exhaust emissions of smoke and NOx were recorded at different values of BMEP of the engine. Combustion characteristics at peak load operation of the engine were

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measured with TDC encoder, pressure transducer, console and special pressure-crank angle software package.

Results: Conventional engine (CE) showed compatible performance, while LHR engine showed improved performance with waste fried vegetable oil based biodiesel at recommended injection timing and pressure. The performance of both versions of the engine was improved with advanced injection timings and at higher injection pressure when compared with CE with pure diesel operation. The optimum injection timing was 33ºbTDC with CE while it was 32ºbTDC for LHR engine with biodiesel operation. Relatively, peak brake thermal efficiency increased by 18%, brake specific energy consumption decreased by 6%, exhaust gas temperature decreased by 75ºC, volumetric efficiency decreased by 5%, coolant load decreased by 30%, sound intensity decreased by 35%, smoke levels decreased by 27% and oxides of nitrogen levels increased by 41% with biodiesel operation on LHR engine at its optimum injection timing, when compared with pure diesel operation on CE at manufacturer's recommended injection timing.

Keywords: Alternate fuels; LHR engine; fuel performance; exhaust emissions; combustion characteristics.

ABREVIATIONS

AVL: A company name; BMEP: Brake mean effective pressure in bar; BP: Brake power in Kw; BSEC: Brake specific energy consumption in kW/kW; BSFC: Brake specific fuel consumption in kg/kW-h; bTDC: Before top dead centre in degrees; BTE: Brake thermal efficiency in %; C: Number of carbon atoms in fuel composition; CE: Conventional engine; CL: Coolant load in kW; CV: Calorific value of the fuel in kJ/kg; DF: Diesel fuel; EGT: Exhaust gas temperature in degree centigrade; G- Giga; H: Number of hydrogen atoms in fuel composition; HSU: Hartridge smoke unit; LHR: Low heat rejection; MRPR: Maximum rate of pressure rise in bar/degree; NOx: Oxides of nitrogen in ppm; NT: Normal temperature in degree centigrade; Pa- Pascal; PP: Peak pressure in bar; Ppm: Parts per million; PT: Preheated temperature in degree centigrade; St: Stoke; TDC: Top dead centre; TOMRPR: Time of occurrence of maximum rate of pressure rise in degrees; TOPP: Time of occurrence of peak pressure in degrees; VE: Volumetric efficiency in %; WFVOBD: Waste fried vegetable oil based biodiesel.

1. INTRODUCTION

The civilization of a particular country has come to be measured on the basis of the number of automotive vehicles being used by the public of the country. The tremendous rate at which population explosion is taking place imposes expansion of the cities to larger areas and common man is forced, these days to travel long distances even for his/her routine works. This in turn is causing an increase in vehicle population at an alarm rate thus bringing in pressure in Government to spend huge foreign currency for importing crude petroleum to meet the fuel needs of the automotive vehicles. The large amount of pollutants emitting out from the exhaust of the automotive vehicles run on fossil fuels is also increasing as this is proportional to number of vehicles. In view of heavy consumption of diesel fuel involved in not only transport sector but also in agricultural sector and also fast depletion of fossil fuels, the search for alternate fuels has become pertinent apart from effective fuel utilization which has been the concern of the engine manufacturers, users and researchers involved in combustion & alternate fuel research.

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. However, 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 mentioned problems can be solved once vegetable oils are converted chemically into biodiesel. 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. These biodiesels have lower viscosity, density, molecular weight and ratio of carbon to hydrogen. Experiments were conducted [2-5] with conventional engine fuelled with biodiesel and it was reported that performance was compatible with conventional engine. The drawbacks associated with biodiesel for use as fuels in compression ignition engine call for LHR diesel engine.

The concept of low heat rejection engine is to reduce the heat flow to the coolant by providing thermal insulation in the path of the heat flow to the coolant. Several methods were adopted for achieving low heat rejection to the coolant. They are classified as low grade, medium grade and high grade LHR engines Low grade engines contained ceramic coatings, which were provided on engine components like piston, liner and cylinder head. Medium grade LHR engines consisted of an air gap created in the piston and the liner with inserts made of low thermal conductivity materials like superni (an alloy of nickel), cast iron and mild steel etc. High grade LHR engine was the combination of low grade and medium grade LHR engines. LHR engines with ceramic coatings fuelled with pure diesel operation provided adequate insulation and improved brake specific fuel consumption which was reported by various researchers [6-8]. However their studies revealed that the thermal efficiency variation of LHR engine not only depended on the heat recovery system, but also depends on the engine configuration, operating condition and physical properties of the insulation material. Experiments were conducted on medium grade LHR engine [9] consisted of air gap insulated piston with superni crown, threaded with the body of the piston fuelled with pure diesel operation with varied injection timing and reported that brake specific fuel consumption decreased by 7% at advanced injection timing of 29.5ºbTDC. Investigations were carried out [10-13] with ceramic coated LHR engines operated with biodiesel and it was reported that thermal efficiency marginally increased, smoke emissions decreased and oxides of nitrogen emissions increased with LHR engine. Experiments were conducted [14-15] on LHR engine with air gap insulated piston with superni crown, and air gap insulated liner with superni insert fuelled with biodiesel with varied injection timing and injector opening pressure and it was reported that performance improved and exhaust emissions of smoke and NOx decreased with increase of injection pressure. Investigations were carried out [16] with LHR engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head fuelled with jatropha oil and pongamia oil based bio-diesel and reported that LHR engine improved performance, decreased smoke levels and increased NOx levels. Sound intensity was important parameter to be measured [13-15] for assessing combustion phenomena. Sound intensity was drastically increased with conventional engine with vegetable oil and biodiesel and decreased with LHR engine. Sound levels decreased with increase of injector opening pressure and advanced injection timing. Sound levels decreased with preheated vegetable oil and biodiesel when compared with normal vegetable oil.

Little literature was available in evaluating the performance of LHR engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head with varying engine parameters at different operating conditions of the waste fried vegetable oil based biodiesel.

There was an attempt to evaluate the performance of LHR engine, which contained an air gap insulated piston with superni crown, air gap insulated liner with superni insert and ceramic coated cylinder head with different operating conditions of waste fried vegetable oil based biodiesel with varied engine parameters of change of nozzle opening pressure and injection timing and compared with conventional engine with pure diesel operation at recommended injection timing and injection pressure.

2. METHODS AND MATERIALS

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 (waste fried vegetable oil) was stirred with methanol at around 60-70ºC 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 separated 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 (biodiesel). The physic-chemical properties of the biodiesel in comparison to ASTME biodiesel standards are presented in Table 1. Biodiesel was heated to a temperature (preheated temperature-90ºC) till its viscosity was matched to that of diesel fuel.

Table 1. Physico-chemical properties of test fuels compared to ASTM biodiesel standards [17]

Property	Units	Diesel	Biodiesel
Carbon chain	--	C_8-C_{28}	C_{16}-C_{24}
Cetane Number		55	50
Density	gm/cc	0.84	0.87
Bulk modulus @ 20Mpa	Mpa	1475	1800
Kinematic viscosity @ 40ºC	cSt	2.25	4.2
Sulfur	%	0.25	0.0
Oxygen	%	0.3	11
Air fuel ratio (stochiometric)	--	14.86	13.8
Lower calorific value	kJ/kg	42 000	37000
Flash point (Open cup)	ºC	66	174
Molecular weight	--	226	261
Colour	--	Light yellow	Yellowish orange

The LHR diesel engine contained a two-part piston - the top crown made of low thermal conductivity material, superni was screwed to aluminum body of the piston, providing a

3mm-air gap in between the crown and the body of the piston. The optimum thickness of air gap in the air gap piston was found to be 3 mm [9] for improved 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. The photograph of ceramic coated cylinder head was shown in Plate 1. The specifications of the test engine were given in Table 2.

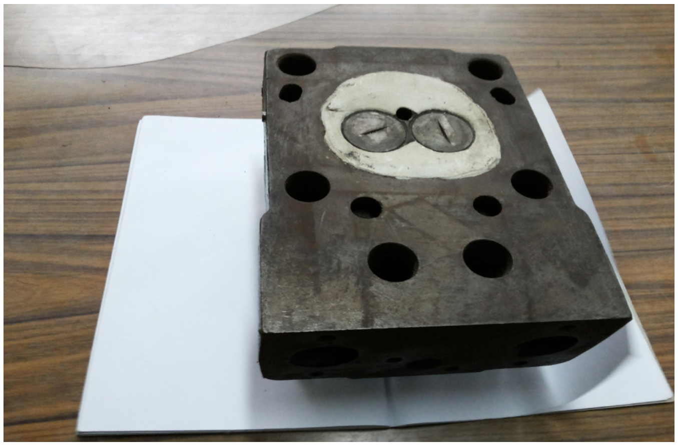

Plate 1. Photographic view of the ceramic coated cylinder head

Table 2. Specifications of the Test Engine

Description	Specification
Engine make and model	Kirloskar (India) AV1
Maximum power output at a speed of 1500 rpm	3.68 kW
Number of cylinders ×cylinder position× stroke	One × Vertical position × four-stroke
Bore × stroke	80 mm × 110 mm
Method of cooling	Water cooled
Rated speed (constant)	1500 rpm
Fuel injection system	In-line and direct injection
Compression ratio	16:1
BMEP @ 1500 rpm	5.31 bar
Manufacturer's recommended injection timing and pressure	27ºbTDC × 190 bar
Dynamometer	Electrical dynamometer
Number of holes of injector and size	Three × 0.25 mm
Type of combustion chamber	Direct injection type

The experimental setup used for the investigations of LHR diesel engine with biodiesel is shown in Fig. 1. The combustion chamber consisted of a direct injection type with no special arrangement for swirling motion of air. The engine was connected to an 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 an air-box method. The naturally aspirated engine was provided with water-cooling system in which inlet temperature of water was maintained at 60ºC 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. EGT was measured with thermocouples made of iron and iron-constantan. 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. Sound intensity was measured with sound analyzer at different values of BMEP of the engine. The specifications of the gas analyzers were given in Table 3.

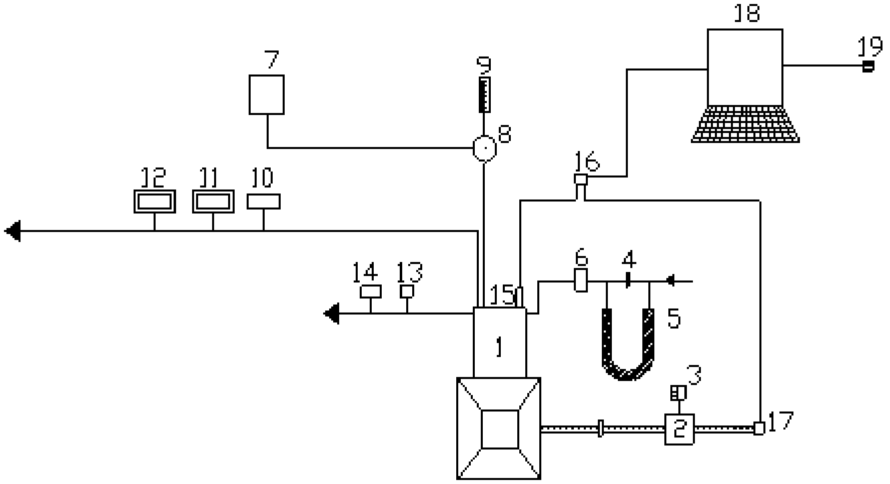

Fig. 1. Experimental Set-up

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.

Table 3. Specifications of exhaust gas analyzer

Name of the analyzer	Measuring range	Precision	Resolution
AVL Smoke meter	0-100 HSU	1 HSU	1 HSU
Netel Chromatograph NOx analyzer	0-2000 ppm	2 ppm	1 ppm
Sound Analyzer	0-150 Decibels	1 decibel	1 decibel

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 PP, TOPP, MRPR and 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 test fuels used in the experimentation were pure diesel and waste fried oil based biodiesel. The various configurations of the engine were CE and LHR. Different operating conditions of the biodiesel were NT and PT. The different injection pressures attempted in this experimentation were 190 bar, 230 bar and 270 bar.

3. RESULTS AND DISCUSSION

3.1 Performance Parameters

From Fig. 2 it indicates that biodiesel in CE with biodiesel operation showed compatible performance at all loads when compared with the pure diesel operation on CE at 27ºbTDC. This was due to difference between calorific value and viscosity between diesel and biodiesel. However, high density compensates the lower value of the heat of combustion of the biodiesel. Higher value of viscosity of biodiesel reduces leakage in plunger and barrel of the fuel pump. Minimum viscosity limits are imposed (preheated condition) to prevent the fuel from causing the wear in the fuel injection pump. As the injection timing was advanced with CE with biodiesel, BTE increased at all loads. 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 33ºbTDC in the CE at the normal temperature of biodiesel. The increase of BTE at optimum injection timing over the recommended injection timing with CE fuelled with biodiesel was attributed to its longer ignition delay and combustion duration.

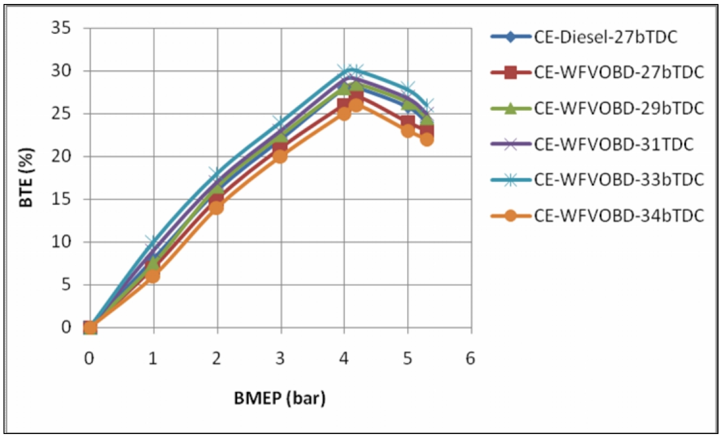

Fig. 2. Variation of BTE with BMEP in CE at different injection timings with bio diesel (WFVOBD) operation

Curves from Fig. 3 indicate that the BTE increased up to 80% of the peak load and beyond that load it decreased in LHR version of the engine with biodiesel at different injection timings as it was noticed with CE. LHR version of engine with biodiesel operation at 27ºbTDC showed an improvement in the performance at all loads compared with CE with pure diesel. High cylinder temperatures [18] helped in improved evaporation and faster combustion of the fuel injected into the combustion chamber. Reduction of ignition delay [18] of the biodiesel in the hot environment of the LHR engine improved heat release rates [18] and efficient energy utilization. The optimum injection timing was found to be 32ºbTDC with LHR engine with normal biodiesel. 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 32ºbTDC.Since the hot combustion chamber of LHR engine reduced ignition delay and combustion duration and hence the optimum injection timing (32ºbTDC) was obtained earlier with LHR engine when compared with CE (33ºbTDC)with the biodiesel operation.

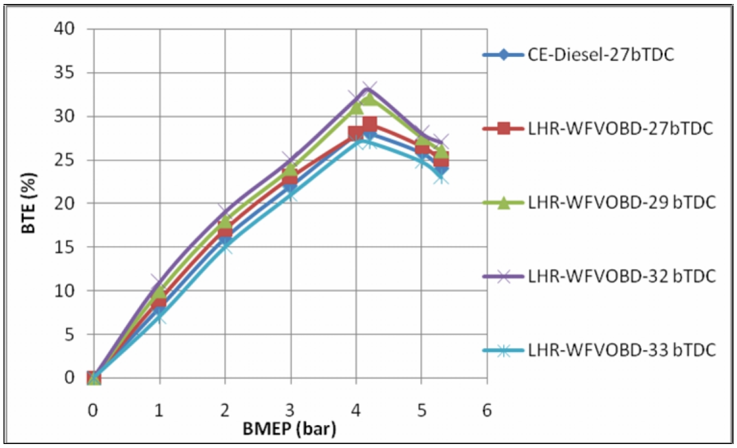

Fig. 3. Variation of BTE with BMEP in LHR engine at different injection timings with biodiesel operation

Fig. 4 indicates that BTE with LHR engine was higher than that of CE at optimum injection timings with biodiesel operation, Decrease of combustion duration and improved evaporation rates and air fuel ratios [18] helped in increasing thermal efficiency of LHR engine.

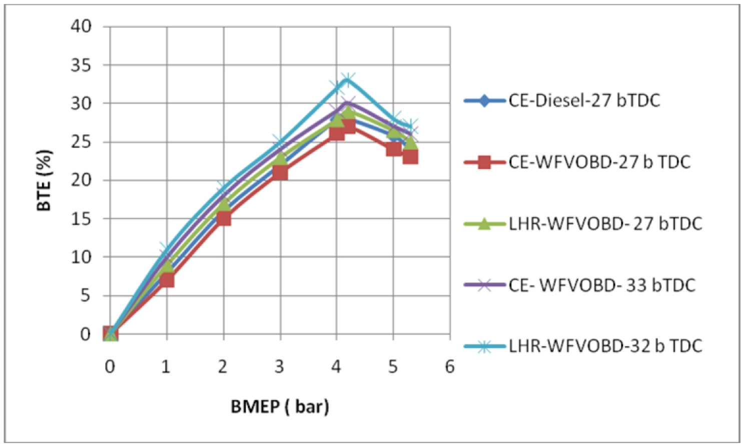

Fig. 4. Variation of BTE with BMEP in different versions of the engine at the recommended injection timing and optimum injection timing at an injection pressure of 190 bar with biodiesel operation

Injection pressure is varied from 190 bars to 270 bar to improve the spray characteristics and atomization of the biodiesel and injection timing is advanced from 27 to 34ºbTDC for CE and LHR engine. As it is observed from Table 4 BTE increased with increase in injection pressure in both versions of the engine at different operating conditions of the biodiesel.

The performance improved further in CE with the preheated biodiesel 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. Optimum injection timing changed with increase of injection pressure with biodiesel. Similarly optimum injection timing was 33ºbTDC at an injection pressure of 190 bar, 32ºbTDC at 230 bar and 31ºbTDC at 270 bar with CE with biodiesel operation. This may be due to change in bulk modulus of the fuel and therefore compressibility of the fuel with the change in injection pressure. However, optimum injection timing remained same for LHR engine with biodiesel.

From Table 5, it is 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.

Bulk modulus and hence compressibility of the fuel also changes with preheating. 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 biodiesel. This was due to initiation of combustion at earlier period and efficient combustion with improved air fuel ratios [18] giving lower BSEC. Bulk modulus of the fuel increased with increase of injection pressure leading to generate higher peak pressure leading to reduce BSEC.

From the Fig. 5, it is observed that CE with biodiesel operation at 27ºb TDC recorded marginally higher EGT at all loads compared with CE with pure diesel operation. Temperature of exhaust gases, leaving the engine cylinder represents the extent of temperature reached in the cylinder during combustion. It is observed that, with increasing load the cylinder pressure increases and more of the fuel is burnt leading to an increase in temperatures as shown in Fig. 5. The temperature of exhaust gases is observed to be lower with fossil diesel as compared to biodiesel for entire range of power output. Though calorific value (or heat of combustion) of fossil diesel is more than that of biodiesel, its density is less in comparison with biodiesel. Therefore lesser the heat is released in the combustion chamber leading to generate lower temperature with diesel operation on CE. Also, there is an advanced combustion of biodiesel due to its higher bulk modulus. However its cetane number is less when compared to fossil diesel. Hence there is no effect of bulk modulus on injection timing (advance or retardation) and heat release. Biodiesel operation on CE exhausted more amount of heat in comparison with pure diesel operation on CE. Lower heat release rates [18] 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. At recommended injection timing. 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 value of EGT decreased with advancing of the injection timing with both versions of the engine with biodiesel operation. At the respective optimum injection timings, the value of EGT was lower with LHR engine than that of CE with biodiesel operation. This was due to more conversion of heat into work with LHR engine than CE.

Table 4. Data of Peak BTE

Injection Timing (ºbTDC)	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	--
	WFVOBD	27	28	28	29	29	30	29	30	30	31	31	32
32	WFVOBD	29.5	30	30	31	29.5	30	33	34	34	35	35	36
33	WFVOBD	30	31	29	30	29.5	30	--	--	--	--	--	--

DE- Diesel fuel, WFVOBD- Biodiesel, WFVO- Crude vegetable oil, NT- Normal temperature , PT- Preheated temperature

Table 5. Data of BSEC at peak load operation

Injection Timing (º 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		4.2		3.92		3.88	
	WFVOBD	4.02	3.96	3.96	3.94	3.94	3.96	3.88	3.84	3.84	3.80	3.80	3.76
32	WFVOBD	3.8	3.78	3.78	3.76	3.88	3.84	3.74	3.70	3.70	3.66	3.66	3.62
33	WFVOBD	3.78	3.76	4.0	3.98	3.98	3.94	3.78	3.74	3.74	3.70	3.70	3.72

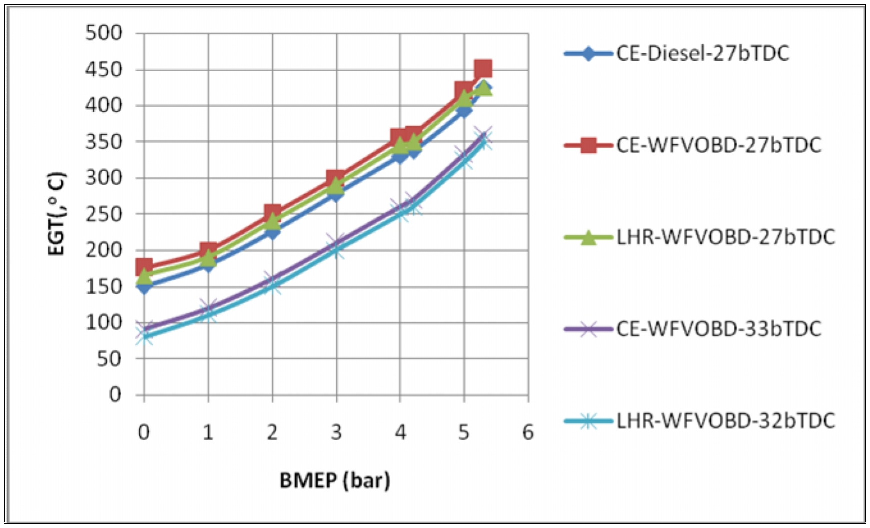

Fig. 5. Variation of EGT with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel operation

From the Table 6, it is observed that EGT decreased with increase of injection pressure and injection timing with both versions of the engine with biodiesel which confirmed that performance increased with increase of injection pressure. This was because of increase of bulk modulus of the fuel with increased injection pressure. Preheating of the biodiesel further reduced the value of EGT, compared with normal biodiesel in both versions of the engine. This was due to improved air fuel ratios [18]. This showed that thermal efficiency increased with preheated condition of the biodiesel when compared with normal condition of the biodiesel leading to less amount of heat rejection and high amount of actual conversion of heat into work.

It can be observed in Fig. 6, that VE decreased with an increase of BMEP in both versions of the engine with biodiesel operation. This was due to increase of gas temperature [18] 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. VE mainly depends on speed of the engine, valve area, valve lift, timing of the opening or closing of valves and residual gas fraction rather than on load variation. Hence with biodiesel operation with CE, VE decreased in comparison with pure diesel operation on CE, as residual gas fraction increased. This was due to increase of deposits with biodiesel operation with CE. The reduction of VE with LHR engine 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 [18] with LHR engine.

From Table 7, VE increased with increase of injection pressure and with advanced injection timing in both versions of the engine with biodiesel. This was also due to improved 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 the biodiesel.

Curves from Fig. 7 indicate that that coolant load (CL) increased with increase of BMEP in both versions of the engine with test fuels. This was due to increase of gas temperatures with increase of fuel consumption. CL was observed to be higher with CE with biodiesel operation when compared with diesel operation on CE. This was because of increase of gas temperatures [18]. However, CL reduced with LHR version of the engine with biodiesel operation when compared with CE with pure diesel operation. Heat output was properly utilized and hence thermal efficiency increased and heat loss to coolant decreased with effective thermal insulation with LHR engine.

CL decreased with advanced injection timing with both versions of the engine with biodiesel. This was due to improved air fuel ratios [18] and reduction of gas temperatures. From Table 8, it is noticed that CL decreased with advanced injection timing and with increase of injection pressure with test fuels. This was because of improved combustion with increase of air fuel ratios [18] and reduction of gas temperatures [18]. 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. This was also because of reduction of bulk modulus of the fuel with preheating, causing lower gas temperatures.

Fig. 8 indicates at recommended injection timing, sound intensities marginally increased in CE with biodiesel operation in comparison with CE with pure diesel operation. Higher viscosity, bulk modulus, duration of combustion and poor volatility caused moderate combustion of biodiesel leading to generate higher 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 the combustion of biodiesel. This was also due to decrease of density and bulk modulus of fuel at higher temperatures leading to produce lower levels of sound with LHR engine. When injection timings were advanced to optimum, sound intensities decreased for both versions of the engine, due to early initiation of combustion and improved air fuel ratios [18].

Table 9 denotes that the Sound intensity decreased with increase of injection pressure for both versions of the engine with the biodiesel. This was because of improved combustion with increased air fuel ratios [18]. This was also due to simultaneous increase of bulk modulus and density. 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 bulk modulus of the fuel.

Table 6. Data of EGT at peak load operation

Injection timing (° b TDC)	Test Fuel	EGT at the peak load (ºC)											
		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	--
	WFVOBD	450	425	425	400	400	375	425	400	400	375	375	350
32	WFVOBD	380	360	360	340	380	360	350	325	325	300	300	280
33	WFVOBD	360	340	380	360	400	380	--	--	--	---	--	--

Table 7. Data of Volumetric efficiency at peak load operation

Injection timing (º bTDC)	Test Fuel	Volumetric efficiency (%)											
		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	85	--	86	--	87	--	78	--	80	--	82	--
	WFVOBD	83	84	84	85	85	86	77	78	78	79	79	80
32	WFVOBD	86	87	87	88	87	88	81	82	82	83	83	84
33	WFVOBD	87	88	89	--	86	--	--	--	--	--	--	--

Table 8. Data of CL at peak load operation

Injection timing (^{o} bTDC)	Test Fuel	Coolant Load (k W)											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	4.0	---	3.8	--	3.6	---	4.5	---	4.3	--	4.1	---
	WFVOBD	4.0	3.8	3.8	3.6	3.6	3.4	3.4	3.2	3.2	3.0	3.0	2.8
32	WFVOBD	3.2	3.0	3.0	2.8	3.2	3.0	2.8	2.6	2.6	2.4	2.4	2.2
33	WFVOBD	3.0	2.8	3.2	3.0	3.4	3.2						

Table 9. Data of sound intensity at peak load operation

Injection timing (ºbTDC)	Test Fuel	Sound Intensity (Decibels)											
		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	--
	WFVOBD	100	95	98	93	96	91	70	65	65	60	60	55
32	WFVOBD	75	89	70	65	75	70	55	50	50	45	45	40
33	WFVOBD	70	65	75	70	80	75	--	--	--	--	--	--

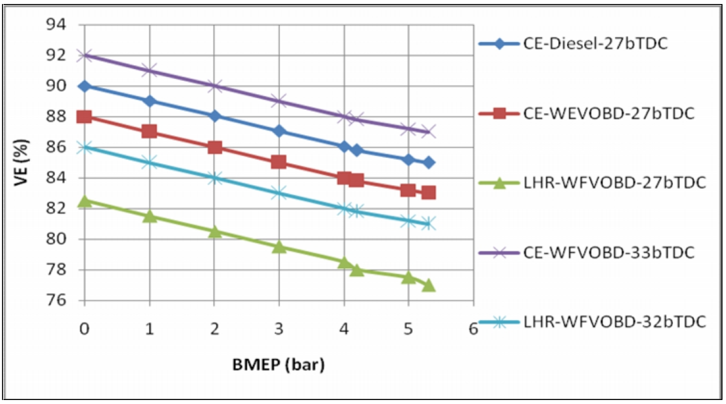

Fig. 6. Variation of VE with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel operation

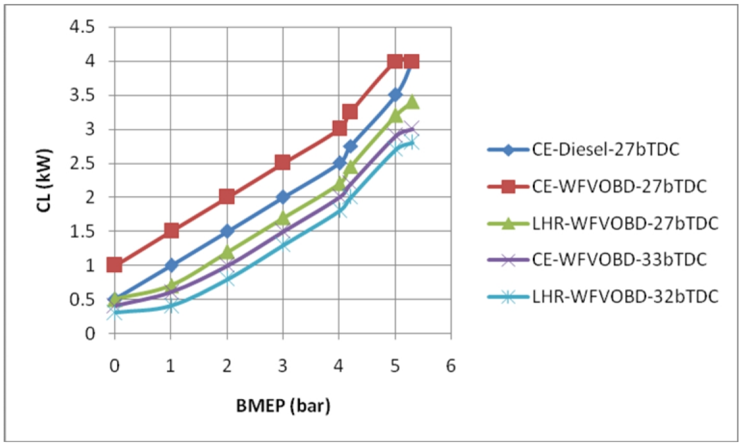

Fig. 7. Variation of CL with BMEP in both versions of the engine at recommended and optimized injection timings with biodiesel operation at an injection pressure of 190 bar

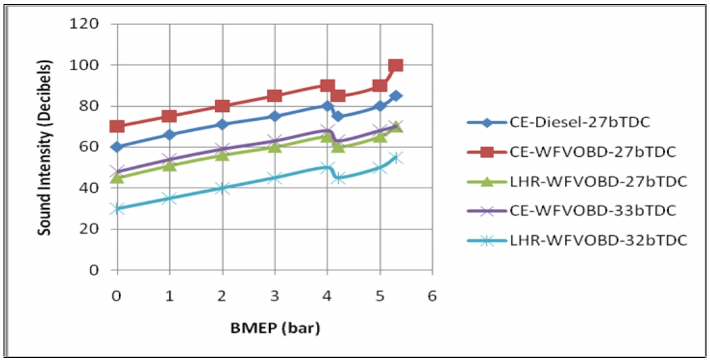

Fig. 8. Variation of sound intensity with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel operation

3.2 Exhaust Emissions

Fig. 9 indicates that the value 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.

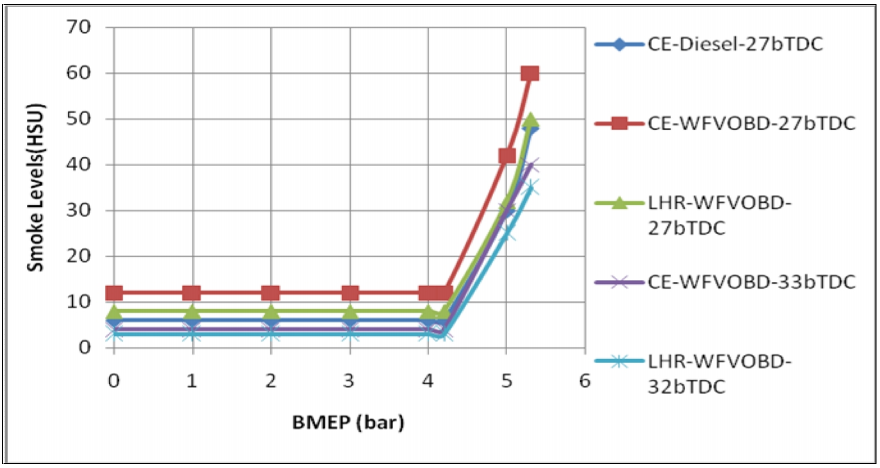

Fig. 9. Variation of smoke intensity in Hartridge Smoke Unit (HSU) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel

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 [18], 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. Marginal increase of smoke levels at all loads with CE fuelled with biodiesel was observed when compared with pure diesel operation on CE. This was due to the higher value of ratio of C/H biodiesel (0.73) when compared with pure diesel (0.45). The increase of smoke levels was also due to decrease of air-fuel ratios [18] and VE. Smoke levels were related to the density of the fuel. Smoke levels were higher with biodiesel due to its high density. However, LHR engine marginally decreased 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. Smoke levels decreased at the respective optimum injection timing with both versions of the engine with biodiesel. This was due to initiation of combustion at early period with both versions of the engine.

The data from Table 10 shows smoke levels decreased 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 with higher injection pressures and increase of air entrainment, at the advanced injection timings, causing lower smoke levels. 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 related 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 was directed into the combustion chamber.

Availability of oxygen and high temperatures are favorable conditions to form NOx levels. Fig. 10 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. 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. Thus NOx emissions should be roughly proportional to the mass of fuel injected (provided burned gas pressures and temperature do not change greatly). It is 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 [18] with the biodiesel operation on CE, which reduced NOx levels. The biodiesel having long carbon chain (C_{16}-C_{24}) is producing more NOx in LHR engine than that of fossil diesel having both medium (C_8-C_{14}) as well as long chain (C_{16}-C_{28}). The increase in NOx emissions in LHR engine might be an inherent characteristic of biodiesel due to the presence of 51.8% of mono-unsaturated fatty acids and 19% of poly-unsaturated fatty acids. Fatty acids are mainly responsible for higher levels of NOx emission [17,19]. Another reason for higher NOx levels in LHR engine is the oxygen (11%) present in the biodiesel. The presence of oxygen in biodiesel leads to improvement in oxidation of the nitrogen available during combustion in the hot environment provided by LHR engine. This will raise the combustion bulk temperature responsible for thermal NOx formation. The production of more NOx with biodiesel in LHR engine is also attributable to an inadvertent advance of fuel injection timing due to higher bulk modulus of compressibility, with the in-line fuel injection system [17]. Biodiesel is less compressible due to the higher bulk modulus, causing nozzle opening pressure to be exceeded prematurely. The earlier injection leads to advancement in combustion timing where a stronger premixed combustion phase follows. This in turn increases the peak in-cylinder temperature, which increases the rate of NOx formation in LHR engine. Increase of combustion temperatures with the faster combustion and improved heat release rates [18] associated with the availability of oxygen in LHR engine caused higher NOx levels.

The data in Table 11 shows that, NOx levels increased with the advancing of the injection timing in CE with different operating conditions of biodiesel.

Table 10. Data of Smoke levels at peak load operation

Injection timing (° bTDC)	Test Fuel	Smoke levels (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	--
	WFVOBD	60	55	55	50	50	45	50	45	45	40	40	35
32	WFVOBD	45	40	40	35	55	50	35	30	30	27	27	25
33	WFVOBD	40	35	45	40	50	45	--	--	--	--	--	--

Table 11. Data of NOx levels at peak load operation

Injection timing (ºbTDC)	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	--
	WFVOBD	800	750	750	700	700	650	1350	1300	1300	1250	1250	1225
32	WFVOBD	950	900	900	850	850	800	1200	1150	1150	1100	1100	1050
33	WFVOBD	1000	950	1050	1000	1100	1050	--	--	--	--	--	--

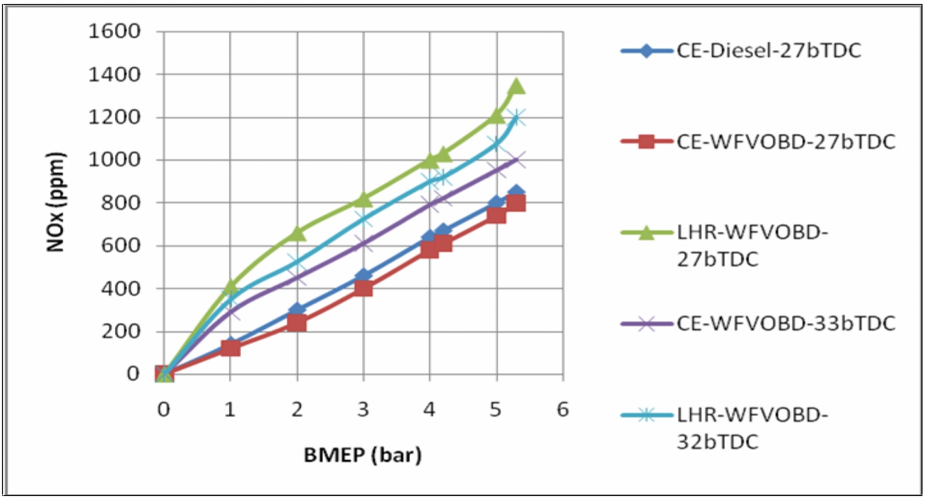

Fig. 10. Variation of NOx levels with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel

Residence time and availability of oxygen had increased, when the injection timing was advanced with biodiesel, which caused higher NOx levels in CE. This was due to higher value of bulk modulus of the biodiesel, which cause changes in injection timing (advanced injection timing) giving rise to higher NOx levels. However, NOx levels decreased marginally with increase of injection timing with in LHR engine at different operating conditions of biodiesel. This was due to decrease of gas temperatures [18] with the increase of air-fuel ratios [18]. NOx levels decreased with increase of injection pressure with different operating conditions of biodiesel. 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 [18] marginally thus leading to decrease in NOx levels. Marginal decrease of NOx levels was observed in LHR engine, due to decrease of combustion temperatures [18] with improved air fuel ratios [18]. The fuel spray properties may be altered due to differences in viscosity and surface tension. The spray properties affected may include droplet size, droplet momentum, and degree of mixing, penetration, and evaporation. The change in any of these properties may lead to different relative duration of premixed and diffusive combustion regimes. Since the two burning processes (premixed and diffused) have different emission formation characteristics, the change in spray properties due to preheating of the biodiesel were lead to reduction in NOx formation. As fuel temperature increased, there was an improvement in the ignition quality, which caused shortening of ignition delay. A short ignition delay period lowered the peak combustion temperature which suppressed NOx formation. Lower levels of NOx was also attributed to retarded injection, improved evaporation, and well mixing of preheated biodiesel due to its low viscosity at preheated temperature of 90ºC. Hence lower levels of NOx were observed with preheated biodiesel in comparison with normal biodiesel.

3.3 Combustion Characteristics

From Table 12, it is 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 higher value of bulk modulus of the biodiesel. PP was slightly higher than that of diesel fuel in LHR engine, even though the CV was lower with biodiesel. The biodiesel advanced the peak pressure position as compared to fossil diesel because of its higher bulk modulus and cetane number. This shift was mainly due to advancement of injection due to higher density or bulk modulus [17] and earlier combustion due to shorter ignition delay caused by higher cetane number of biodiesel in the hot environment provided by LHR engine. When, a high density (or high bulk modulus) fuel was injected, the pressure wave traveled faster from pump end to nozzle end, through a high pressure in-line tube. This caused early lift of needle in the nozzle, causing advanced injection [17]. Hence, the combustion took place very close to TDC and the peak pressure slightly high due to existence of smaller cylinder volume near TDC. But in case of CE, combustion was not proper with high viscous fuel like biodiesel and hence PP was always lower than those of diesel fuel.

The advantage of using LHR engine for biodiesel was obvious as it could burn low cetane and high viscous fuels. Preheated biodiesel registered marginally higher value of PP than normal biodiesel. This was due to reduction of ignition delay. 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 test fuels. 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 produced 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. It is observed that, PP was higher and TOPP was lower with biodiesel operation even though biodiesel has lower CV that that of diesel as biodiesel has higher bulk modulus and compatible cetane number. The value 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 the biodiesel. TOPP was found to be higher with different operating conditions of the biodiesel in CE, 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 form compared with the normal biodiesel. MRPR showed similar trends as those of PP in both versions of the engine at different operating conditions of the biodiesel. This trend of increase of MRPR indicated improved and faster energy substitution and utilization by biodiesel in LHR engine, which could replace 100% diesel fuel. However, these combustion characters were within the limits hence the biodiesel can be effectively substituted for diesel fuel.

Table 12. Data of PP, MRPR and TOPP at peak load operation

Injection timing (ºbTDC) / Test fuel	Engine version	PP(bar)				MRPR (Bar/deg)				TOPP (Deg)			
		Injection pressure (Bar)				Injection pressure (Bar)				Injection pressure (Bar)			
		190		270		190		270		190		270	
		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	--
	LHR	48.1	--	53.0	--	2.9	--	3.1	--	10	--	9	--
27/WFVOBD	CE	49.4	50.6	52.5	53.5	3.2	3.3	3.4	3.5	10	9	10	9
	LHR	51.6	52.8	54.3	55.5	3.3	3.4	3.5	3.6	9	8	9	8
32/WFVOBD	LHR	62.4	63.5	64.3	65.5	3.5	3.6	3.6	3.7	10	9	10	9
33/WFVOBD	CE	54.4	55.6	56.6	57.6	3.4	3.5	3.5	3.6	11	10	11	10

4. CONCLUSIONS

Biodiesel operation on CE showed compatible thermal efficiency, while it improved the performance with LHR engine in comparison with pure diesel operation on CE. Preheating of the biodiesel further increased the performance in both versions of the engine. With biodiesel operation, smoke levels increased and NOx levels decreased with CE while smoke levels decreased and NOx levels increased drastically with LHR engine when compared with pure diesel operation on CE. Combustion characteristics further improved with biodiesel operation on LHR engine compared with diesel operation on CE.

5. RESEARCH FINDINGS

LHR engine with an air gap insulated piston, air gap insulated liner and ceramic coated cylinder head improved the performance with waste fried vegetable oil based biodiesel in comparison with CE with pure diesel operation. However, it increased NOx levels drastically and hence research on reduction of these emissions is a worthy.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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