

Research paper

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

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Author's contributions

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

ABSTRACT

Aim: Experiments were conducted 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 waste fried vegetable oil based biodiesel (WFVOBD) with varied injection pressure and injection timing and compared the performance with one over the other and also with pure diesel operation on conventional engine (CE).

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 special pressure-crank angle software package.

Results: CE showed compatible performance, while LHR engine showed improved performance with waste fried vegetable oil in biodiesel form at recommended injection timing and pressure and 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°bTDC for CE while it is 32°bTDC with LHR engine with biodiesel operation. Relatively, peak brake thermal efficiency increased by 18%, at peak load operation-brake specific energy consumption decreased by 6%, exhaust gas temperature decreased by 75°C, volumetric efficiency decreased by 5%, coolant load decreased by 30%, sound intensity decreased by 35%, smoke levels decreased by 27% and NOx levels increased by 41% with biodiesel operation on LHR engine at its optimum injection timing.

Conclusion: LHR Engine is more suitable for Bio-diesel based Vegetable oils.

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Key words: CE, LHR engine, Alternate fuels, Performance, Exhaust emissions, Combustion characteristics.

1. INTRODUCTION

The advancement of civilization is connected with vehicle population which is causing depletion of fossil fuels particularly diesel fuel as it is being used in not only transport sector but also in agriculture sector and increase of pollution levels with these fossil fuels, alternate fuel research has become pertinent for the engine manufacturers, users and researchers involved in the combustion research. Vegetable oils are substitutes for diesel fuel as they have properties compatible to diesel fuel. When Rudolf Diesel 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 modified chemically into biodiesel. Biodiesels derived from vegetable oils present a very promising alternative to diesel fuel since biodiesels have numerous advantages compared to fossil fuels as they are renewable, biodegradable, provide energy security and foreign exchange savings besides addressing environmental concerns and socio-economic issues. These biodiesels have lower viscosity, lower density, lower molecular weight and lower ratio of C/H (C= Number of carbon atoms, H= Number of hydrogen atoms in fuel composition). Experiments were conducted [1-5] with CE with biodiesel and reported that performance was compatible with CE. The drawbacks of the biodiesel for use as fuels in CE call for hot combustion chamber provided by low heat rejection (LHR) diesel engine.

The concept of LHR engine is to prevent heat flow to the coolant by providing insulation in the path of the heat flow to the coolant. Several methods adopted for achieving LHR to the coolant are low grade LHR engines- using ceramic coatings on piston, liner and cylinder head, medium grade LHR engines-creating air gap in the piston and other components with low-thermal conductivity materials like superni, cast iron and mild steel etc, high grade LHR engines- combination of low grade and medium grade LHR engines. Ceramic coatings with pure diesel operation provided adequate insulation and improved brake specific fuel consumption (BSFC) which was reported by various researchers [6-8]. However their studies revealed that the thermal efficiency variation of LHR engine not only depends 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 LHR engine [9] consisted of air gap insulated piston with superni crown, threaded with the body of the piston with pure diesel operation with varied injection timing and reported that brake specific fuel consumption decreased by 7% at advanced injection timing of 29.5°bTDC. Investigations were carried out [10-13] with ceramic coated LHR engines with biodiesel and reported that thermal efficiency marginally increased and smoke emissions decreased with LHR engine. Experiments were conducted [14] on LHR engine with air gap insulated piston with superni crown, and air gap insulated liner with superni insert with biodiesel and reported that performance improved with LHR engine with biodiesel. Investigations were carried out [15-17] with LHR engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head with bio-diesel and reported that LHR engine improved performance, decreased smoke levels and increased NO_x levels. Little literature was available in evaluating the comparative performance of LHR engine with air gap insulated piston and air gap insulated liner with ceramic coated cylinder head with varying engine parameters at different operating conditions of the waste fried vegetable oil based biodiesel. 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 waste fried vegetable oil in biodiesel form with varying engine parameters of change of injection pressure and timing and compared with CE with pure diesel operation at recommended injection timing and injection pressure.

2. MATERIALS AND METHODS

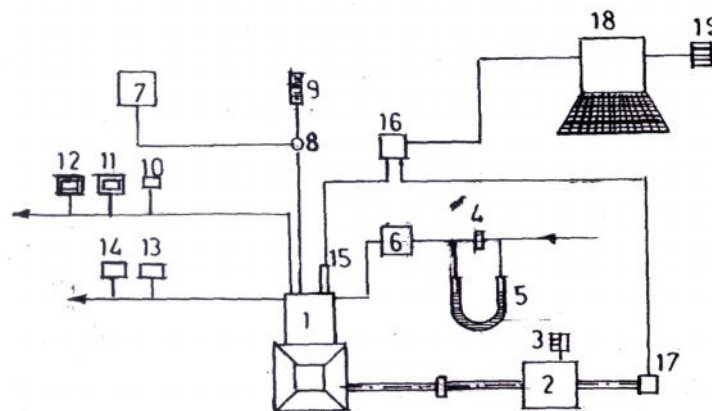
The term esterification means conversion of one ester into the other. In the present case glycerol was replaced with methyl alcohol, the fatty acids remaining the same. The chemical conversion reduced viscosity four fold. As it is evident glycerol was the byproduct of the reaction and a valuable commercial 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 (waste fried vegetable oil) was stirred with methanol at around 60-70°C with 0.5% of NaOH based on weight of the oil, for about 3 hours. At the end of the reaction, excess methanol was removed by distillation and glycerol, which 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 properties of test fuels used in the experimentation were shown in Table-1. The biodiesel was heated to a temperature (preheated temperature) till its viscosity was matched to that of diesel fuel.

Table 1. Properties of the Test Fuels

Test Fuel	Viscosity at 25°C (Centi-poise)	Density at 25 °C	Cetane number	Calorific value (kJ/kg)
Diesel	12.5	0.84	55	42000
Biodiesel (WFOBD)	48	0.86	55	35500

The LHR diesel engine contained a two-part piston - the top crown made of low thermal conductivity material, superni-90 (an alloy of nickel) 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 [14] 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 3mm 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.

Experimental setup used for the investigations of LHR diesel engine with biodiesel was shown in Fig.1.



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

CE had an aluminum alloy piston with a bore of 80 mm and a stroke of 110mm. 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 is 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. Exhaust emissions of smoke and NO_x were recorded by AVL smoke meter and Netel Chromatograph NO_x analyzer respectively at different values of BMEP. Sound intensity at various values of BMEP was measured with sound analyzer. 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) and maximum rate of pressure rise (MRPR) 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 in the experimentation was 0.1%. The test fuels used in the experimentation were pure diesel. The various configurations of the

engine were CE and LHR. Different operating conditions of the biodiesel were normal temperature (NT) and preheated temperature (PT).

3. RESULTS AND DISCUSSION

3.1 Performance Parameters

From Fig. 2, it indicates that biodiesel in CE with biodiesel operation showed compatible performance for the for entire load range when compared with the pure diesel operation on CE at recommended injection timing. This was due to low calorific value of biodiesel and difference of viscosity between diesel and biodiesel caused compatible performance with CE. 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 33°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 was attributed to its longer ignition delay and combustion duration.

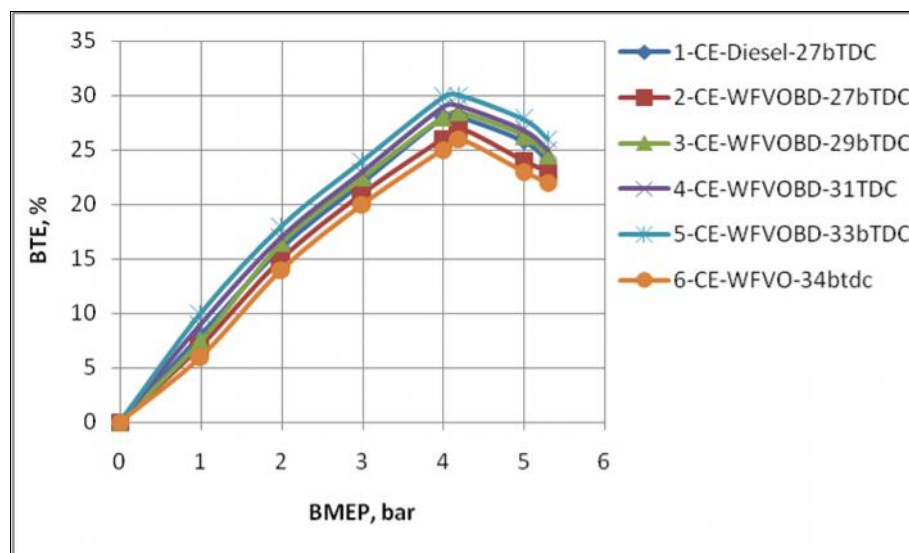


Fig.2. Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in conventional engine (CE) at different injection timings with bio diesel (WFVOBD) oil operation

Curves from Fig.3 indicate that the BTE increased up to 80% of the full 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 recommended injection timing showed improvement in the performance for the entire load range compared with CE with pure diesel. High cylinder temperatures helped in better evaporation and faster combustion of the fuel injected into the combustion chamber. Reduction of ignition delay of the biodiesel in the hot environment of the LHR engine improved heat release rates and efficient energy utilization. The optimum injection timing was found to be 32°bTDC 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 32°bTDC. Since the hot combustion chamber of LHR engine reduced ignition delay and combustion duration and hence the optimum injection timing (32°bTDC) was obtained earlier with LHR engine when compared with CE (33°bTDC) with the biodiesel operation.

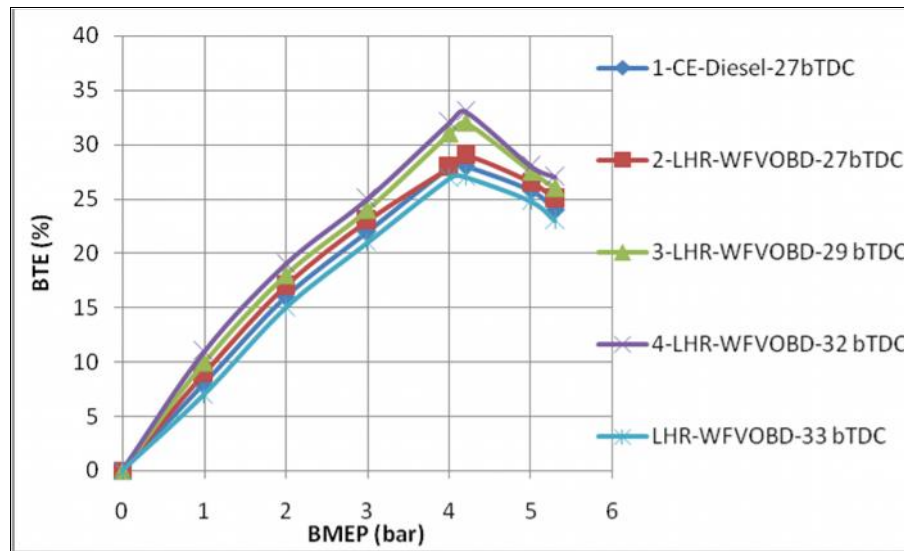


Fig.3. Variation of BTE with BMEP in LHR engine at different injection timings with biodiesel operation (WFOBD).

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

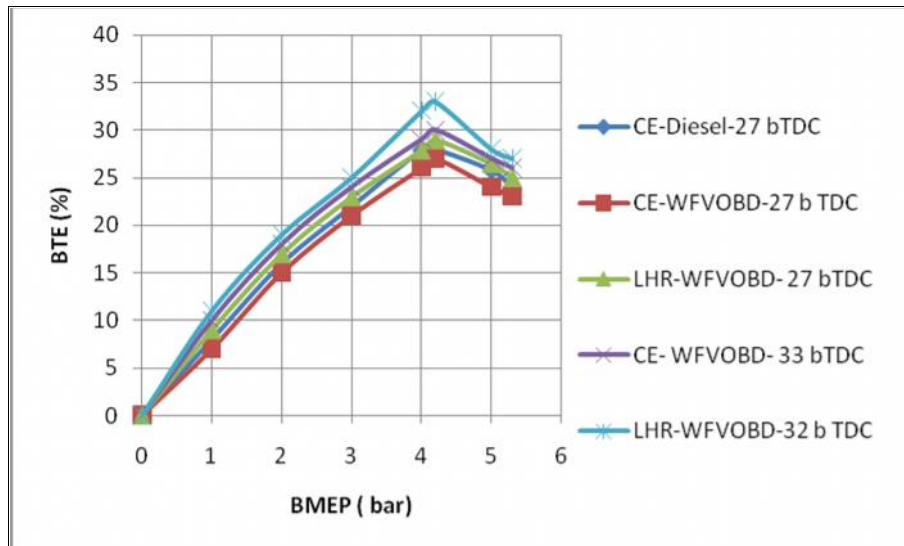


Fig.4. Variation of BTE with BMEP in different versions of the engine at the recommended injection timing and optimum injection timing at an injection pressure of 190 bar with biodiesel operation

Injection pressure is varied from 190 bars to 270 bars to improve the spray characteristics and atomization of the vegetable oils and injection timing is advanced from 27 to 34°bTDC for CE and LHR engine. As it is observed from Table 2, BTE increased with increase in injection pressure in both versions of the engine at different operating conditions of the vegetable oil in crude form and in biodiesel form.

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Table 2. 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	--
	WFOBD	27	28	28	29	29	30	29	30	30	31	31	32
32	WFOBD	29.5	30	30	31	29.5	30	33	34	34	35	35	36
33	WFOBD	30	31	29	30	29.5	30	--	--	--	--	--	--

245 DE- Diesel fuel, WFOBD- Biodiesel, WFVO- Crude vegetable oil, NT- Normal temperature , PT- Preheated
 246 temperature
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248 The performance is improved further in CE with the preheated biodiesel for entire load
 249 range when compared with normal biodiesel. Preheating of the biodiesel reduced the
 250 viscosity, which improved the spray characteristics of the oil and reduced the
 251 impingement of the fuel spray on combustion chamber walls, causing efficient
 252 combustion thus improving BTE. Optimum injection timing changed with increase of
 253 injection pressure with biodiesel. Similarly optimum injection timing was 33°bTDC at an
 254 injection pressure of 190 bar, 32°bTDC at 230 bar and 31°bTDC at 270 bar with CE with
 255 biodiesel operation. However, optimum injection timing remained same for LHR engine
 256 with biodiesel.

257 From Table 3, it is noticed that the performance improved in both versions of the engine
 258 with the preheated biodiesel at peak load operation when compared with normal
 259 biodiesel. Preheating of the biodiesel reduced the viscosity, which improved the spray
 260 characteristics of the oil. Brake specific energy consumption (BSEC) at peak load
 261 operation decreased with the advanced injection timing and increase of injection
 262 pressure with both versions of the engine with different operating conditions of biodiesel.
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Table 3. Data of BSEC at peak load operation

Injection Timing (° bTDC)	Test Fuel	Brake Specific Energy (BSEC) at peak load operation (kW/kW)											
		Conventional Engine (CE)						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	4.0		3.96		3.92		4.2		3.92		3.88	
	WFOBD	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	WFOBD	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	WFOBD	3.78	3.76	4.0	3.98	3.98	3.94	3.78	3.74	3.74	3.70	3.70	3.72

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266 This was due to initiation of combustion at earlier period and efficient combustion with
 267 the increase of air entrainment in fuel spray giving lower BSEC.

268 From the Figure 5, it is observed that CE with biodiesel operation at the recommended
 269 injection timing recorded marginally higher EGT at all loads compared with CE with pure
 270 diesel operation. Lower heat release rates and retarded heat release associated with
 271 high specific energy consumption caused increase in EGT in CE. Ignition delay in the CE
 272 with different operating conditions of biodiesel increased the duration of the burning
 273 phase. At recommended injection timing, LHR engine recorded compatible value of EGT
 274 when compared with CE with biodiesel operation. This was due to reduction of ignition
 275 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.

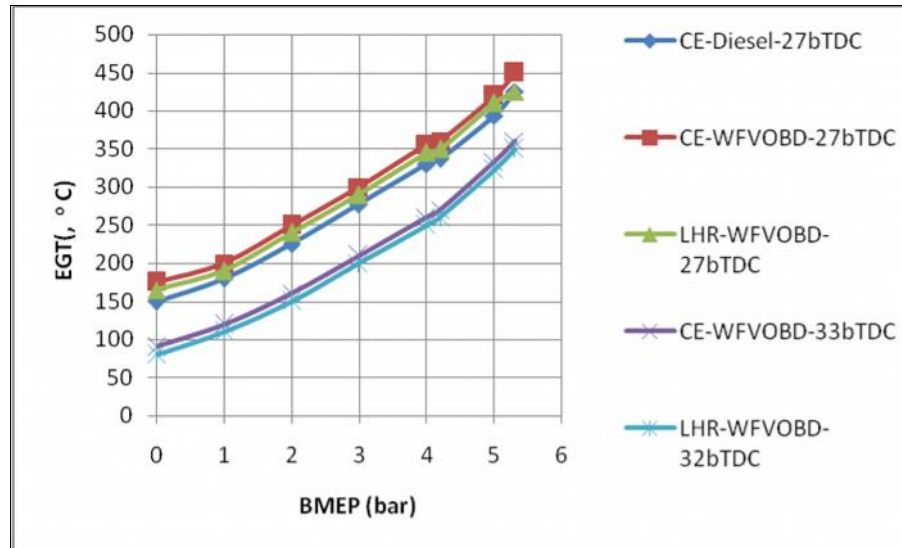


Fig.5. Variation of exhaust gas temperature (EGT) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel operation.

From Table. 4, it is observed that EGT decreased with increase in injection pressure and injection timing with both versions of the engine with biodiesel form, which confirmed that performance increased with increase of injection pressure. Preheating of the biodiesel further reduced the magnitude of EGT, compared with normal biodiesel in both versions of the engine. 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

Table 4. Data of EGT at peak load operation

Injection timing (° b TDC)	Test Fuel	EGT at the peak load (°C)											
		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	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	--	--	--	---	--	--

It can be observed in Figure 6 that volumetric efficiency (VE) decreased with an increase of BMEP in both versions of the engine with biodiesel operation. This was due to increase of gas temperature with the load.

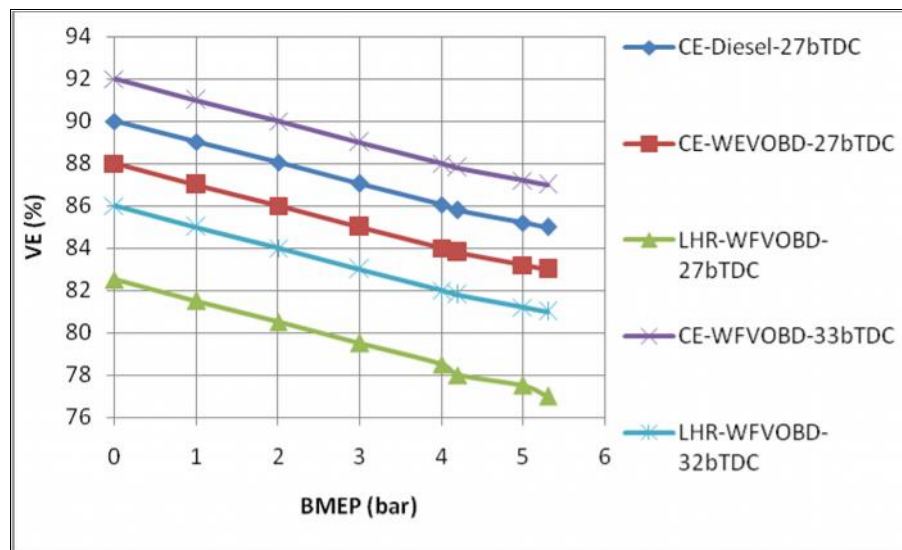


Fig.6. Variation of volumetric efficiency (VE) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel operation.

At the recommended injection timing, VE in the both versions of the engine with biodiesel operation decreased at all loads when compared with CE with pure diesel operation. This was due to increase of deposits with biodiesel operation with CE. 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 with LHR engine.

From Table-5, 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 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 the biodiesel.

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Table 5. Data of Volumetric efficiency at peak load operation

Injection timing (° 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
	DF	85	--	86	--	87	--	78	--	80	--	82	--
27	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	--	--	--	--	--	--	--

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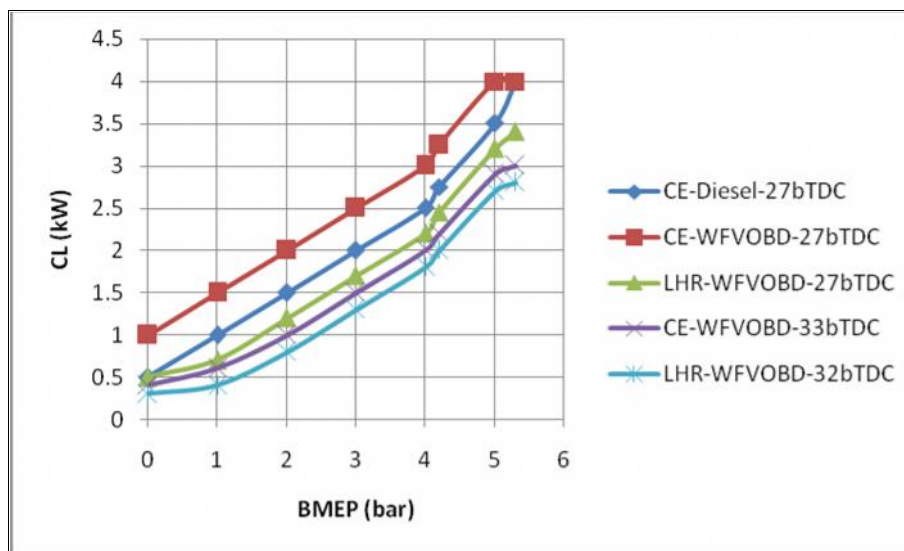
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Curves from Figure 7 indicate that that coolant load (CL) increased with BMEP in both versions of the engine with test fuels. However, CL reduced with LHR version of the engine with biodiesel operation when compared with CE with pure diesel operation. Heat output was properly utilized and hence thermal efficiency increased and heat loss to coolant decreased with effective thermal insulation with LHR engine.



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Fig.7. Variation of coolant load (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.

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However, CL was compatible with CE with biodiesel operation in comparison with pure diesel operation on CE. CL decreased with advanced injection timing with both versions of the engine with biodiesel. This was due to improved air fuel ratios and reduction of gas temperatures. From Table.6, it is noticed that CL decreased with advanced injection timing and with increase of injection pressure with test fuels. This was because of improved combustion and proper utilization of heat energy with reduction of gas temperatures. CL decreased with preheated condition of biodiesel in comparison with normal biodiesel in both versions of the engine. This was because of improved spray characteristics

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Table 6. Data of CL at peak load operation

Injection timing (° 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
	DF	4.0	---	3.8	--	3.6	---	4.5	---	4.3	--	4.1	---
27	WFOBD	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	WFOBD	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	WFOBD	3.0	2.8	3.2	3.0	3.4	3.2						

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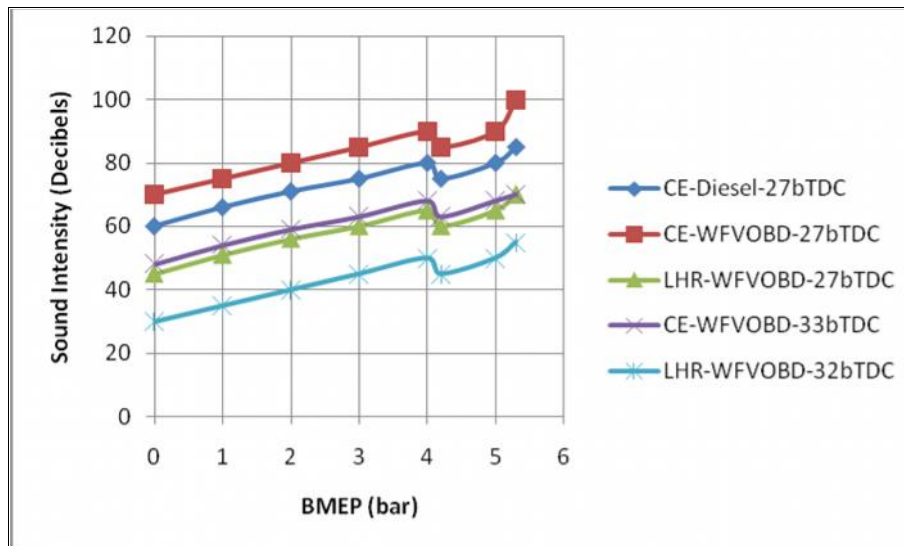
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Fig.8 indicates at recommended injection timing, sound intensities marginally increased in CE with biodiesel operation in comparison with CE with pure diesel operation. High viscosity, poor volatility and high duration of combustion caused moderate combustion of biodiesel leading to generate high sound levels. LHR engine decreased sound intensity when compared with pure diesel operation on CE. This was because of hot environment in LHR engine improved combustion of biodiesel. When injection timings were advanced to optimum, sound intensities were reduced for both versions of the engine, due to early initiation of combustion.



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Fig.8. Variation of sound intensity with BMEP in CE and LHR engine at recommended injection timing and optimized injection timings with crude vegetable oil operation.

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Table 7 denotes that the Sound intensity decreased with increase of injection pressure for both versions of the engine with the biodiesel. This was due to improved spray characteristic of the fuel, with which there was no impingement of the fuel on the walls of the combustion chamber leading to produce efficient combustion. Sound intensities were lower at preheated condition of biodiesel when compared with their normal condition. This was due to improved spray characteristics, decrease of density and reduction of viscosity of the fuel.

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Table 7 Data of sound intensity at peak load operation

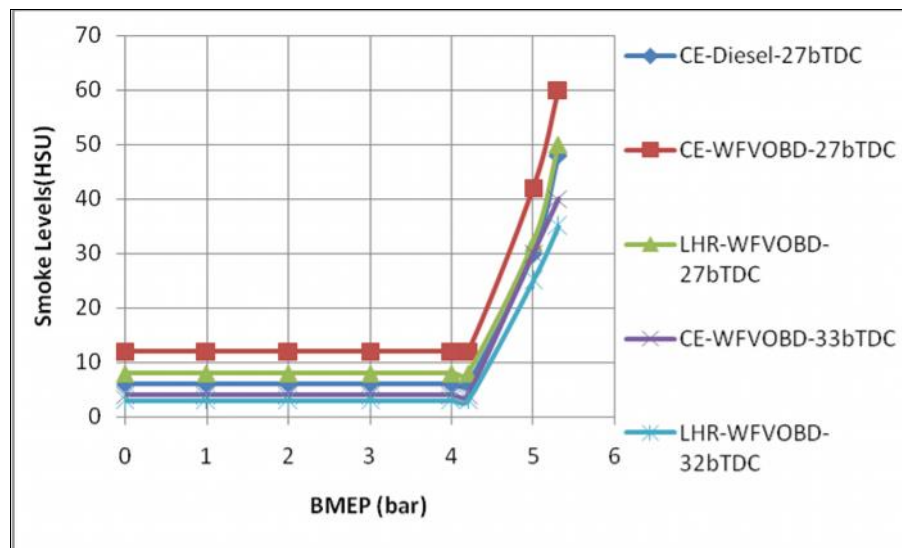
Injection timing (° bTDC)	Test Fuel	Sound Intensity (Decibels)											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	85	--	80	--	95	--	95	--	90	--	85	--
	WFVOBD	100	95	98	93	96	91	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	--	--	--	--	--	--

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392 **3.2 Exhaust Emissions**

393 Fig.9 indicates that the magnitude of smoke intensity increased from no load to full load
 394 in both versions of the engine with test fuels. During the first part, the smoke level was
 395 more or less constant, as there was always excess air present.

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398 **Fig.9. Variation of smoke intensity in Hartridge Smoke Unit (HSU) with BMEP in CE**
 399 **and LHR engine at recommend injection timing and optimized injection**
 400 **timings with crude vegetable oil**

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402 However, in the higher load range there was an abrupt rise in smoke levels due to less
 403 available oxygen, causing the decrease of air-fuel ratio, leading to incomplete
 404 combustion, producing more soot density. The variation of smoke levels with the brake
 405 power, typically showed a U-shaped behavior due to the pre-dominance of hydrocarbons
 406 in their composition at light load and of carbon at high load. Marginal increase of smoke
 407 levels at peak load operation with CE with biodiesel was observed compared with pure
 408 diesel operation on CE. This was due to the higher value of ratio of C/H of biodiesel
 409 (0.73) when compared with pure diesel (0.45). The increase of smoke levels was also
 410 due to decrease of air-fuel ratios and VE with biodiesel compared with pure diesel
 411 operation. Smoke levels were related to the density of the fuel. Smoke levels were higher
 412 with biodiesel due to its high density. However, LHR engine marginally reduced smoke
 413 levels due to efficient combustion and less amount of fuel accumulation on the hot

414 combustion chamber walls of the LHR engine at different operating conditions of the
415 biodiesel compared with the CE. Smoke levels decreased at the respective optimum
416 injection timing with both versions of the engine with crude vegetable oil. This was due to
417 initiation of combustion at early period with both versions of the engine.

418 The data from Table 8 shows a decrease in smoke levels with increase of injection
419 timing and the injection pressure in both versions of the engine, with different operating
420 conditions of the biodiesel. This was due to improvement in the fuel spray characteristics
421 at higher injection pressures and increase of air entrainment, at the advanced injection
422 timings, causing lower smoke levels. The reason for reduction of smoke levels in the
423 LHR engine was reduction of gas temperatures, with the availability of more of oxygen.
424 This was confirmed by the observation of improved air fuel ratios with the increase of
425 injection pressure and with the advancing of the injection timing with both versions of the
426 engine. Preheating of the biodiesel reduced smoke levels in both versions of the engine,
427 when compared with normal temperature of the biodiesel. This was due to i) the
428 reduction of density of the biodiesel, as density was directly proportional to smoke levels,
429 ii) the reduction of the diffusion combustion proportion in CE with the preheated
430 biodiesel, iii) the reduction of the viscosity of the biodiesel, with which the fuel spray does
431 not impinge on the combustion chamber walls of lower temperatures rather than it
432 directed into the combustion chamber. Density influences the fuel injection system.
433 Decreasing the fuel density tends to increase spray dispersion and spray penetration. At
434 the preheated condition, smoke levels were observed to be less in comparison with
435 normal condition of the biodiesel, as the density decreased.

436
437 **Table 8. Data of Smoke 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	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	--	--	--	--	--	--

438

439 Fig.10 indicates for both versions of the engine, NO_x concentrations raised steadily as
440 the fuel/air ratio increased with increasing BP/BMEP, at constant injection timing. At part
441 load, NO_x concentrations were less in both versions of the engine. This was due to the
442 availability of excess oxygen. At remaining loads, NO_x concentrations steadily increased
443 with the load in both versions of the engine. This was because, local NO_x concentrations
444 raised from the residual gas value following the start of combustion, to a peak at the
445 point where the local burned gas equivalence ratio changed from lean to rich. At peak
446 load, with higher peak pressures, and hence temperatures, and larger regions of close-
447 to-stoichiometric burned gas, NO_x levels increased in both versions of the engine.
448 Though amount of fuel injected decreased proportionally as the overall equivalence ratio
449 was decreased, much of the fuel still burns close to stoichiometric. Thus NO_x emissions
450 should be roughly proportional to the mass of fuel injected (provided burned gas
451 pressures and temperature do not change greatly). It is noticed that NO_x levels were
452 lower in CE while they were higher in LHR engine at different operating conditions of the
453 biodiesel at the peak load when compared with diesel operation. This was due to lower
454 heat release rate because of high duration of combustion causing lower gas
455 temperatures with the biodiesel operation on CE, which reduced NO_x levels. Increase of
456 combustion temperatures with the faster combustion and improved heat release rates in
457 LHR engine caused higher NO_x levels.

458

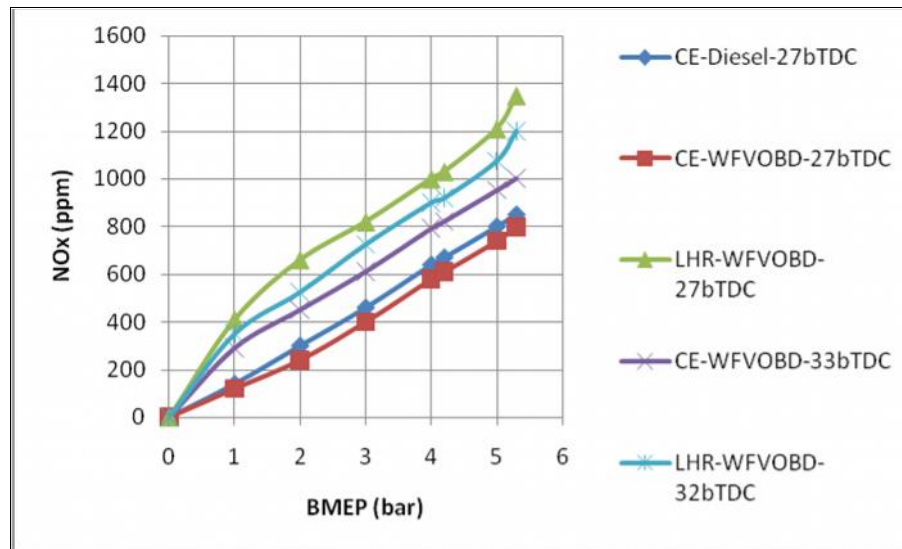


Fig.10.. Variation of NOx levels with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with crude vegetable oil

The data in Table 9 shows that, NOx levels increased with the advancing of the injection timing in CE with different operating conditions of biodiesel.

Table : 9. 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	--
	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	--	--	--	--	--	--

Residence time and availability of oxygen had increased, when the injection timing was advanced with biodiesel, which caused higher NOx levels in CE. 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 with the increase of air-fuel ratios. 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 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. 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.

485
486

3.3 Combustion Characteristics

487 From Table 10, it is observed that peak pressures were compatible in CE while they
488 were higher in LHR engine at the recommended injection timing and pressure with
489 biodiesel operation, when compared with pure diesel operation on CE. This was due to
490 increase of ignition delay, as biodiesel requires high duration of combustion. Mean while
491 the piston started making downward motion thus increasing volume when the
492 combustion takes place in CE. LHR engine increased the mass-burning rate of the fuel in
493 the hot environment leading to produce higher peak pressures. The advantage of using
494 LHR engine for biodiesel was obvious as it could burn low cetane and high viscous fuels.
495 Preheated biodiesel registered marginally higher value of PP than normal biodiesel. This
496 was due to reduction of ignition delay. Peak pressures increased with the increase of
497 injection pressure and with the advancing of the injection timing in both versions of the
498 engine, with the test fuels. Higher injection pressure produced smaller fuel particles with
499 low surface to volume ratio, giving rise to higher PP. With the advancing of the injection
500 timing to the optimum value with the CE, more amount of the fuel accumulated in the
501 combustion chamber due to increase of ignition delay as the fuel spray found the air at
502 lower pressure and temperature in the combustion chamber. When the fuel- air mixture
503 burns, it produced more combustion temperatures and pressures due to increase of the
504 mass of the fuel. With LHR engine, peak pressures increases due to effective utilization
505 of the charge with the advancing of the injection timing to the optimum value. The value
506 of TOPP decreased with the advancing of the injection timing and with increase of
507 injection pressure in both versions of the engine, at different operating conditions of the
508 biodiesel. TOPP was found to be higher with different operating conditions of the
509 biodiesel in CE, when compared with pure diesel operation on CE.

510

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

Injection timing (°bTDC) / 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

511

512 Preheating of the biodiesel showed lower TOPP, compared with biodiesel at normal
513 temperature. This once again confirmed by observing the lower TOPP and higher PP,
514 the performance of the both versions of the engine improved with the preheated
515 biodiesel form compared with the normal biodiesel. MRPR showed similar trends as
516 those of PP in both versions of the engine at different operating conditions of the
517 biodiesel. This trend of increase of MRPR indicated improved and faster energy
518 substitution and utilization by biodiesel in LHR engine, which could replace 100% diesel
519 fuel. However, these combustion characters were within the limits hence the biodiesel
520 can be effectively substituted for diesel fuel.

521

522 4. CONCLUSIONS

523 Biodiesel operation on CE showed compatible thermal efficiency, while it improved the
524 performance with LHR engine in comparison with pure diesel operation on CE.
525 Preheating of the biodiesel further increased the performance in both versions of the
526 engine. Smoke levels decreased and NOx levels increased marginally with CE with
527 biodiesel operation while smoke levels decreased and NOx levels increased drastically
528 with LHR engine with biodiesel operation when compared with pure diesel operation on
529 CE. Combustion characteristics were further improved with biodiesel when compared
530 with crude vegetable oil operation on both versions of the engine. CE with biodiesel
531 operation showed the optimum injection timing at 33°bTDC, while the LHR engine
532 showed the optimum injection at 32°bTDC at an injection pressure of 190 bars.
533

534 ACKNOWLEDGMENTS

535 Authors thank authorities of Chaitanya Bharathi Institute of Technology, Hyderabad for
536 providing facilities for carrying out research work. Financial assistance provided by All
537 India Council for Technical Education (AICTE), New Delhi, is greatly acknowledged.
538

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