RESEARCH ARTICLE OPEN ACCESS

Performance, Emissions and Combustion Characteristics of Mohr Oil in Crude and Biodiesel Form in High Grade Low Heat Rejection Diesel Engine

P. V. K. Murthy*, M.V.S. Murali Krishna**
*(Jaya prakash Narayan Educational Society Group of Institutions, Mahabubnagar-509001, Andhra Pradesh, India)
** (Mechanical Engineering Department, Chaitanya Bharathi Institute of Technology, Gandipet, Hyderabad-500 075, Andhra Pradesh, India)

ABSTRACT
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 in crude and biodiesel form with varied injection pressure and injection timing. Performance parameters of brake thermal efficiency, exhaust gas temperature, coolant load and volumetric efficiency were determined at various values of brake mean effective pressure (BMEP). Sound emissions **and e**xhaust 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 at peak load operation of the engine. Conventional engine (CE) showed deteriorated performance with crude Mohr oil (CMO) operation and compatible performance with Mohr oil based biodiesel operation (MOBD), while LHR engine showed improved performance with CMO and MOBD at recommended injection timing and pressure of 27^{o}bTDC (before top dead centre) and 190 bar. The performance of both version of the engine improved with advanced injection timing and at higher injection pressure with Mohr oil in crude form and biodiesel form with different operating conditions (normal temperature and preheated temperature) of the vegetable oil when compared with CE with pure diesel operation. The optimum injection timings were 30^{o}bTDC and 31^{o}bTDC for CE with CMO and MOBD, while they were 29^{o}bTDC and 30^o bTDC for LHR engine with CMO and MOBD operation.
***Key words**:* Crude Mohr oil, Bio-diesel, CE, LHR engine, Fuel performance, Exhaust emissions, Sound intensity, Combustion characteristics.

I. 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 their 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.

It has been found that the vegetable oils and alcohols are promising substitutes for use them as fuels in diesel engines, as they are renewable in nature. However, alcohols have low cetane number and engine modification is necessary if they are to be used as fuels in diesel engines. That too, most of the alcohol produced in India is consumed in Petro-chemical industries. On the other hand, the properties of vegetable oils are similar to those of diesel fuel and they are renewable and can be easily produced. Rudolph Diesel, [1] the inventor of the diesel engine that bears his name, experimented with fuels ranging from powdered coal to peanut oil. Several researchers [2-8] experimented the use of vegetable oils as fuels on conventional engines (CE) and reported that the performance was poor, citing the problems of high viscosity and low volatility. 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 [9-19] with bio-diesel on CE and reported performance was compatible with pure diesel operation on CE. The drawbacks of the crude vegetable oil and 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 provide thermal insulation in the path of heat flow to the coolant and increase thermal efficiency of the engine. Several methods adopted for achieving LHR to the coolant are i) using ceramic coatings on piston, liner and cylinder head and 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 aluminium alloy), cast iron and mild steel etc. LHR engines with pure diesel operation with ceramic coatings provided adequate insulation and improved brake specific fuel consumption (BSFC) which was reported by various researchers. However previous studies [20-22] revealed that the variation of thermal efficiency of LHR engine with pure diesel operation not only depended on the heat recovery system, but also depended on the engine configuration, operating condition and physical properties of the insulation material. Experiments were conducted [23-25] with ceramic coated LHR engine with biodiesel and reported that LHR engine marginally improved thermal efficiency and decreased smoke levels. Air gap was created [26] in the crown of piston made of nimonic and experiments were conducted with pure diesel and reported that BSFC increased by 7% with varied injection timings. Investigations were carried [27-28] with air gap insulated piston with superni crown and air gap insulated liner with superni insert with varied injection pressure and injection timing with vegetable oils and reported LHR engine improved efficiency and decreased pollution levels. Experiments were carried [29-30] out on LHR engine, which consisted of an air gap insulated piston with superni crown, air gap insulated liner with superni insert and ceramic coated cylinder head operated with vegetable oil and it was reported that LHR engine improved thermal efficiency and decreased smoke emissions and increased NOx emissions.

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 Mohr oil in crude form and bio-diesel form with varied engine parameters of injection pressure and injection timing and compared with CE with pure diesel operation at recommended injection timing and injection pressure.

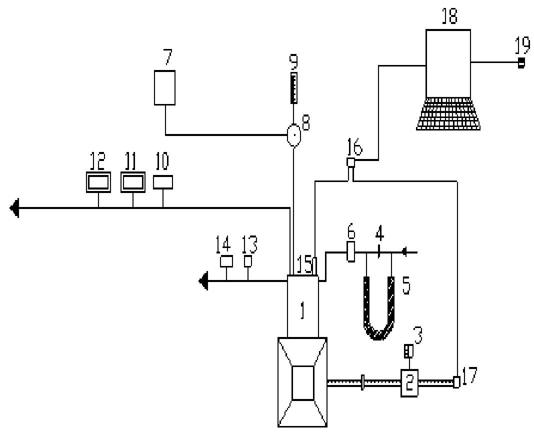
II. MATERIAL AND METHODS

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^{o}C with 0.5% of NaOH based on weight of the oil, for about 3 hours. At the end of the reaction, excess methanol was removed by distillation and glycerol, which 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 the test fuels of crude vegetable oil, bio-diesel 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 [26] to be 3-mm for improved performance of the engine 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 experimental setup used for the investigations of LHR diesel engine with CMO / 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 speed of 1500 rpm. The compression ratio was 16:1 and manufacturer's recommended injection timing and injection pressures were 27^{o}bTDC and 190 bar respectively. The fuel injector had 3-holes of size 0.25-mm.

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
Crude mohr oil (CMO)	120	0.91	45	38000
Mohr oil (Bio-diesel) (MOBD)	53	0.87	55	37500

The combustion chamber consisted of a direct injection type with no special arrangement for swirling motion of air. The engine was connected to electric dynamometer for measuring its brake power. Burette method was used for finding fuel consumption of the engine. Air-consumption of the engine was measured by air-box method. The naturally aspirated engine was provided with water-cooling system in which inlet temperature of water was maintained at 60°C by adjusting the water flow rate. Engine oil was provided with a pressure feed system. No temperature control was incorporated, for measuring the lube oil temperature. Copper shims of suitable size were provided in between the pump body and the engine frame, to vary the injection timing and its effect on the performance of the engine was studied, along with the change of injection pressures from 190 bar to 270 bar (in steps of 40 bar) using nozzle testing device. The maximum injection pressure was restricted to 270 bar due to practical difficulties involved. Exhaust gas temperature (EGT) was measured with thermocouples made of iron and iron-constantan. Exhaust emissions of smoke and NO_x were recorded by AVL smoke meter and Netel Chromatograph NOx analyzer respectively at different values of BMEP. Crude vegetable oil and biodiesel are heated to a temperature (Pre-heated temperature) where their viscosities are matched to that of diesel fuel.



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

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 measuring instruments used in the experimentation is 0.1%

III. RESULTS AND DISCUSSION

3.1 Performance Parameters

From Fig. 2, it indicates that biodiesel in CE 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. BTE increased up to 80% of the full load and later it decreased in CE with biodiesel operation. This was due to increase of fuel conversion efficiency up to 80% of the full load and increase of friction power beyond 80% of the load. 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 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 was attributed to its longer ignition delay and combustion duration.

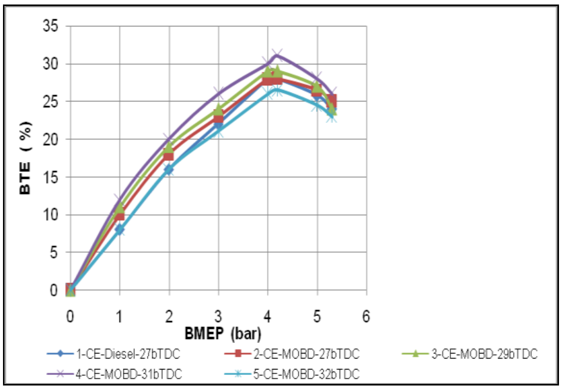


Fig. 2 Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in conventional engine (CE) at different injection timings with mohr oil based bio diesel (MOBD) oil operation

Curves from Fig. 3 indicate that CE operated with crude mohr oil (CMO) showed deteriorated performance for the for entire load range when compared with the pure diesel operation on CE at recommended injection timing. Although carbon accumulations on the nozzle tip might play a partial role for the general trends observed, the difference of viscosity between the diesel and crude vegetable oil provided a possible explanation for the deteriorated performance with crude vegetable oil operation. BTE increased with the advancing of the injection timing with CE with crude vegetable oil at all loads, when compared with CE at the recommended injection timing and pressure. Crude vegetable oil has loner duration of combustion and longer ignition delay. Hence advancing of injection timing helped the initiation of combustion, when the piston was at TDC. BTE increased at all loads when the injection timing was advanced to 30^{o}bTDC in the CE at the normal temperature of CMO. The optimum injection timing (30^{o}bTDC) with CE with crude vegetable oil was less than that of biodiesel (31^{o}bTDC). Higher cetane number of the fuel permitted higher value of advanced injection timing.

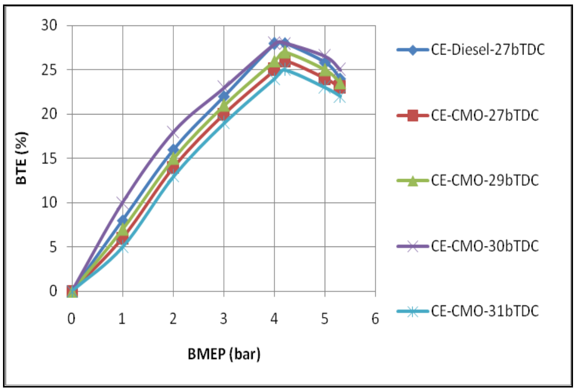


Fig. 3. Variation of BTE with BMEP in CE at different injection timings with crude vegetable oil (CMO) operation

Curves from Fig. 4 indicate that the 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 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 30^{o}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 30^{o}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.

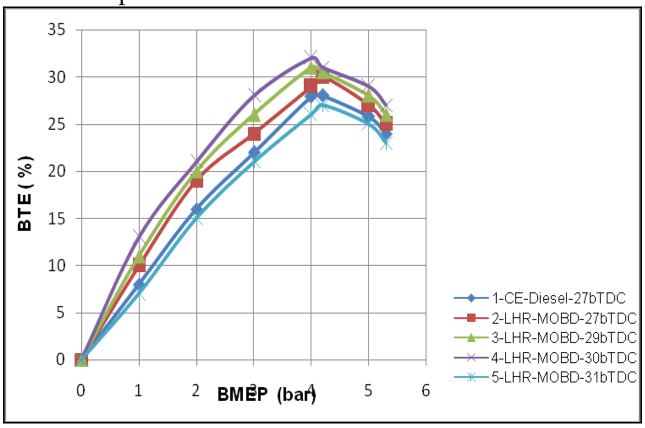


Fig. 4 Variation of BTE with BMEP in LHR ngine at different injection timings with biodiesel (MOBD) operation.

From Fig. 5, it is observed that the LHR version of engine with crude vegetable oil showed marginal improvement in the performance for the entire load range compared with CE with pure diesel. Reduction of ignition delay of the CMO in the hot environment of the LHR engine improved heat release rates and efficient energy utilization. The optimum injection timing was found to be 29^{o}bTDC with LHR engine with normal crude vegetable oil. 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 29^{o}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 crude vegetable oil operation. Crude vegetable oil absorbed more heat thus reducing the temperatures of combustion chamber to the marginal extent hence permitting the advancing of the injection timing closer to TDC when compared to biodiesel operation for both versions of the engine.

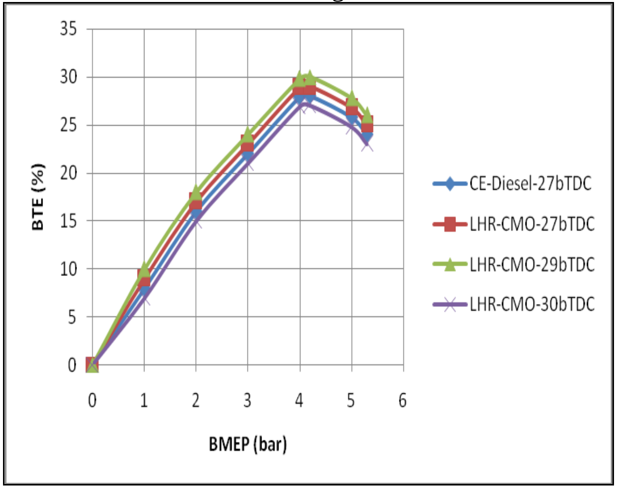


Fig. 5 Variation of BTE with BMEP in LHR engine at different injection timings with crude vegetable oil (CMO) operation.

Fig. 6 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.

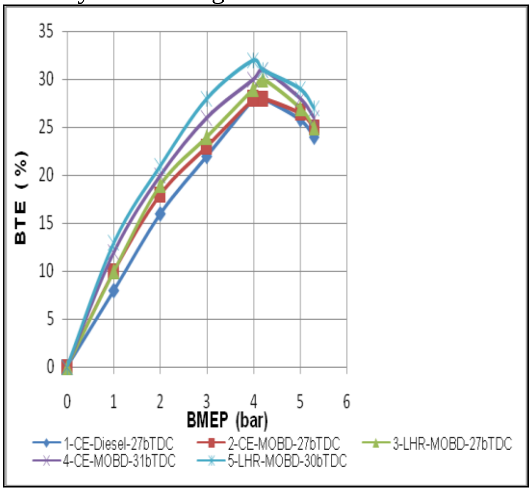


Fig. 6 Variation of BTE with BMEP in different versions of the engine at the recommended injection timing and optimum injection timing at an injection pressure of 190 bar with biodiesel (MOBD) operation.

Fig. 7 indicates that at optimum injection timings with crude vegetable oil operation. BTE with LHR engine was marginally higher than that of CE. The marginal increase in efficiency with LHR engine was due to high viscous nature of the fuel and high duration of combustion. Injection pressure was varied from 190 bars to 270 bar to improve the spray characteristics and atomization of the crude vegetable oil and biodiesel and injection timing was advanced from 27 to 34^{o}bTDC for CE and LHR engine. From Table-2, it is noticed that BTE increased with increase in injection pressure in both versions of the engine at different operating conditions of the Mohr oil in crude and in biodiesel form. 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.

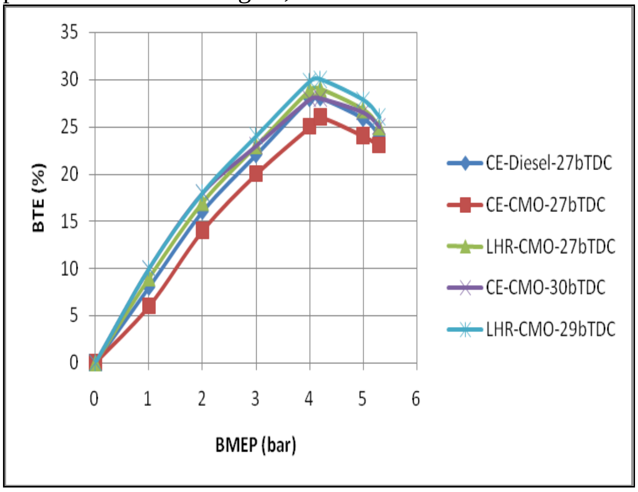


Fig. 7 Variation of BTE with BMEP in different versions of the engine at the recommended injection timing and optimum injection timing at an injection pressure of 190 bar with CMO operation

Hence it was concluded that with biodiesel operation. the optimum injection timing was 31^{o}bTDC at 190 bar, 30^{o}bTDC at 230 bar and 29^{o}bTDC at 270 bar for CE. The optimum injection timing for LHR engine was 30^{o}bTDC irrespective of injection pressure with biodiesel. Peak BTE was higher in LHR engine when compared with CE with different operating conditions of the biodiesel. BTE increased with biodiesel in both versions of the engine when compared with normal temperature of biodiesel. This was due to decrease of viscosity and improved spraying characteristics of fuel. The trends were similar with crude vegetable oil operation also. Hence it was concluded that with crude vegetable oil operation, the optimum injection timing was 30^{o}bTDC at 190 bar, 29^{o}bTDC at 230 bar and 28^{o}bTDC at 270 bar for CE. BTE increased with preheated crude vegetable oil in both versions of the engine when compared with normal temperature of vegetable oil. The optimum injection timing for LHR engine was 29^{o}bTDC irrespective of injection pressure with crude vegetable oil.

Table 2. Data of peak BTE

Injection Timing (° bTDC)	Test Fuel	Peak Brake Thermal Efficiency (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	--
	CMO	26	27	27	28	28	29	29	30	30	31	31	32
	MOBD	28	29	29	30	30	31	30	31	31	32	32	33
29	CMO	27	28	28	29	27	28	30	31	31	32	32	33
	MOBD	29	30	30	31	31	32	31	32	32	33	33	34
30	CMO	28	29	27	28	26	27	28	29	29	30	30	31
	MOBD	30	31	31	32	30.5	31	32	33	33	34	34	35
31	CMO	27	28	26	27	25	26	27	28	27	28	26	27
	MOBD	31	32	30.5	31.5	30	31	31	31.5	31.5	32	32.5	33

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

From Table 3, it is noticed that the performance was improved in both versions of the engine with the preheated vegetable oil at peak load operation when compared with normal vegetable oil. Preheating of the vegetable oil reduced the viscosity, which improved the spray characteristics of the oil. Both versions of the engine at different operating conditions of biodiesel showed improved performance over the crude vegetable oil operation. Esterification reduced the viscosity, molecular weight of the fuel and improved the cetane number, which reduced the ignition delay thus improving the performance of both versions of the engine, when compared to the crude vegetable oil. Brake specific energy consumption (BSEC) at peak load operation decreased with the advanced injection timing and increase of injection pressure with both versions of the engine with different operating conditions of crude vegetable oil and biodiesel. This was due to initiation of combustion at earlier period and efficient combustion with the increase of air entrainment in fuel spray giving lower BSEC.

Table 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	
	CMO	4.62	4.2	4.2	3.98	3.98	3.94	3.96	3.92	3.92	3.88	3.88	3.84
	MOBD	3.96	3.92	3.92	3.88	3.88	3.84	3.88	3.84	3.84	3.80	3.80	3.76
29	CMO	4.4	4.0	4.0	3.96	3.96	3.92	3.86	3.82	3.82	3.78	3.78	3.74
	MOBD	3.88	3.84	3.84	3.80	3.8	3.76	3.80	3.76	3.76	3.72	3.72	3.68
30	CMO	4.0	3.96	4.2	3.98	3.98	3.94	3.90	3.86	3.86	3.82	3.82	3.78
	MOBD	3.84	3.80	3.80	3.76	3.82	3.78	3.76	3.72	3.72	3.68	3.68	3.64
31	CMO	4.2	3.98	4.0	3.96	4.2	3.98	3.94	3.90	3.90	3.86	3.86	3.80
	MOBD	3.80	3.76	3.82	3.78	3.84	3.80	3.80	3.76	3.82	3.78	3.84	3.78

From the Fig. 8, it is observed that CE with biodiesel 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. 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 was 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.

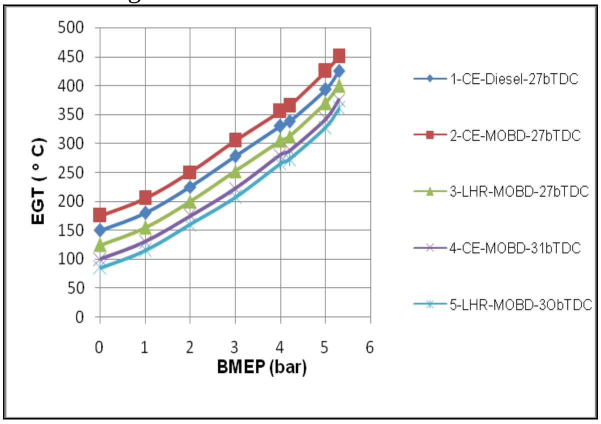


Fig..8 Variation of exhaust gas temperature (EGT) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel (MOBD) operation.

From the Table-4, it is observed that EGT decreased with increase in injection pressure and injection timing with both versions of the engine with mohr oil in crude and biodiesel form, which confirmed that performance increased with increase of injection pressure. EGT was lower with biodiesel operation in both versions of the engine when compared with crude vegetable oil operation. This was due to improvement of cetane number of the vegetable oil with the esterification, which leads to improved combustion and reduced EGT, causing wastage of exhaust gas enthalpy with crude vegetable oil operation instead of actual conversion of heat into work. By observing lower EGT, it established a fact that the performance of the engine was improved with the biodiesel, compared with crude vegetable oil. Preheating of the vegetable oil further reduced the magnitude of EGT, compared with normal vegetable oil in both versions of the engine. This showed that thermal efficiency increased with preheated condition of the vegetable oil in crude and biodiesel form when compared with normal condition of the vegetable oil 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 (^{o} b TDC)	Test Fuel	EGT at the peak load (^{o}C)											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	425	--	410	---	395	--	460	---	450	--	440	--
	CMO	500	470	470	440	440	410	480	460	450	430	430	390
	MOBD	450	425	425	400	400	375	400	375	375	350	350	325
29	CMO	460	430	430	400	400	370	410	390	390	370	370	350
	MOBD	425	400	400	375	450	400	380	360	360	340	340	320
30	CMO	430	400	400	370	370	400	440	420	420	400	410	390
	MOBD	400	375	375	350	400	375	360	340	340	320	320	300
31	CMO	450	430	440	410	450	430	460	440	430	410	420	400
	MOBD	375	350	400	375	425	400	400	380	380	360	360	340

It can be observed in Fig. 9 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. 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 is 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.

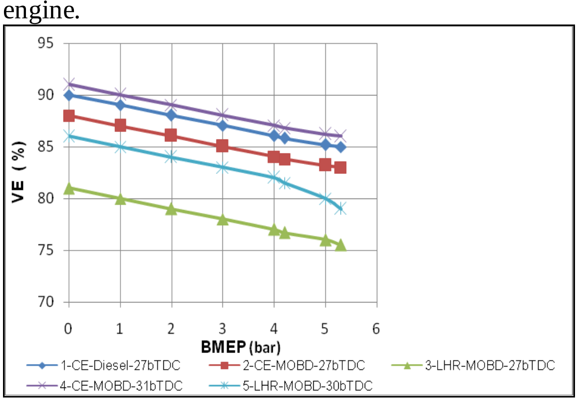


Fig. 9 Variation of volumetric efficiency (VE) with BMEP in CE and LHR engine at recommend injection timing and optimized

injection timings with biodiesel (MOBD) operation.

From Table-5, VE increased with increase of injection pressure and with advanced injection timing in both versions of the engine with test fuels. 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 Mohr oil in crude and biodiesel form 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 test fuels. VE was higher with biodiesel in both versions of the engine at different operating conditions of the vegetable oil in comparisons with crude vegetable oil. This was due to clean and efficient combustion with high cetane value of biodiesel.

Table 5. Data of volumetric efficiency at peak load operation

Injection timing (^{o}bTDC)	Test Fuel	Volumetric efficiency (%)											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	85	--	86	--	87	--	78	--	80	--	82	--
	CMO	81	82	82	83	83	84	74	75	75	76	76	77
	MOBD	83	84	84	85	85	86	75.5	76.5	76.5	77.5	77.5	78.5
29	CMO	82	83	83	84	82	81	75	76	76	77	77	78
	MOBD	84	85	85	86	86	87	77	77.5	78.5	79.5	79.5	80.5
30	CMO	83	84	82	83	81	82	74	75	73	74	72	73
	MOBD	85	86	86	87	85	86	78	78.5	78.5	79	79	79.5
31	CMO	82	83	81	82	80	81	73	74	72	73	71	72
	MOBD	86	87	85	86	84	85	77	78	78	78.5	78.5	79

Curves from Fig. 10 indicate that that coolant load (CL) increased with BMEP in both versions of the engine with test fuels. However, CL reduced with LHR version of the engine with biodiesel operation when compared with CE with pure diesel operation.

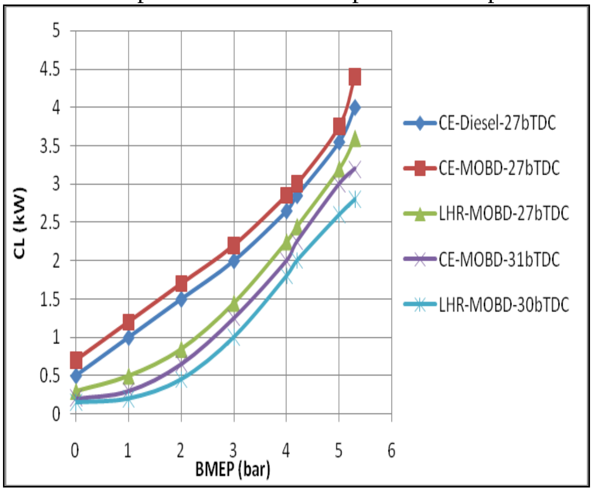


Fig.10 Variation of coolant load (CL) with BMEP in both versions of the engine at recommended and optimized injection timings with MOBD operation at an injection pressure of 190 bar.

Heat output was properly utilized and hence thermal efficiency increased and heat loss to coolant decreased with effective thermal insulation with LHR engine. However, CL increased with CE with biodiesel operation in comparison with pure diesel operation on CE. This was due to concentration of un-burnt fuel at the walls of combustion chamber. CL decreased with advanced injection timing with both versions of the engine with biodiesel operation. This was due to improved air fuel ratios and reduction of gas temperatures. From Table.6, it is noticed that CL decreased with advanced injection timing and with increase of injection pressure with test fuels.

f injection pressure and with the advancing of the injection timing with both versions of the engine. 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**.** Density influences the fuel injection system. Decreasing the fuel density tends to increase spray dispersion and spray penetration. At the preheated condition, smoke levels were observed to be less in comparison with normal condition of the vegetable oil in crude and biodiesel form, as the density decreased. Crude vegetable oil at its different operating conditions gave higher value of smoke levels in comparison with biodiesel in both versions of the engine.

Table 8 Data of smoke levels in Hartridge smoke unit (HSU) at peak load operation

Injection timing (° bTDC)	Test Fuel	Smoke intensity (HSU) at peak load operation											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	48	--	38	--	34	--	55	--	50	--	45	--
	CMO	70	65	65	60	60	55	60	50	55	45	50	45
	MOBD	60	55	55	50	50	45	50	45	45	40	40	35
29	CMO	60	55	55	50	60	55	50	40	45	35	40	30
	MOBD	55	50	50	45	45	40	45	40	40	35	35	30
30	CMO	55	50	60	55	65	60	60	50	65	55	70	60
	MOBD	50	45	45	40	50	45	40	35	35	30	30	25
31	CMO	60	55	65	60	70	65	65	55	70	60	75	65
	MOBD	45	40	50	45	55	50	45	40	40	35	35	30

Due to higher molecular weight, crude vegetable oil has low volatility and because of their un-saturation, crude vegetable oil is inherently more reactive than biodiesel, which results that they are more susceptible to oxidation and thermal polymerization reactions. By the esterification process, the viscosity of the vegetable oil was brought down many times lower than the viscosity of the raw or crude vegetable oil. This was because of the removal of glycerol molecules, which caused the vegetable oil to be more viscous. Since there was drop in the viscosity, naturally the density of the Esterified oil was also dropped at the room temperature. Volatility of the vegetable oil also increased with the esterification process. Hence biodiesel reduced smoke levels when compared to the crude vegetable oil in both versions of the engine.

Fig. 13 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-stochiometric burned gas, NOx levels increased in both versions of the engine.

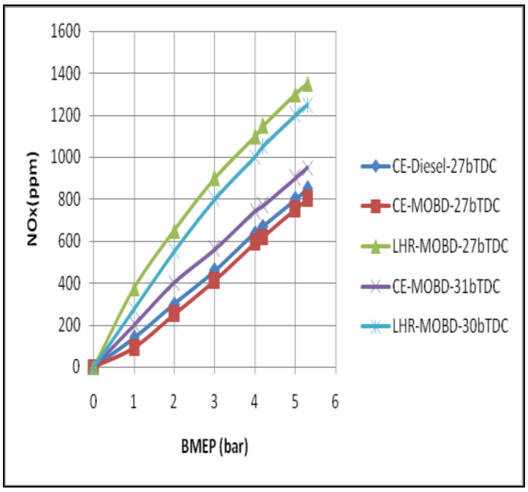


Fig. 13 Variation of NOx levels with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with biodiesel (MOBD) operation.

Though amount of fuel injected decreased proportionally as the overall equivalence ratio was decreased, much of the fuel still burns close to stochiometric. 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 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.

The data in Table-9 shows that, NOx levels increased with the advancing of the injection timing in CE with different operating conditions of crude vegetable oil and biodiesel. Residence time and availability of oxygen had increased, when the injection timing was advanced with these fuels, 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 crude vegetable oil and 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 vegetable oils. With the increase of injection pressure, fuel droplets penetrate and find oxygen counterpart easily.

Table 9 Data of NOx levels at peak load operation

Injection timing (bTDC)	Test Fuel	NOx levels (ppm) at peak load operation											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	850	----	810	----	770	---	1300	--	1280	--	1260	--
	CMO	750	700	700	650	650	600	1300	1225	1225	1150	1150	1075
	MOBD	800	750	750	700	700	650	1350	1300	1300	1250	1250	1200
29	CMO	800	750	750	700	700	650	1250	1200	1200	1150	1100	1050
	MOBD	850	800	800	750	750	700	1300	1250	1250	1200	1200	1150
30	CMO	850	800	800	750	750	700	1300	1250	1250	1200	1200	1150
	MOBD	900	850	850	800	800	750	1250	1200	1200	1150	1150	1100
31	CMO	900	850	900	850	850	800	1350	1300	1300	1250	1200	1150
	MOBD	950	900	900	850	850	800	1300	1250	1250	1200	1200	1150

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.

3.3 Combustion Characteristics

From Table-10, 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 increase of ignition delay, as biodiesels require moderate 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 and crude vegetable oil was obvious as it could burn low cetane and high viscous fuels. Peak pressures were found to be lower with crude vegetable oil in comparison with biodiesel in both versions of the engine at different operating conditions of the test fuels. This was due to low cetane value of crude vegetable oils. Preheated vegetable oils registered marginally higher value of PP than normal vegetable oils. 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.

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 the test fuels. TOPP was found to be more with different operating conditions of the test fuels in CE, when compared with pure diesel operation on CE.

Table 10 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)			
		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/CMO	CE	46.3	47.3	48.5	49.4	2.0	2.1	2.7	2.8	11	10	11	9
	LHR	55.5	57.5	58.6	59.6	3.0	3.1	3.3	3.4	10	9	9	8
27/MOBD	CE	48.9	50.9	51.1	52.4	2.2	2.3	2.9	3.0	11	10	11	9
	LHR	59.8	60.7	63.1	64.8	3.3	3.4	3.5	3.5	10	9	9	8
29/CMO	LHR	60.5	61.5	63.5	64.8	3.4	3.5	3.6	3.7	9	8	8	8
30/CMO	CE	49.4	50.6	--	--	3.2	3.3	--	--	10	9	--	--
30/MOBD	LHR	62.5	63.8	65.1	65.8	3.7	3.9	3.9	4.0	9	8	8	8
31/MOBD CPO	CE	53.3	54.6			3.5	3.7			10	9		

This was due to moderate to higher ignition delay with the vegetable oil when compared with pure diesel fuel. This once again established the fact by observing lower peak pressures and higher TOPP, that CE with crude vegetable oil and biodiesel operation showed deterioration in the performance with crude vegetable oil and compatible performance with biodiesel operation when compared with pure diesel operation on CE. Preheating of the vegetable oil and biodiesel showed lower TOPP, compared with test fuels 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 vegetable oils in crude and biodiesel form compared with the normal test fuels. MRPR showed similar trends as those of PP in both versions of the engine at different operating conditions of the test fuels. This trend of increase of MRPR indicated improved and faster energy substitution and utilization by crude vegetable oil and biodiesel in LHR engine, which could replace 100% diesel fuel. However, these combustion characters were within the limits hence the crude vegetable oil and biodiesel can be effectively substituted for diesel fuel

IV. CONCLUSIONS

4.1 Crude vegetable oil

The crude vegetable oil operation at 27°bTDC on CE showed the deteriorated performance while LHR engine showed improved performance, at all loads when compared with CE with pure diesel operation. CE with crude vegetable oil operation showed the optimum injection timing at 30°bTDC, while the LHR engine at 29°bTDC at an injection pressure of 190 bar. Performance parameters, emissions and combustion characteristics improved with increase of injection pressure.

4.1.1. At an injection timing of 27°bTDC

Peak BTE increased by 3%,at peak load operation-BSEC decreased by 1%, EGT increased by 55°C, VE decreased by 13%, CL decreased by 10%, sound intensity decreased by 6%, smoke levels increased by 25% and NOx levels increased by 59% with LHR engine in comparison with CE with pure diesel operation.

4.1.2. At an injection timing of 29°bTDC

BTE increased by 7%,at peak load operation-BSEC decreased by 3.5%, EGT decreased by 15°C, VE decreased by 12%, CL decreased by 12.5%, sound intensity decreased by 9%, smoke levels increased by 4% and NOx levels increased by 47% with LHR engine in comparison with CE with pure diesel operation at 27°bTDC.

4.2 Biodiesel

The biodiesel operation at 27°bTDC on CE showed the compatible performance, while LHR engine showed improvement in the performance, at all loads when compared with CE with pure diesel operation. CE with biodiesel oil operation showed the optimum injection timing at 31°bTDC, while the LHR engine at 30°bTDC at an injection pressure of

190 bar. Performance parameters, emissions and combustion characteristics improved with increase of injection pressure.

4.2.1At an injection timing of 27^{o}bTDC,

Peak BTE increased by 7%,at peak load operation-BSEC decreased by 3%, EGT decreased by 25^{o}C, VE decreased by 11%, CL decreased by 15%, sound intensity decreased by 18%, smoke levels increased by 4% and NOx levels increased by 58% with LHR engine in comparison with CE with pure diesel operation.

4.2.2 At an injection timing of 30^{o}bTDC

Peak BTE increased by 14%,at peak load operation-BSEC decreased by 6%, EGT decreased by 65^{o}C, VE decreased by 8%, CL decreased by 30%, sound intensity decreased by 23%, smoke levels decreased by 16% and NOx levels increased by 47% with LHR engine in comparison with CE with pure diesel operation.

Preheated test fuels improved performance when compared with normal condition of the test fuels.

V. ACKNOWLEDGMENTS

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

REFERENCES

[1] Cummins, C. Lyle, Jr. *Diesel's Engine, Volume: From Conception To 1918.* Wilsonville, OR, USA: Carnot Press,, 1993

[2] Babu, A.K. and Devarajane,G. Vegetable oils and their derivatives as fuels for CI engines: an overview. SAE Paper No.2003-01-0767, 2003.

[3] Nwafor, O.M.L. The effect of elevated fuel inlet temperature on the performance of diesel engine running on a neat vegetable oil at constant speed conditions. *Renewable energy*, *28*, 2003. 171-180.

[4] Forson, F.K., Oduro, E.K., and Hammond-Donkoh, E. Performance of Jatropha oil blends in a diesel engine. *Renewable Energy*, *29*, 2009, 1135–1145.

[5] Mahanta, P., Mishra, S.C. and Kushwash, Y.S. (2006). An experimental study of pongamia pinnata oil as a diesel ubstitute fuel. *Proceedings IMechE. Journal of Power and Energy, , Part-A*, *220*, 2006, 803-808.

[6] Saravanan,S., Nagarajan, G .,Lakshmi Narayana Rao^c,G. and Sampath,S. Feasibility study of crude rice bran oil as a diesel substitute in a DI-CI engine without modifications, *Energy for Sustainable Development*, 11(3), 2007, 83-92.

[7] Deepak Agarwal, Lokesh Kumar and Avinash Kumar Agarwal. Performance evaluation of a vegetable oil fuelled compression ignition engine. *Renewable Energy*, *33(6)*, 2008, 1147–1156.

[8] Misra, R.D., Murthy, M.S. Straight vegetable oils usage in a compression ignition engine—A review.*Renewable and Sustainable Energy Reviews*, *14*, 2010, 3005–3013.

[9] Agarwal, A.K. (2006). Bio-fuels (alcohols and biodiesel) applications as fuels for internal combustion engines. International Journal Energy Combustion Science, 33,233-271

[10] Raheman, H., Ghadege, S.V. Performance of compression ignition engine with mahua bio diesel. *Fuel*, *86*, 2007, 2568-2573.

[11] Srivastava,P.K. and Verma, M. Methyl ester of karanja oil as alternate renewable source energy. *Fuel*, *87*, 2007, 1663-1670.

[12] Banapurmath, N.R., Tewari, P.G., Hosmath, R.S. Performance and emission characteristics of direct injection compression ignition engine operated on honge, jatropha and sesame oil methyl ester. *Journal of Renewable energy, 33,* 2008, 1982-1988.

[13] Murat, K., Gokhan, Ergen. and Murat, H. The effects of preheated cottonseed oil methyl ester on the performance and exhaust emissions of a diesel engine. *Applied Thermal Engineering*, 2008, 2136-2143

[14] Jayant Singh, Mishra, T.N., Bhattacharya, T.K. and Singh, M.P. Emission aracteristics of methyl ester of rice bran oil as fuel in compression ignition engine. *International Journal of Chemical and Biological Engineering*, *1(2)*, 2008, 62-66.

[15] Sahoo, P.K., Das, L.M.,Babu, M.K.G., Arora, P., Singh, V.P., Kumar, N,R., Varyani, T.S. Comparative evaluation of performance and emission characteristics of jatropha, curanja and polanga based biodiesel as fuel in tractor engine. *Fuel, 88(9)*, 2009, 1698-170.

[16] Devan, P.K. and Mahalakshmi, N.V. Performance, emission and combustion characteristics of a compression ignition engine using methyl ester of paradise oil-eucalyptus oil blends, *Applied Energy, 86,* 2009, 675-680.

[17] Nabi, N., Rahman. M. and Akhter, S. Biodiesel from cottonseed and its effect on engine performance and exhaust emissions. *Applied Thermal Engineering*, *29*, 2009, 2265-2270.

[18] Jindal, S., Nandwana, B.P., Rathore, N.S., ,V..Experimental investigation of the effect of compression ratio and injection pressure in a direct injection diesel engine running on Jatropha methyl ester. *Applied Thermal Eng, 30*, 2010, 442–448.

[19] Venkatramn., Devaradjane, G. Experimental investigation of performance and emission characteristics of diesel-pungam oil , methyl esters diesel blends fueled DI engine at optimum engine operating parameters. *International Journal of Green energy and env, 1,* 2010, 7-12.

[20] Parlak, A., Yasar, H., ldogan O. The effect of thermal barrier coating on a turbocharged Diesel engine performance and exergy potential of the exhaust gas. *Energy Conversion and Management, 46(3),* 2005, 489–499.

[21] Ekrem, B., Tahsin, E., Muhammet, C. Effects of thermal barrier coating on gas emissions and performance of a LHR engine with different injection timings and valve adjustments. *Journal of Energy Conversion and Management, 47***,** 2006. 1298-1310.

[22] Ciniviz, M., Hasimoglu, C., Sahin, F., Salman, M. S. Impact of thermal barrier coating application on the performance and emissions of a turbocharged diesel engine. *Proceedings of The Institution of Mechanical Engineers Part D-Journal Of Automobile Eng*, 222 (D12), 2008, 2447–2455.

[23] Hanbey Hazar. Effects of bio-diesel on a low heat loss diesel engine. *Renewable Energy, 34***,** 2008, 1533–1537.

[24] Modi, A.J., Gosai, D.C. Experimental study on thermal barrier coated diesel engine performance with blends of diesel and palm bio-diesel. SAE *International Journal of Fuels and Lubricants, 3 (2),* 2010, 246-259.

[25] Rajendra Prasath, B., P. Tamilporai, P., Mohd.Shabir, F. Analysis of combustion, performance and emission characteristics of low heat rejection engine using biodiesel. *International Journal of Thermal Sci, 49*, 2010, 2483-2490.

[26] Rama Mohan, K., Vara Prasad, C.M., Murali Krishna, M.V.S. Performance of a low heat rejection diesel engine with air gap insulated piston, *ASME Journal of Engineering for Gas Turbines and Power, 121(3),* 1999, 530-540.

[27] Ratna Reddy, T., Murali Krishna, M.V.S., Kesava Reddy, Ch., and Murthy, P.V.K. Performance evaluation of a medium grade low heat rejection diesel engine with mohr oil. *International Journal of Recent Advances in Mechanical Engineering, 1(1)*, 2012, 1-17.

[28] Janardhan, N., Murali Krishna, M.V.S., Ushasri, P. and Murthy, P.V.K. Potential of a medium low heat rejection diesel engine with crude jatropha oil. *International Journal of Automotive Engineering and Technologies*, *1(2*), 2012, 1-16.

[29] *Kesava Reddy, Ch., Murali Krishna, M.V.S., P.V.K. and Ratna Reddy, T.*, Performance evaluation Of a high grade low heat rejection diesel engine with crude pongamia oil. *International Journal of Engineering Research and Applications, 2(5), 2012, 1505-1516.*

[30] Ratna Reddy, T., Murali Krishna, M.V.S., Kesava Reddy, Ch., and Murthy, P.V.K., Performance evaluation of a low heat rejection diesel engine with Mohr oil based biodiesel. *British Journal of Applied Science & Technology, 2(2),* 2012, 179-198.