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A Comparative Study of the Performance of a Low Heat Rejection Engine with Three Different Levels of Insulation with Waste Fried Vegetable Oil Operation

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ABSTRACT

Investigations are carried out to evaluate the performance of a low heat rejection (LHR) diesel engine consisting of different versions such as ceramic coated cylinder head engine-LHR-1; Air gap insulated piston and air gap insulated liner-LHR-2; and Ceramic coated cylinder head, air gap insulated piston and air gap insulated liner –LHR-3 with normal temperature condition of linseed oil with varied injection pressure. Performance parameters are determined at various magnitudes of brake mean effective pressure. Pollution levels of smoke and oxides of nitrogen (NOx) are recorded at the peak load operation of the engine. Combustion characteristics of the engine are measured with TDC (top dead centre) encoder, pressure transducer, console and special pressure-crank angle software package. Conventional engine (CE) showed deteriorated performance and LHR engines showed improved performance at recommended injection timing of 27^{o}bTDC and recommend injection pressure of 190 bar with vegetable oil operation, when compared with CE with pure diesel operation. Peak brake thermal efficiency increased by 12.5%, compatible smoke levels and NOx levels increased by 49% with LHR-3 engine at an injection pressure of 190 bar when compared with pure diesel operation on CE at an injection pressure of 190 bar.

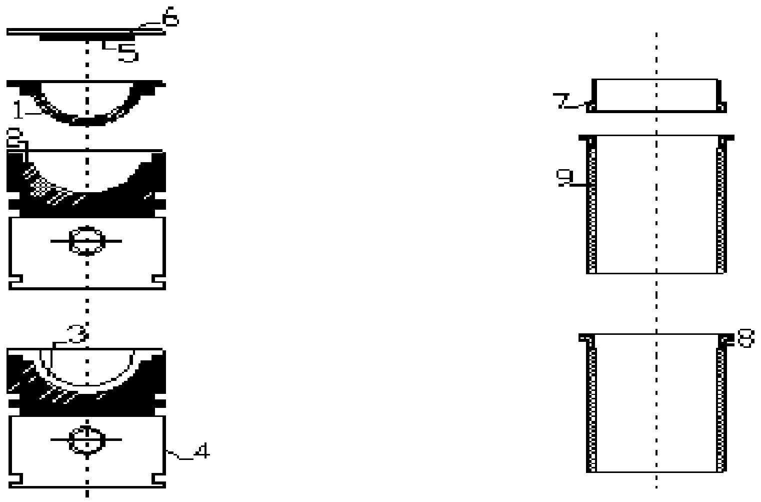
Keywords: *Waste fried vegetable oil, LHR-1, LHR-2, LHR-3 Performance, Pollution levels, Combustion characteristics.*

1. INTRODUCTION

The fossil fuels, particularly diesel fuel is depleting due to increase of vehicle population at an alarming rate due to advancement of civilization and also diesel is consumed not only in transport sector but also in agricultural sector. Pollution levels are also increasing with these fuels and there is economic burden on Government of India as it has to spend foreign exchange for importing crude petroleum, which has lead to search for alternate and renewable fuels and become pertinent for the engine manufacturers, users and researchers involved in the combustion research. Most of the energy supplied to the engine is lost through the coolant, friction and other losses, thus leaving less energy for useful purposes. In view of the above, the major thrust in engine research during the last two or three decades has been on development of LHR engines. The concept of LHR engine is to minimize the heat loss to the coolant by providing thermal resistance in the path of the coolant by which energy can be gained. Several methods adopted for achieving LHR to the coolant are i) using ceramic coatings on piston, liner and cylinder head ii) creating air gap in the piston and other components with low-thermal conductivity materials like superni, cast iron and mild steel etc. Investigations were carried out by various researchers [1-6] on ceramic coated engines and reported brake specific fuel consumption (BSFC) was improved in the range 5-9% and pollution levels decreased with ceramic coated engine. The technique of providing an air gap in the piston involved the complications of joining two different metals. Investigations were carried out [7] on LHR engine with air gap insulated piston with pure diesel. However, the bolted design employed by them could not provide complete sealing of air in the air gap. Investigations [8-9] were carried out with air gap insulated piston with nimonic crown with pure diesel operation and reported brake specific fuel consumption was improved by 8%. Experiments were conducted [10] on different degrees of insulation and reported that performance was improved with higher degree of insulation. Experiments were conducted [11] with air gap insulated piston with superni crown and air gap insulate liner with superni insert with varied injection timing and injection pressure with different alternate fuels like vegetable oils and alcohol and reported that LHR engine improved the performance with alternate fuels. Vegetable oils have cetane number comparable with diesel fuel, but they have high viscosity and low volatility. Experiments were also conducted [12] with bio-diesel at different conditions of vegetable oil with air gap insulated piston with superni crown, air gap insulated liner with superni insert and ceramic coated cylinder head with varied injection time and injection pressure and reported that LHR engine improved the performance of the engine when compared with pure diesel operation. Experiments were [13-18] conducted with vegetable oils in CE and reported that performance was deteriorated with CE. However, no systematic investigations were reported with waste fried vegetable oil with different degrees of insulation. The present paper attempts to evaluate the performance of LHR engine, with different degrees of insulation with waste fried vegetable oil collected from hotels and restaurants with varied injection pressure and compared with pure diesel operation on CE at recommended injection timing and injection pressure.

2. EXPERIMENTAL PROGRAMME

Fig.1gives the details of insulated piston, insulated liner and ceramic coated cylinder head employed in the experimentation. LHR diesel engine contains a two-part piston; the top crown made of low thermal conductivity material, superni-90 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 is found to be 3-mm [8], for better performance of the engine with superni inserts with diesel as fuel. A superni-90 insert is screwed to the top portion of the liner in such a manner that an air gap of 3mm is maintained between the insert and the liner body.

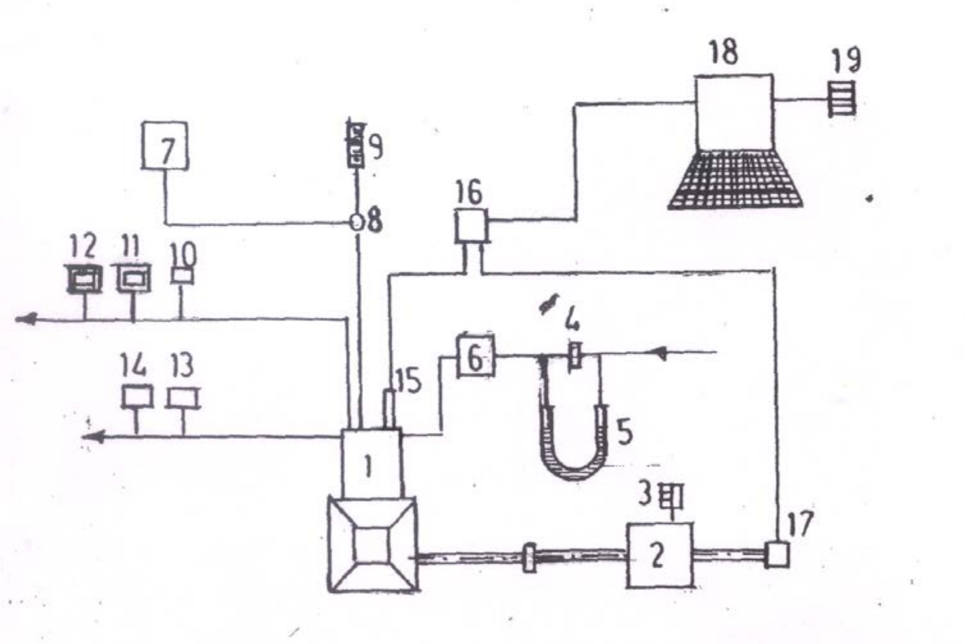


1. Crown, 2 Gasket, 3.Air Gap. 4. Body
5. Ceramic Coating, 6. Cylinder head 7.Insert, 8. Air gap, 9. Liner,

Insulated piston Insulated liner Ceramic coated cylinder head

Fig.1: Assembly Details of Insulated Piston, Insulated Liner and Ceramic Coated Cylinder Head

At 500°C the thermal conductivity of superni-90 and air are 20.92 and 0.057 W/m-K respectively. Partially stabilized zirconium (PSZ) of thickness 500 microns is coated by means of plasma coating technique. The properties of vegetable oil are taken from reference No-11. Experimental setup used for the investigations of LHR diesel engine with waste fried vegetable oil is shown in Fig .2. CE has an aluminum alloy piston with a bore of 80 mm and a stroke of 110mm. The rated output of the engine is 3.68 kW at a rate speed of 1500 rpm. The compression ratio is 16:1 and manufacturer's recommended injection timing and injection pressures are 27°bTDC (before top dead centre) and 190 bar respectively. The fuel injector has 3 holes of size 0.25mm. The combustion chamber consists of a direct injection type with no special arrangement for swirling motion of air. The engine is connected to electric dynamometer for measuring brake power of the engine. Fuel consumption of the engine is measured with burette method. Air-consumption of the engine is measured by air-box method. The naturally aspirated engine is provided with water-cooling system in which inlet temperature of water is maintained at 60°C by adjusting the water flow rate. The engine oil is provided with a pressure feed system. No temperature control is incorporated, for measuring the lube oil temperature. The injection pressure is changed from 190 bar to 270 bar (in steps of 40 bar) using nozzle testing device. The maximum injection pressure is restricted to 270 bar due to practical difficulties involved. Exhaust gas temperature (EGT) is measured with thermocouples made of iron and iron-constantan.



1.Engine, 2.Electical Dynamo meter, 3.Load Box, 4.Orifice meter, 5.U-tube water manometer, 6.Air box, 7.Fuel tank, 8, Three way valve, 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.2: Experimental Set-up

Pollution levels of smoke and NO_x are recorded by AVL smoke meter and Netel Chromatograph NOx analyzer respectively at the peak load operation of the engine respectively.

Piezo electric transducer, fitted on the cylinder head to measure pressure in the combustion chamber is connected to a console, which in turn is connected to Pentium personal computer. TDC encoder provided at the extended shaft of the dynamometer is connected to the console to measure the crank angle of the engine. A special P-θ software package evaluates 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.

3. RESULTS AND DISCUSSION

A. Performance Parameters

Here onwards, the engine with ceramic coated cylinder head is termed as LHR-1 engine; the insulated engine with air gap insulated piston and air gap insulated liner is termed as LHR-2 engine while insulated engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head is termed as LHR-3 engine. The variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) with pure diesel operation with different versions of the engine is shown in Fig.3. BTE decreased up to 80% of the peak load in the LHR-1 engine and LHR-2 engine at the recommended injection timing and beyond this load, it increased over and above that of the CE. As the combustion chamber is insulated to greater extent, it is expected that high combustion temperatures would be prevalent in LHR engine. It tends to decrease the ignition delay thereby reducing pre-mixed combustion as a result of which, less time is available for proper mixing of air and fuel in the combustion chamber leading to incomplete combustion, with which BTE decreased beyond 80% of the full load. More over at this load, friction and increased diffusion combustion resulted from reduced ignition delay. Increased radiation losses might have also contributed to the deterioration. BTE decreased at all loads for LHR-3 engine in comparison with CE because of decrease ignition delay. At peak load operation, BTE is marginally higher with LHR-1 engine when compared with LHR-2 engine. The reduction of ignition delay is higher with LHR-2 engine leading to deteriorate in the performance of the engine.

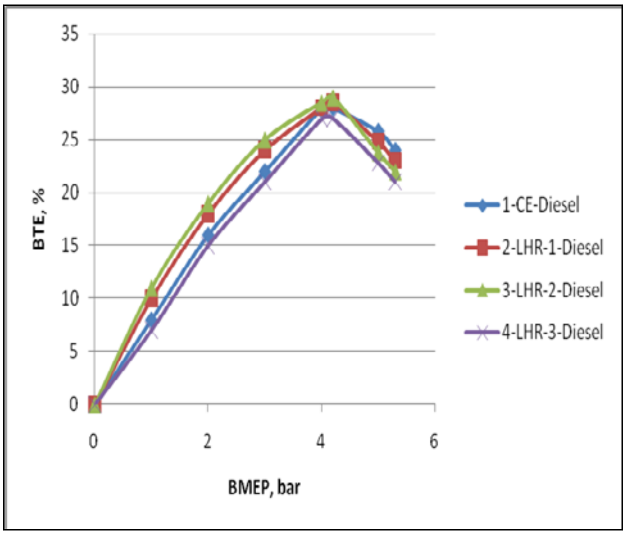


Fig.3: Variation of Brake Thermal Efficiency (BTE) with Brake Mean Effective Pressure (BMEP) in Different Versions of the Engine with Pure Diesel Operation

The variation of BTE with BMEP in CE, LHR-1, LHR-2, LHR-3 engine with test fuels at 27^{o}bTDC and at an injection pressure of 190 bars, is shown in Fig.4.

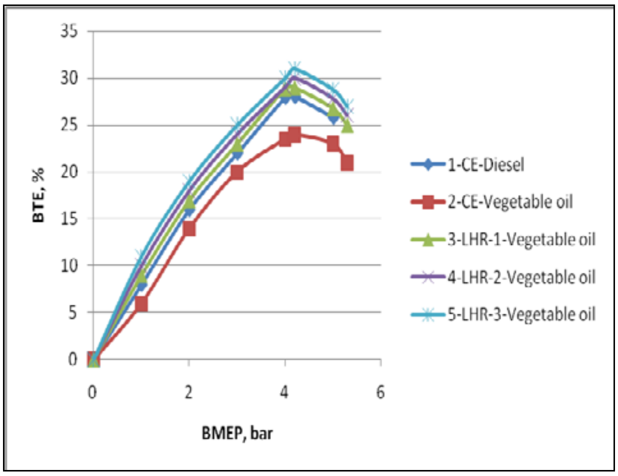


Fig.4: Variation of BTE with BMEP in Different Versions of the Engine with Test Fuels

The trend exhibited by the conventional engine with crude vegetable oil is similar to that of the CE with pure diesel fuel. However, CE with crude vegetable oil showed the deterioration in the performance for entire load range when compared with pure diesel operation. Although carbon accumulations on the nozzle tip might play a partial role for the general trends observed, the difference of viscosity between the diesel and crude vegetable oil provided a possible explanation for the deterioration in the performance of the engine with crude vegetable oil operation. The result of lower jet exit Reynolds numbers with vegetable oils adversely affected the atomization. The amount of air entrained by the fuel spray is reduced, since the fuel spray plume angle is reduced, resulting in slower fuel- air mixing. In addition, less air entrainment by the fuel spray suggested that the fuel spray penetration might increase and resulted in more fuel reaching the combustion chamber walls. Furthermore droplet mean diameters (expressed as Sauter mean) are larger for vegetable oils leading to higher droplet evaporation thus slowing the preparation of the vegetable oil and reducing the rate of heat release as compared to diesel fuel operation. This also, contributed the higher ignition (chemical) delay of the crude vegetable oil due to lower cetane number. According to the qualitative image of the combustion under the crude vegetable oil operation with conventional engine, the lower BTE is attributed to the relatively retarded and lower heat release rate. BTE increased in LHR versions of the engine in comparison with CE with vegetable oil operation. High cylinder temperatures helped in better evaporation and faster combustion of the fuel injected into the combustion chamber. Reduction of ignition delay of the vegetable oil in the hot environment of the LHR-3 engine improved heat release rates and efficient energy utilization. LHR-3 engine showed improved performance when compared with LHR-1 and LHR-2 versions of the engine. This is due to hot environment provided by LHR-3 engine which caused efficient burning of high viscous fuel.

By controlling the injector opening pressure and the injection rate, the spray cone angle is found to depend on injection pressure. Further increasing the injector opening pressure increases the nominal mean spray velocity resulting in better fuel-air mixing in the combustion chamber. Higher fuel injection pressures increase the degree of atomization. The fineness of atomization reduces the ignition lag, due to higher surface volume ratio. Smaller droplet size will have a low depth of penetration, due to less momentum of the droplet and less velocity relative to air, from where it has to find oxygen after evaporation. Because of this, air utilization will be reduced due to fuel spray being shorter. Also with smaller droplets, aggregate area of inflammation will increase after ignition, resulting high-pressure rise during second stage of combustion. Thus lower injection pressure giving larger droplet size may give lower pressure rise during the second stage of combustion and probably smoother running. However, poor performance at lower injector opening pressures indicates slow mixing probably because of insufficient spray penetration with consequent slow mixing during diffusion burning. Hence an optimum mean diameter of the droplet should be attempted as a compromise. The variation of injection opening pressure is done with nozzle-testing device. Performance of the engine is evaluated with varying injection pressure from 190 to 270 bars for CE and LHR engine. Table-1 shows the variation of peak BTE with injection pressure in both versions of the engine with test fuels.

Table 1: Data of Peak BTE

Peak Brake Thermal Efficiency (%)						
Engine Version	Pure Diesel operation			Waste fried vegetable oil operation		
	Injection Pressure (bar)			Injection Pressure (bar)		
	190	230	270	190	230	270
CE	28	29	30	24	25	26
LHR-1	28.5	29	29.5	29.5	30	30.5
LHR-2	29	30	30.5	30.5	31	31.5
LHR-3	27	27.5	28	31.5	32	32.5

CE-Conventional engine, LHR1-Engine with ceramic coated cylinder head, LHR-2- Insulated engine with air gap insulated piston and air gap insulated liner, LHR-3 Insulated engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head

Peak brake thermal efficiency increased with increase of injection pressure with vegetable oil operation in different versions of the engine. Performance is improved with LHR versions of the engine and LHR-2 engine registered higher value of peak BTE with vegetable oil operation.

Table-2 presents data of brake specific energy consumption (BSEC) at peak load operation in different versions of the engine with injection pressure with vegetable oil operation.

Table 2: Data of Peak BSEC at Peak Load Operation

Brake Specific Energy Consumption (kW/kW)						
Engine Version	Pure Diesel operation			Waste fried vegetable oil operation		
	Injection Pressure (bar)			Injection Pressure (bar)		
	190	230	270	190	230	270
CE	4.0	3.92	3.84	4.98	4.78	4.68
LHR-1	4.12	4.04	3.96	3.96	3.92	3.88
LHR-2	4.16	4.08	4.00	3.92	3.88	3.84
LHR-3	4.3	4.1	4.05	3.80	3.76	3.74

CE-Conventional engine, LHR1-Engine with ceramic coated cylinder head, LHR-2- Insulated engine with air gap insulated piston and air gap insulated liner, LHR-3 Insulated engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head.

BSEC at peak load operation decreased with increase of injection pressure in both versions of the engine with different test fuels. BSEC is higher in conventional engine with vegetable oil operation in comparison with pure diesel operation at peak load. However, BSEC decreased in LHR engines with vegetable oil operation. LHR-3 gave lower BSEC when compared with other versions of LHR engines because of provision of higher degree of insulation and energy is effectively utilized in converting heat into work.

Table-3 shows data of brake specific fuel consumption (BSFC) at peak load operation which varies with injection pressure in both version of the engine with test fuels. BSFC increased with LHR versions of the engine with pure diesel operation when compared with CE with pure diesel operation. This is due to increase of ignition delay. BSFC at peak load operation is observed to be less with LHR versions of the engine with vegetable oil operation when compared with CE with vegetable oil operation. This is due to efficient combustion of vegetable oils in the hot environment of LHR engines, as components are insulated leading to decrease in BSFC or increase of BTE. BSFC decreased with increase of injection pressure in all versions of the engine due to improved spray characteristics.

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Table 3: Data of BSFC at Peak Load Operation

Brake Specific Fuel Consumption (BSFC) at peak load operation (kg/h-kW)						
Engine Version	Pure Diesel operation			Waste fried vegetable oil operation		
	Injection Pressure (bar)			Injection Pressure (bar)		
	190	230	270	190	230	270
CE	0.343	0.336	0.329	0.498	0.478	0.468
LHR-1	0.353	0.346	0.339	0.396	0.392	0.388
LHR-2	0.356	0.349	0.343	0.392	0.388	0.384
LHR-3	0.368	0.351	0.347	0.380	0.376	0.374

CE-Conventional engine, LHR1-Engine with ceramic coated cylinder head, LHR-2- Insulated engine with air gap insulated piston and air gap insulated liner, LHR-3 Insulated engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head.

The variation of exhaust gas temperature (EGT) with brake mean effective pressure (BMEP) with pure diesel operation with different versions of the engine is shown in Fig.5. EGT increases with an increase of BMEP in all versions of the engine. EGT is lower in LHR-1 and LHR-2 engine upto 80% of the full load and beyond that it increased when compared with CE. Hence it is confirmed that performance of LHR-1 and LHR-2 engines is improved upto 80% of the full load and beyond that it deteriorated. However, EGT is found to be higher at all loads in comparison with CE. This indicated that heat rejection is restricted through the piston, liner and header, thus maintaining the hot combustion chamber as result of which the exhaust gas temperature increased. This also confirms lower BTE in LHR-3 engine, as more amount of heat is wasted instead of actual utilization or converting into actual work.

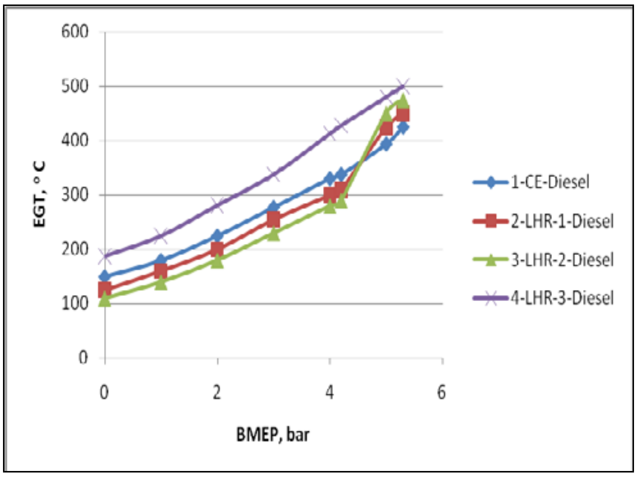

Fig.5: Variation of EGT with BMEP in different versions of the engine with pure diesel operation

The variation of EGT with BMEP in CE, LHR-1, LHR-2 and LHR-3 engines with crude vegetable oil at 27°bTDC and at an injection pressure of 190 bars, is shown in Fig.6.

CE with vegetable oil operation at the recommended injection timing recorded higher EGT at all loads when 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 vegetable oil increased the duration of the burning phase. LHR versions of engine recorded lower value of
EGT when compared with CE with vegetable oil operation. This is due to reduction of ignition delay in the hot environment with the provision of the insulation in the LHR engine, which caused the gases expand in the cylinder giving higher work output and lower heat rejection. This showed that the performance is improved with LHR engine over CE with vegetable oil operation. LHR-3 engine recorded lower magnitude of EGT when compared with other versions of the engine.

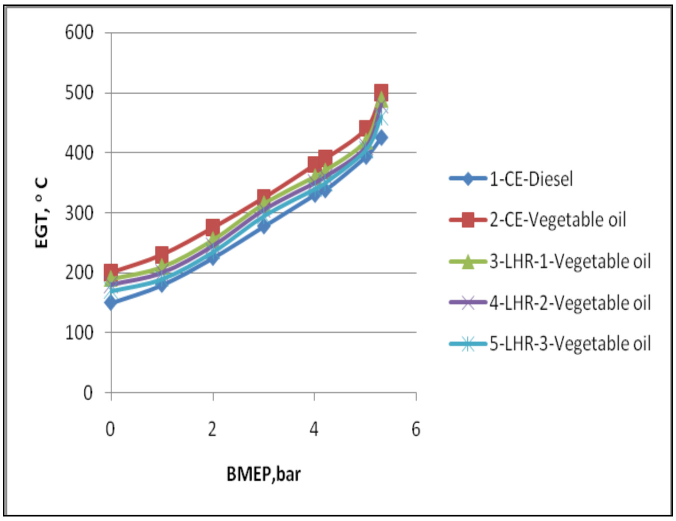

Fig.6.: Variation of EGT with BMEP in different versions of the engine with vegetable oil operation

Table-4 shows data of EGT which varies with injection pressure in both version of the engine with test fuels. EGT decreased with increase in injection pressure in different versions of the engine. LHR-3 engine recorded higher value of EGT when compared with other versions of the engine with pure diesel operation. Since for LHR-3 engine, all the components are insulated and engine combustion is maintained at higher temperature leading to increase of EGT.

Table 4: Data of EGT at Peak Load Operation

Exhaust Gas Temperature (^{o}C)						
Engine Version	Pure Diesel operation			Waste fried vegetable oil operation		
	Injection Pressure (bar)			Injection Pressure (bar)		
	190	230	270	190	230	270
CE	425	410	395	500	475	460
LHR-1	450	425	400	470	445	430
LHR-2	475	460	445	460	440	420
LHR-3	500	480	460	440	420	400

CE-Conventional engine, LHR1-Engine with ceramic coated cylinder head, LHR-2- Insulated engine with air gap insulated piston and air gap insulated liner, LHR-3 Insulated engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head.

The magnitude of EGT at peak load decreased with increase of injection pressure in both versions of the engine with vegetable oil. This is due to improved atomization characteristics of the fuel and improved air-fuel ratios.

The variation in the magnitude of coolant load (CL) with BMEP in CE and LHR engines with pure diesel, at the recommended injection timing at an injection pressure of 190 bar, is shown in Fig.7. CL increased with the increase of load in CE and LHR engines. LHR engines gave lesser CL upto 80% of the peak load, when compared with CE. Air being a bad conductor offers thermal resistance for heat flow through the piston and liner. It is therefore evident that thermal barrier provided in the piston and liner resulted in reduction of CL upto 80% of the full load. Beyond 80% of the full load, CL in LHR engine increased over and above that of the CE, with which efficiency is deteriorated at peak load of LHR engine, when compared with CE. This is because in cylinder, the heat rejection at full load is primarily due to un-burnt fuel concentration near the combustion chamber walls. The air-fuel ratio got reduced to a reasonably low value at this load confirming the above trend. However, when heat rejection calculations of coolant load are made, the heat lost to lubricant should also be considered. As in the present investigations the lubricant heat loss is not considered, this aspect is not depicted in CL calculations. Heat can also escape through un-insulated cylinder head for LHR-2 version of the engine.

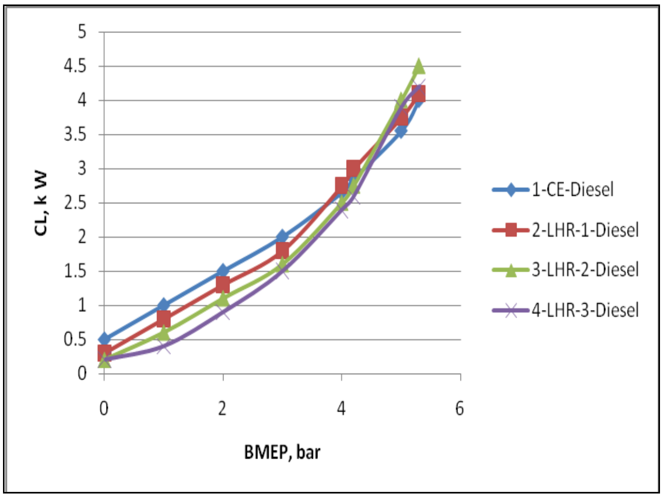

Fig.7: Variation of Coolant Load with BMEP in Different Versions of the Engine with Pure Diesel Operation.

The variation of coolant load with BMEP in CE, LHR-1, LHR-2 and LHR-3 engine, with crude vegetable oil at 27^{o}bTDC and at an injection pressure of 190 bars, is shown in Fig.8.

Coolant load is reduced with LHR versions of the engine with vegetable oil operation when compared with CE with pure diesel operation. Heat output is properly utilized and hence efficiency is increased and heat loss to coolant is decreased with effective thermal insulation with LHR engine. As it is obvious, LHR-3 version of the engine registered lower value of coolant loss, as it is provided with high degree of insulation.

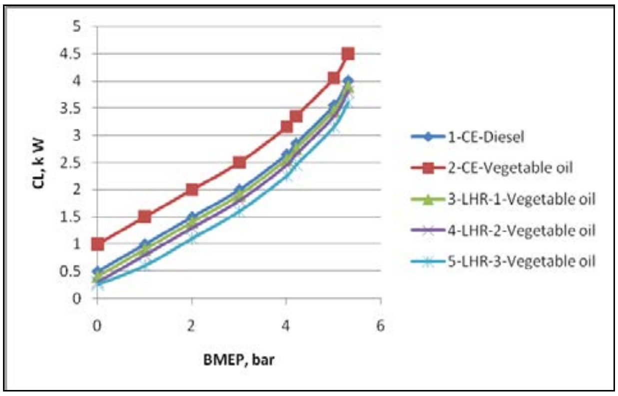

Fig.8.: Variation of Coolant Load with BMEP in Different Versions of the Engine with Vegetable Oil Operation

Table-5 shows data of coolant load, which varies with injection pressure in both version of the engine with test fuels. From the Table, it can be observed that CL decreased with increase of injection pressures in LHR engines while it increased in CE. Decrease of gas temperatures in the LHR engine with the increase of injection pressure any way decreased CL and exhaust gas temperatures. CL increased marginally in CE, while it decreased in LHR engine with increasing of the injection pressure. This is due to the fact with increase of injection pressure with CE, increased nominal fuel spray velocity resulting in better fuel-air mixing with which gas temperatures increased.

Table 5: Data of Coolant Load at Peak Load Operation

Engine Version	Coolant Load (kW)					
	Pure Diesel operation			Waste fried vegetable oil operation		
	Injection Pressure (bar)			Injection Pressure (bar)		
	190	230	270	190	230	270
CE	4.0	4.1	4.2	4.5	4.6	4.7
LHR-1	4.1	3.6	3.1	3.8	3.6	3.4
LHR-2	4.5	4.0	3.40	3.7	3.5	3.3
LHR-3	4.2	3.7	3.2	3.5	3.3	3.1

CE-Conventional engine, LHR1-Engine with ceramic coated cylinder head, LHR-2- Insulated engine with air gap insulated piston and air gap insulated liner, LHR-3 Insulated engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head.

The reduction of CL in LHR engine is not only due to the provision of the insulation but also it is due to better fuel spray characteristics and increase of air-fuel ratios causing decrease of gas temperatures and hence the CL. The magnitude of coolant load at peak load decreased with increase of injection pressure in LHR versions of the engine, however, it increases with CE with vegetable oil. This is due to decrease of gas temperatures in LHR versions of the engine and increase of the same with CE.

The variation of volumetric efficiency with brake mean effective pressure (BMEP) with pure diesel operation in different versions of the engine is shown in Fig.9. Volumetric efficiency decreased in LHR versions of the engine at all loads in comparison with other versions of the engine. Air gets heated with insulated components of engine less amount of air is inducted in insulated engine and hence its mass flow rate decreases.

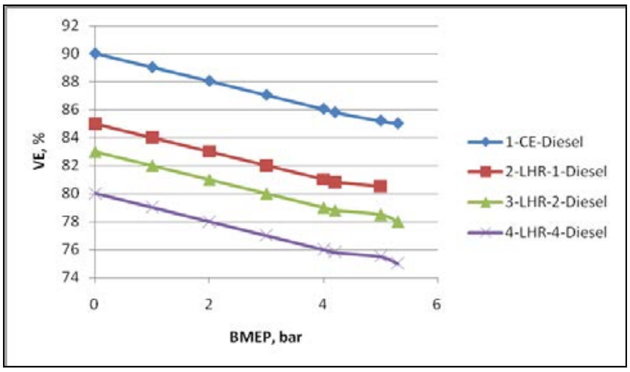

Fig 9: Variation of volumetric efficiency (VE) with BMEP in different versions of the engine with pure diesel operation.

The variation of volumetric efficiency with BMEP in CE, LHR-1, LHR-2 and LHR-3 engines with crude vegetable oil at 27°bTDC and at an injection pressure of 190 bars, is shown in Fig.10.Volumetric efficiency decreased with vegetable oil operation when compared with CE with pure diesel operation. This is due to increase of deposits. LHR versions of the engine further decreased volumetric efficiency with vegetable oil operation.

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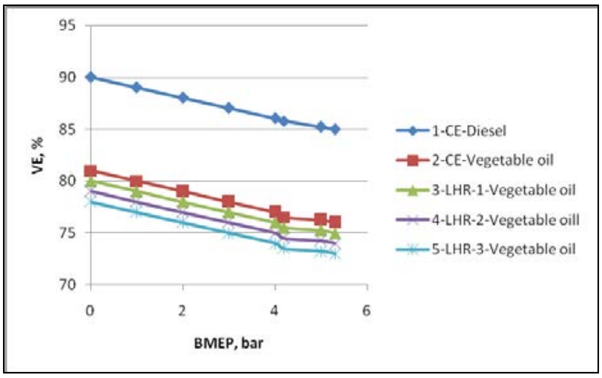

Fig.10: Variation of volumetric efficiency (VE) with BMEP in different versions of the engine with vegetable oil operation.

This is due to hot environment provided by LHR versions of the engine. LHR-3 engine showed lower volumetric efficiency when compared with other versions of the engine. This is due to high degree of insulation provided with LHR-3 engine.

Table-6 shows the data of volumetric efficiency (VE) at peak load operation in different versions of the engine with injection pressure with test fuels.

Table 6: Data of Volumetric Efficiency at Peak Load

Volumetric Efficiency (%)						
Engine Version	Pure Diesel operation			Waste fried vegetable oil operation		
	Injection Pressure (bar)			Injection Pressure (bar)		
	190	230	270	190	230	270
CE	85	86	87	76	78	80
LHR-1	80	82	84	75	77	78
LHR-2	78	80	82	74	76	77
LHR-3	75	76	77	73	75	76

CE-Conventional engine, LHR1-Engine with ceramic coated cylinder head, LHR-2- Insulated engine with air gap insulated piston and air gap insulated liner, LHR-3 Insulated engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head.

Volumetric efficiency increased with increase of injection pressure in both versions of the engine with different test fuels. This is because of reduction of deposits and improved air fuel ratios with increase of injection pressure in different configurations of the engine. This is also due to fuel air ratios improved with increase of injection pressures leading to increase of volumetric efficiency in both versions of the engine. CE recorded higher volumetric efficiency in comparison with LHR versions of the engine as air gets heated with hot components of insulated engine leading to reduce mass flow rate of air into the engine.

B. Pollution Levels with Test Fuels

The variation of smoke levels with brake mean effective pressure (BMEP) with pure diesel operation in different versions of the engine is shown in Fig.11. Smoke levels increase with as increase of BMEP in all versions of the engine. Smoke levels are higher al all loads in LHR-3 engine when compared with other versions of the engine. This is due to fuel cracking at higher temperatures in LHR-3 engine. At recommended injection timing and pressure, increase of smoke intensity is observed in LHR-3 engine, when compared with CE. This is due to the decreased oxidation rate of soot in relation to soot formation. Higher surface temperatures of LHR-3 engine aided this process. LHR-3 engine shorten the delay period, which increases thermal cracking, responsible for soot formation. Higher temperature of LHR-3 engine produced increased rates of both soot formation and burn up. The reduction in VE and air-fuel ratio are responsible factors for increasing smoke levels in LHR-3 engine near peak load operation of the engine. As expected, smoke increased in LHR-2 engine because of higher temperatures and improper utilization of the fuel consequent upon predominant diffusion combustion. LHR-1 engine registered marginally higher value of smoke intensity when compared with CE. It followed the same trend as followed by LHR-2 engine.

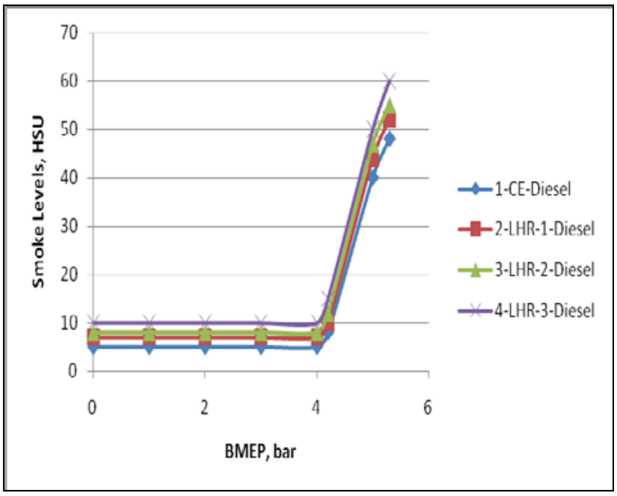

Fig.11 : Variation of smoke levels with BMEP in different versions of the engine with pure diesel operation.

The variation of smoke levels with BMEP in CE, LHR-1, LHR-2 and LHR-3 engines with crude vegetable oil at 27^{o}bTDC and at an injection pressure of 190 bars, is shown in Fig.12. Smoke levels are observed to be higher with CE at all loads with vegetable oil operation when compared with pure diesel operation on CE. This is due to the higher magnitude of the ratio of C/H of crude linseed oil (0.8) when compared to pure diesel (0.45). The increase of smoke levels is also due to decrease of air-fuel ratios and volumetric efficiency with crude vegetable oil compared to pure diesel operation. Smoke levels are proportional to the density of the fuel. Since vegetable oils have higher density compared to diesel fuels, smoke levels are higher with vegetable oils.. Due to higher molecular weight, crude vegetable oils have low volatility and because of their un-saturation, crude vegetable oils are inherently more reactive than diesel fuels, which results that they are more susceptible to oxidation and thermal polymerization reactions leading to produce higher smoke levels. However, LHR engines decreased smoke levels due to efficient combustion and less amount of fuel accumulation on the hot combustion chamber walls of the LHR engine at different operating conditions of the vegetable oil compared with CE. LHR-3 engine registered lower value of smoke levels in comparison with other versions of LHR engine due to efficient combustion in LHR-3 engine.

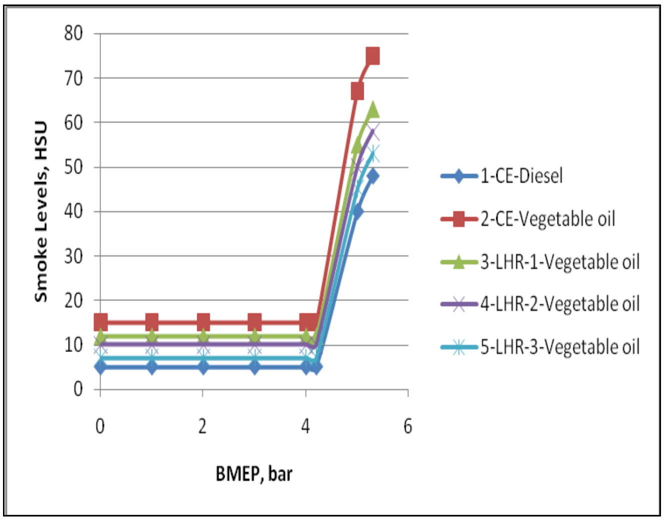

Fig.12 : Variation of smoke levels with BMEP in different versions of the engine with vegetable oil operation.

Table -7 presents the data of smoke levels which shows the variation of injection pressure in both versions of the engine with test fuels.

Table 7: Data of Smoke Levels at Peak Load

Smoke Levels (HSU)						
Engine Version	Pure Diesel operation			Waste fried vegetable oil operation		
	Injection Pressure (bar)			Injection Pressure (bar)		
	190	230	270	190	230	270
CE	48	38	34	70	65	60
LHR-1	52	45	40	58	53	48
LHR-2	55	50	45	53	48	43
LHR-3	60	55	50	48	43	38

CE-Conventional engine, LHR1-Engine with ceramic coated cylinder head, LHR-2- Insulated engine with air gap insulated piston and air gap insulated liner, LHR-3 Insulated engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head, HSU-Hartridge smoke unit.

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Smoke levels decreased with increase of injection pressure, in both versions of the engine, with vegetable oil operation. This is due to improvement in the fuel spray characteristics at higher injection pressures causing lower smoke levels.

The variation of NOx levels with brake mean effective pressure (BMEP) with pure diesel operation in different versions of the engine is shown in Fig.13. For all versions of the engine, NOx concentrations raised steadily as the fuel/air ratio increased with increasing BMEP, at constant injection timing. LHR-3 engine recorded higher NOx at all loads when compared with other versions of the engine. It is due to the reduction of fuel-air equivalence ratio with LHR engine, which is approaching to the stoichiometric ratio, causing more NOx concentrations.

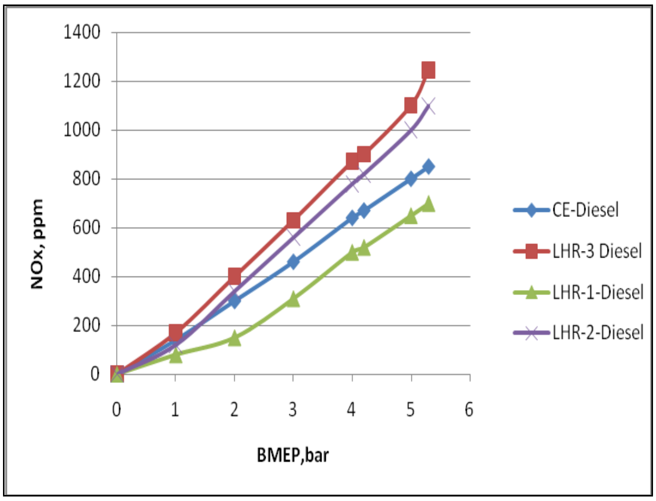

Fig.13: Variation of NOx Levels with Brake Mean Effective Pressure (BMEP) with Pure Diesel Operation in Different Versions of the Engine

The variation of NOx levels with BMEP in CE, LHR-1, LHR-2 and LHR-3 engines with crude vegetable oil at 27^{o}bTDC and at an injection pressure of 190 bars, is shown in Fig.14. NOx levels are lower in CE while they are higher in LHR engines when compared with diesel operation. This is due to lower heat release rate because of high duration of combustion causing lower gas temperatures with the vegetable oil operation on CE, which reduced NOx levels. Increase of combustion temperatures with the faster combustion and improved heat release rates in LHR engine cause higher NOx levels. NOx levels are higher with LHR-3 engine when compared with other versions of the engine. This is due to high degree of insulation provided with LHR-3 version of the engine.

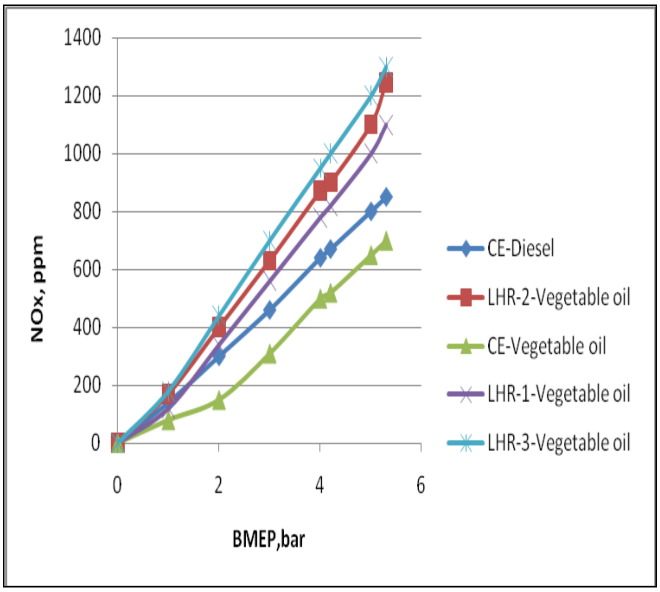

Fig.14: Variation of NOx Levels with Brake Mean Effective Pressure (BMEP) with Test Fuels in Different Versions of the Engine

Table-8 presents the data of NOx levels which varies with injection pressure with test fuels in different versions of the engine. From the Table, it can be observed that increase of injection pressure decreased NOx emissions in both versions of the engine. This is because of decrease of gas temperatures with the increase of injection pressure. With the increase of injection pressure, fuel droplets penetrate and find oxygen counterpart easily.

Table 8: Data of NOx Emissions at Peak Load

	NOx Levels (ppm)					
Engine Version	Pure Diesel operation			Waste fried vegetable oil operation		
	Injection Pressure (bar)			Injection Pressure (bar)		
	190	230	270	190	230	270
CE	850	800	750	675	700	710
LHR-1	1150	1100	1050	1080	1030	980
LHR-2	1300	1280	1260	1225	1210	1160
LHR-3	1400	1380	1360	1270	1240	1190

CE-Conventional engine, LHR1-Engine with ceramic coated cylinder head, LHR-2- Insulated engine with air gap insulated piston and air gap insulated liner, LHR-3 Insulated engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head.

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Turbulence of the fuel spray increased the spread of the droplets thus leading to decrease in NOx levels. In case of LHR engine, decrease of NOx levels is due to decrease of combustion temperatures with increase of injection pressure**.**

C. Combustion Characteristics

Table-9 and Table-10 present the data of peak pressure (PP) and Maximum Rate of Pressure Rise (MRPR) at peak load operation which varies with injection pressure with test fuels in different versions of the engine respectively. The peak pressures are lower in LHR engine with pure diesel operation in comparison with CE. This is because the LHR engine exhibited higher temperatures of combustion chamber walls leading to continuation of combustion, giving peak pressures away from TDC. The magnitude of PP increased with the increase of injection pressures, in both versions of the engine.

With vegetable oil operation, PP are lower in CE while they were higher in the LHR engines at the recommended injection timing and pressure, when compared to pure diesel operation on CE. This is due to increase of ignition delay, as vegetable oils require large duration of combustion. Mean while the piston started making downward motion thus increasing volume when the combustion takes place in CE. LHR engines 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 vegetable oils is obvious as it could burn low cetane and high viscous fuels. PP increased with the increase of injection pressure in all versions of the engine, with the vegetable oils operation. Higher injection pressure produces smaller fuel particles with low surface to volume ratio, giving rise to higher PP. The trend followed by MRPR is similar to PP in both versions of the engine. This trend of increase of MRPR and decrease of TOMRPR indicated better and faster energy substitution and utilization by vegetable oils, which could replace 100% diesel fuel. However, these combustion characters were within the limits hence the vegetable oils could be effectively substituted for diesel fuel.

Table 9: Data of Peak Pressure at Peak Load Operation

PP (bar)						
Engine Version	Pure Diesel operation			Waste fried vegetable oil operation		
	Injection Pressure (bar)			Injection Pressure (bar)		
	190	230	270	190	230	270
CE	50.4	51.7	53.5	46.1	49.6	49.7
LHR-1	49.4	52.2	54.3	56.1	59.1	60.2
LHR-2	48.1	51.1	53.0	59.2	61.8	63.2
LHR-3	46.1	48.4	51.1	62.1	64.1	66.2

CE-Conventional engine, LHR1-Engine with ceramic coated cylinder head, LHR-2- Insulated engine with air gap insulated piston and air gap insulated liner, LHR-3 Insulated engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head.

Table 10: Data of Maximum Rate of Pressure Rise (MRPR) at Peak Load Operation

MRPR (bar/deg)						
Engine Version	Pure Diesel operation			Waste fried vegetable oil operation		
	Injection Pressure (bar)			Injection Pressure (bar)		
	190	230	270	190	230	270
CE	3.1	3.3	3.4	2.4	2.6	2.9
LHR-1	3.0	3.3	3.4	3.2	3.3	3.4
LHR-2	2.9	3.2	3.3	3.3	3.4	3.5
LHR-3	2.7	2.8	2.9	3.4	3.5	3.6

CE-Conventional engine, LHR1-Engine with ceramic coated cylinder head, LHR-2- Insulated engine with air gap insulated piston and air gap insulated liner, LHR-3 Insulated engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head.

Table-11 presents the data of Time of Occurrence of Peak Pressure (TOPP) at peak load operation which varies with injection pressure with test fuels in different versions of the engine respectively. The magnitude of TOPP decreased with the increase of injection pressure in different versions of the engine, with vegetable oil operation. From the Table, it can be noticed that the magnitude of TOPP decreased (shifted towards TDC) with the increasing of injection pressure in all versions of the engine. This is confirmed that both versions of the engine showed improvement in performance, when the injection pressures are increased. TOPP is more with different operating conditions of vegetable oils in CE when compared to pure diesel operation on the CE. This is due to higher ignition delay with the vegetable oil when compared to pure diesel fuel. This once again established the fact by observing lower peak pressures and higher TOPP, that CE with vegetable oil operation showed the deterioration in the performance when compared to pure diesel operation on CE.

Table 11: Data of Time of Occurrence of Peak Pressure (TOPP) at Peak Load Operation

Engine Version	TOPP (bar/deg)					
	Pure Diesel operation			Waste fried vegetable oil operation		
	Injection Pressure (bar)			Injection Pressure (bar)		
	190	230	270	190	230	270
CE	9	9	8	11	11	11
LHR-1	9	9	9	10	10	10
LHR-2	10	10	9	10	9	9
LHR-3	11	10	9	10	9	9

CE-Conventional engine, LHR1-Engine with ceramic coated cylinder head, LHR-2- Insulated engine with air gap insulated piston and air gap insulated liner, LHR-3 Insulated engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head.

4. CONCLUSIONS

LHR versions of the engine are suitable for vegetable oil operation. Performance is improved with vegetable oil operation on LHR versions of the engine, particularly LHR-3 version of the engine. However, performance is deteriorated with pure diesel at peak load operation with LHR version of the engine.

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