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M.V.S. MURALI KRISHNA [*], *N. JANARDHAN* [*], *P.V.K. MURTHY* [**], *P. USHASRI* [***], *NAGA SARADA* [****]

A COMPARATIVE STUDY OF THE PERFORMANCE OF A LOW HEAT REJECTION ENGINE WITH THREE DIFFERENT LEVELS OF INSULATION WITH VEGETABLE OIL OPERATION

Investigations were 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 degrees of insulation with normal temperature condition of linseed oil with varied injection pressure. Performance parameters were determined at various magnitudes of brake mean effective pressure. Pollution levels of smoke and oxides of nitrogen (NOx) were recorded at the peak load operation of the engine. Combustion characteristics of the engine were measured with TDC (top dead centre) encoder, pressure transducer, console and special pressure-crank angle software package. Conventional engine (CE) showed deteriorated performance, while LHR engine showed improved performance at recommended injection timing of 27°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 14%, smoke levels decreased by 10% and NOx levels increased by 30% with LHR engine at an injection pressure of 270 bar when compared with pure diesel operation on CE at manufacturer's recommended injection timing.

[*] *Mechanical Engineering Department, Chaitanya Bharathi Institute of Technology, Gandipet, Hyderabad-500 075, Andhra Pradesh, India, E-mail: maddalivs@gmail.com*

[**] *Vivekananda Institute of Science and Information Technology, Shadnagar, Mahabubnagar-509216, Andhra Pradesh, India*

[***] *Mechanical Engineering Department, College of Engineering, Osmania University, Hyderabad, Andhra Pradesh, India*

[****] *Mechanical Engineering Department, J.N.T.U. College of Engineering, Kukatpally, Hyderabad- 500 085, Andhra Pradesh, India*

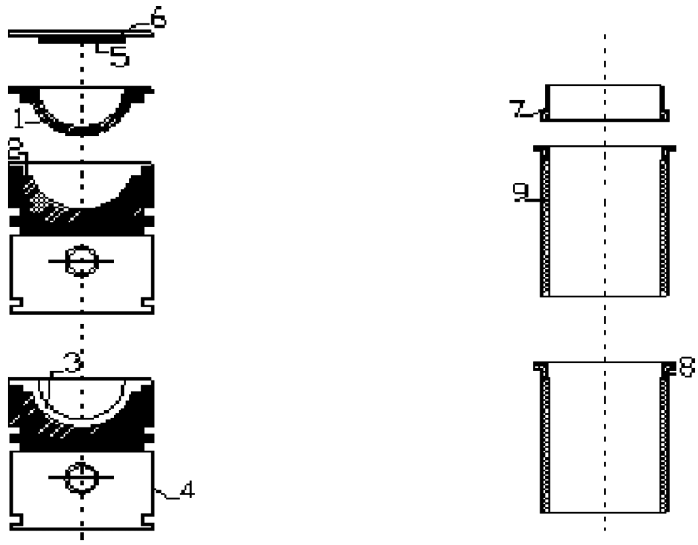
1. Introduction

The alternate fuels for internal combustion engines is the topic of the today as the fossil fuels are depleting due to increase in vehicle population at an alarming rate due to advancement of civilization. Diesel fuel is used not only in transport sector, but also in agriculture sector, and increase in pollution levels with these fuels lead to search for alternate fuels, which has 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 one or two 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 [1-4] on ceramic coated engines, and the reported brake specific fuel consumption (BSFC) was improved in the range 5-9% and pollution levels decreased with ceramic coated engine. Investigations [5] were carried out with air gap insulated piston with nimonic crown with pure diesel operation, and the reported brake specific fuel consumption was improved by 8%. Experiments were conducted [6] with air gap insulated piston with superni crown and air gap insulated 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 [7] with crude jatropha oil and crude pongamia oil based bio-diesel on LHR engine consisted of 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 [8-15] conducted with vegetable oils in CE, and reported that performance was deteriorated with CE. The present paper attempted to evaluate the performance of LHR engine, with different degrees of insulation, with crude linseed oil with varied injection pressure, and compared with pure diesel operation on CE at recommended injection timing and injection pressure.

2. Experimental Programme

Figure 1 gave the details of insulated piston, insulated liner and ceramic coated cylinder head employed in the experimentation. LHR diesel engine contained 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 was found to be 3-mm [5], for better performance of the engine with superni inserts with diesel as fuel.

A superni-90 insert was screwed to the top portion of the liner in such a manner that an air gap of 3mm was maintained between the insert and the liner body. 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 was coated by means of plasma coating technique. The properties of vegetable oil are taken from reference-7.



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

Experimental setup used for the investigations of LHR diesel engine with linseed oil was shown in Fig. 2. CE had an aluminum alloy piston with a bore of 80 mm and a stroke of 110 mm. The rated output of the engine was 3.68 kW at a rate speed of 1500 rpm. The compression ratio was 16:1 and manufacturer's recommended injection timing and injection pressures were 27°bTDC and 190 bar respectively. The fuel injector had three-holes of size 0.25mm. The combustion chamber consisted of a direct injection type with no special arrangement for swirling motion of air was made. The engine was connected to electric dynamometer for measuring brake power of the engine. Fuel consumption of the engine was measured with burette method. 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. The engine oil was provided with a pressure feed system. No temperature control was incorporated, for measuring the lube oil temperature.

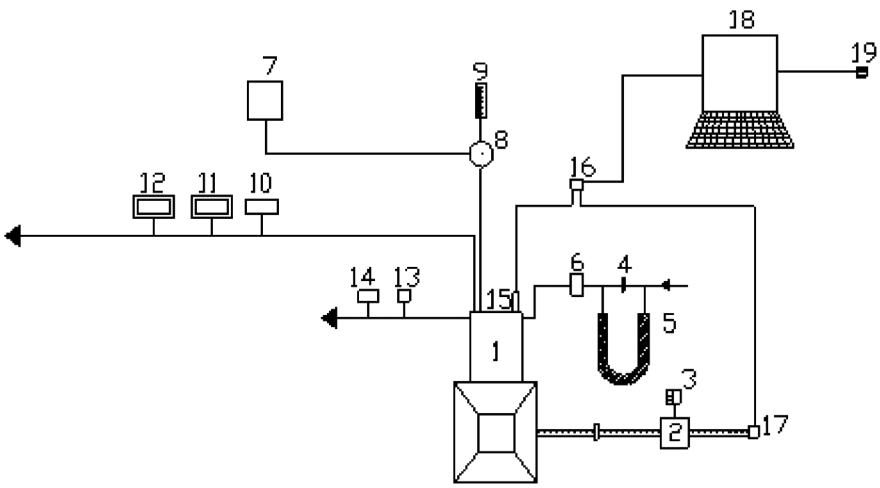


Fig. 2. Experimental Set-up

1. Engine, 2. Electical Dynamo meter, 3. Load Box, 4. Orifice meter, 5. U-tube water manometer, 6. Air box, 7. Fuel tank, 8. 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.

Pollution levels of smoke and NO_x were recorded by AVL smoke meter and Netel Chromatograph NOx analyzer respectively, at the peak load operation of the engine. Piezoelectric transducer, fitted on the cylinder head to measure pressure in the combustion chamber was connected to a console, which in turn is connected to a Pentium personal computer. TDC encoder provided at the extended shaft of the dynamometer was connected to the console to measure the crank angle of the engine. A special P-θ software package evaluated the combustion characteristics such as peak pressure (PP), time of occurrence of peak pressure (TOPP), maximum rate of pressure rise (MRPR) and time of occurrence of maximum rate of pressure rise (TOMR-PR) from the signals of pressure and crank angle at the peak load operation of the engine. Pressure-crank angle diagram was obtained on the screen of the personal computer.

3. Results and Discussion

I. Pure Diesel operation

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. BTE was calculated as it was the ratio of brake power to energy supplied to the engine. Energy supplied to the engine was the product of mass of fuel consumed (kg/s) and calorific value. The variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) with pure diesel operation with different versions of the engine was 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 was insulated to greater extent, it was expected that high combustion temperatures would be prevalent in LHR engine. It tended to decrease the ignition delay thereby reducing pre-mixed combustion, as a result of which, less time was 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 was marginally higher with LHR-1 engine when compared with LHR-2 engine. The reduction of ignition delay was higher with LHR-2 engine leading to deteriorate in the performance of the engine.

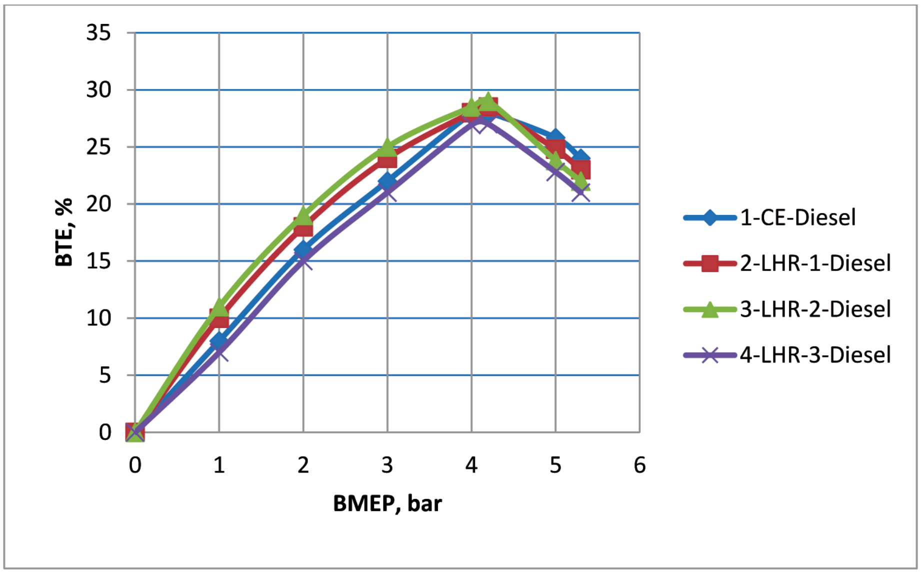


Fig. 3. Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in different versions of the engine with pure diesel operation

By controlling the injector opening pressure and the injection rate, the spray cone angle was found to depend on injection pressure. Further increasing the injector opening pressure increased the nominal mean spray velocity resulting in better fuel-air mixing in the combustion chamber. Higher fuel injection pressures increased the degree of atomization. The fineness of atomization reduced the ignition lag, due to higher surface volume ratio. Smaller droplet size would have a low depth of penetration, due to less momentum of the droplet and less velocity relative to air, from where it had to find oxygen after evaporation. Because of this, air utilization would be reduced due to fuel spray being shorter. Also, with smaller droplets, aggregate area of inflammation would increase after ignition, resulting high-pressure rise during second stage of combustion. Thus lower injection pressure giving larger droplet size might give lower pressure rise during the second stage of combustion and probably smoother running. However, poor performance at lower injector opening pressures indicated 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 was done with nozzle-testing device. Performance of the engine was evaluated with varying injection pressure from 190 to 270 bars for conventional and LHR engines. Table.1 represents the variation of peak BTE in different versions of the engine with injection pressure with pure diesel operation.

Table 1.

Peak Brake Thermal Efficiency (%)			
Engine Version	Injection Pressure (bar)		
	190	230	270
CE	28	29	30
LHR-1	28.5	29	29.5
LHR-2	29	30	30.5
LHR-3	27	27.5	28

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 BTE decreased in LHR-3 engine when compared with other versions of the engine because of reduction of ignition delay with pure diesel operation. However, peak BTE increased with the increase in injection pressure in both versions of the engine because of improved spray characteristics with pure diesel operation.

Table 2 represents the variation of brake specific fuel consumption (BSFC) at peak load operation in different versions of the engine with injection pressure with pure diesel operation.

Table 2.

Brake Specific Fuel Consumption (BSFC) at peak load operation (kg/h-kW)			
Engine Version	Injection Pressure (bar)		
	190	230	270
CE	0.3428	0.3258	0.3040
LHR-1	0.3530	0.3344	0.3130
LHR-2	0.3633	0.3454	0.3240
LHR-3	0.3702	0.3554	0.3340

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.

BSFC at peak load operation is observed to be greater for LHR versions of the engine when compared with CE. This is due to reduction of ignition delay. And also, since the components were insulated higher heat loss is occurring through exhaust gas leading to decrease brake thermal efficiency or increase BSFC. However, BSFC decreased with the increase in injection pressure in all versions of the engine due to improved spray characteristics.

The variation of exhaust gas temperature (EGT) with BMEP with pure diesel operation with different versions of the engine was shown in Fig. 4. EGT increases with an increase in BMEP in all versions of the engine. EGT was lower in LHR-1 and LHR-2 engine up to 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 up to 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.

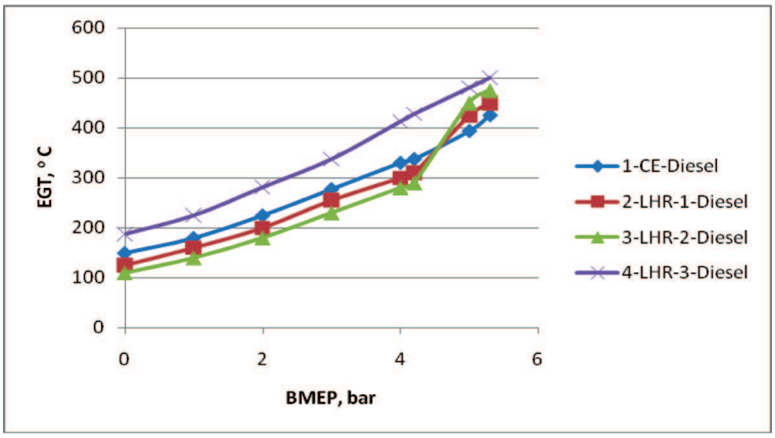


Fig. 4. Variation of exhaust gas temperature (EGT) with brake mean effective pressure (BMEP) in different versions of the engine with pure diesel operation

Table 3 represents the variation of exhaust gas temperature (EGT) at peak load operation in different versions of the engine with injection pressure with pure diesel operation.

Table 3.

EGT at peak load (Degree Centigrade)			
Engine Version	**Injection Pressure (bar)**		
	190	**230**	**270**
CE	**425**	**410**	**395**
LHR-1	**450**	**425**	**400**
LHR-2	**475**	**460**	**445**
LHR-3	**500**	**480**	**460**

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.

EGT decreased with increase in injection pressure in both versions of the engine. LHR-2 engine recorded higher value of EGT when compared with other versions of the engine with pure diesel operation. Since for LHR-2 engine, all the components are insulated and engine combustion is maintained at higher temperature leading to increase in EGT in LHR-2 engine.

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, was shown in Fig. 5 CL increased with the increase of load in CE and LHR engines. LHR engines gave lesser CL up_to 80% of the peak load, when compared with CE. Air being a bad conductor offered thermal resistance for heat flow through the piston and the liner. It was therefore evident that thermal barrier provided in the piston and liner resulted in reduction of CL up to 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 was because in the cylinder, the heat rejection at full load was 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 were made, the heat lost to lubricant should also be considered. As in the present investigations the lubricant heat loss was not considered, this aspect was not depicted in CL calculations. Heat can also escape through un-insulated cylinder head for LHR-2 version of the engine.

Table 4 presents the data of coolant load (CL) at peak load operation in different versions of the engine which varies with injection pressure with pure diesel operation.

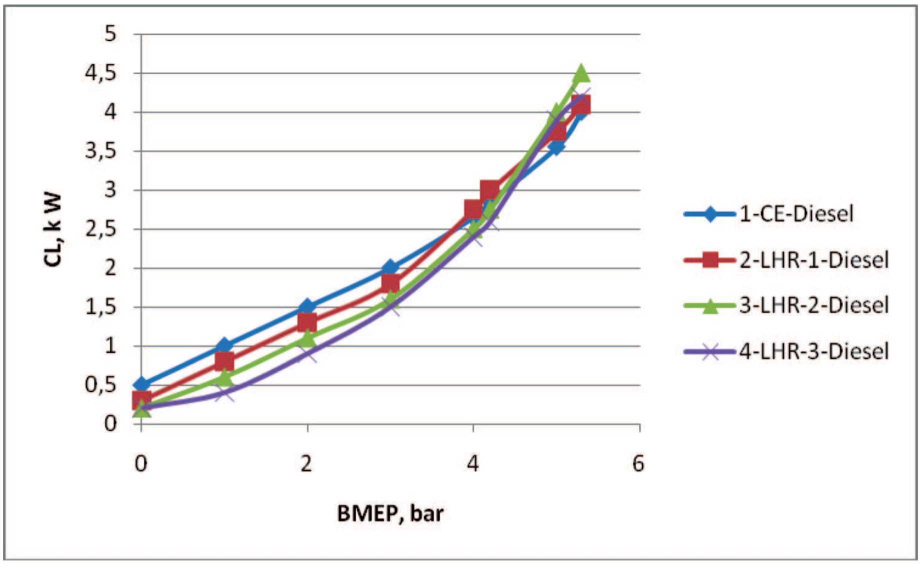


Fig. 5. Variation of coolant load (CL) with brake mean effective pressure (BMEP) in different versions of the engine with pure diesel operation

Table 4.

Coolant Load (kW)			
Engine Version	**Injection Pressure (bar)**		
	190	**230**	**270**
CE	4.0	4.1	4.2
LHR-1	4.1	3.6	3.1
LHR-2	4.5	4.0	3.40
LHR-3	4.2	3.7	3.2

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.

From the Fig. 5, it can be observed that CL decreased with increase in injection pressures in LHR engine, while it is increased in CE. Decrease in gas temperatures in the LHR engine with the increase in injection pressure any way decreased CL and exhaust gas temperatures. CL increased marginally in CE, while it decreased in LHR engine with increasing injection pressure. This is due to the fact that with increase in injection pressure with CE, increased nominal fuel spray velocity result in better fuel-air mixing with which gas temperatures increased. The reduction of CL in LHR engine was not only due to the provision of the insulation, but also it was due to better fuel spray characteristics and increase in air-fuel ratios causing decrease in gas temperatures and hence the CL.

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. 6. 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.

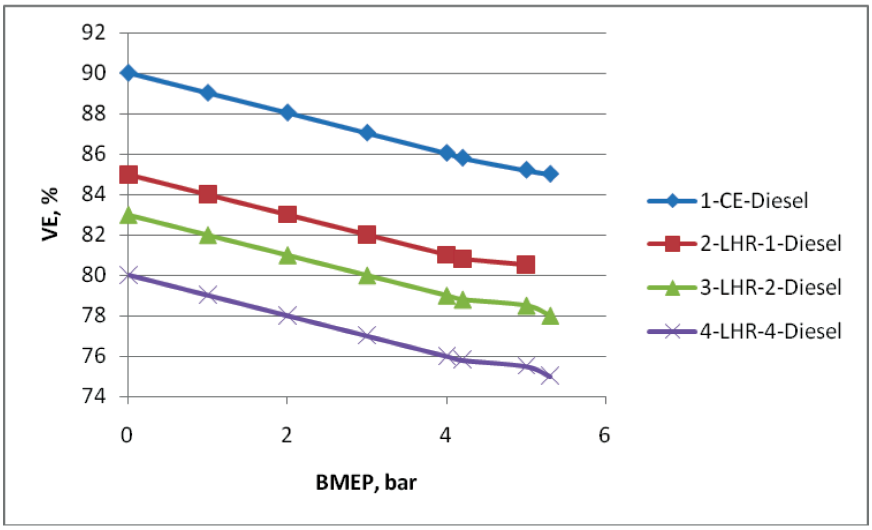


Fig. 6. Variation of volumetric efficiency (VE) with brake mean effective pressure (BMEP) in different versions of the engine with pure diesel operation

Table 5 represents the variation of volumetric efficiency (VE) at peak load operation in different versions of the engine with injection pressure with pure diesel operation.

Table 5.

Volumetric Efficiency (%)			
Engine Version	**Injection Pressure (bar)**		
	190	**230**	**270**
CE	**85**	**86**	**87**
LHR-1	**80**	**82**	**84**
LHR-2	**78**	**80**	**82**
LHR-3	**75**	**76**	**77**

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 at peak load operation increased with increase in injection pressure in different versions of the engine. This is because of reduction of deposits and improved air fuel ratios with increase in injection pressure in different configurations of the engine.

B. Pollution Levels with Pure Diesel Operation

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. 7 Smoke levels increase with as increase in 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 in 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 shortens 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 is the responsible factor for increasing smoke levels in LHR-3 engine near peak load operation of the

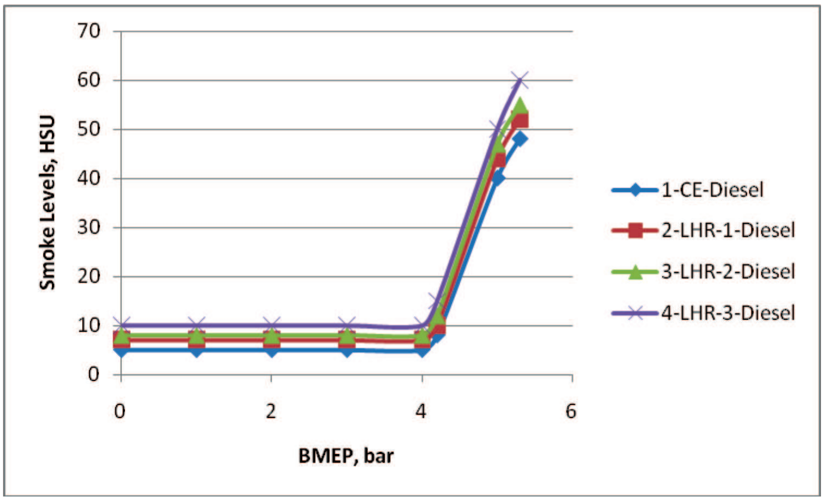


Fig. 7. Variation of smoke levels with brake mean effective pressure (BMEP) in different versions of the engine with pure diesel operation

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.

Table 6 represents the variation of smoke levels at peak load operation in different versions of the engine with injection pressure with pure diesel operation.

Table 6.

Smoke Levels (HSU)			
Engine Version	**Injection Pressure (bar)**		
	190	**230**	**270**
CE	**48**	**38**	**34**
LHR-1	**52**	**45**	**40**
LHR-2	**55**	**50**	**45**
LHR-3	**60**	**55**	**50**

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 NOx levels with brake mean effective pressure (BMEP) with pure diesel operation in different versions of the engine is shown in Table 7. 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.

Table 7.

NOx Levels (ppm)			
Engine Version	**Injection Pressure (bar)**		
	190	**230**	**270**
CE	850	890	930
LHR-1	1150	1100	1050
LHR-2	1300	1280	1260
LHR-3	1400	1380	1360

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.

C. Combustion Characteristics

Table 8 represents the variation of peak pressure (PP) at peak load operation in different versions of the engine with injection pressure with pure diesel operation. The peak pressures are lower in LHR engine 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 in injection pressures, in both versions of the engine.

Table 8.

Peak Pressure (bar)			
Engine Version	**Injection Pressure (bar)**		
	190	**230**	**270**
CE	50.4	51.7	53.5
LHR-1	49.4	52.2	54.3
LHR-2	48.1	51.1	53.0
LHR-3	46.1	48.4	51.1

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.

Table 9 represents the variation of maximum rate of pressure rise (MRPR) at peak load operation in different versions of the engine with injection pressure with pure diesel operation. MRPR increased with the increase in injection pressure with both versions of the engine.

Table 9.

Maximum Rate of Pressure Rise (bar/deg)			
Engine Version	**Injection Pressure (bar)**		
	190	**230**	**270**
CE	3.1	3.3	3.4
LHR-1	3.0	3.3	3.4
LHR-2	2.9	3.2	3.3
LHR-3	2.7	2.8	2.9

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.

Table 10 represents the variation of time of occurrence of peak pressure (TOPP) at peak load operation in different versions of the engine with injection pressure with pure diesel operation. From the Fig., 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.

Table 10.

Time of Occurrence of Peak Pressure (TOPP), (Deg)			
Engine Version	**Injection Pressure (bar)**		
	190	**230**	**270**
CE	9	9	8
LHR-1	9	9	9
LHR-2	10	10	9
LHR-3	11	10	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.

II. Vegetable Oil Operation

A. Performance Parameters

The variation of BTE with BMEP in CE, LHR-1, LHR-2, LHR-3 engine with crude vegetable oil at 27°bTDC and at an injection pressure of 190 bars, is shown in Fig. 8.

The trend exhibited by the conventional engine with crude vegetable oil is similar to that of the conventional engine with pure diesel fuel. However, the conventional engine with crude vegetable oil showed 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 jatropha oil provided a possible explanation for the deterioration in the performance of the engine with crude jatropha 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.

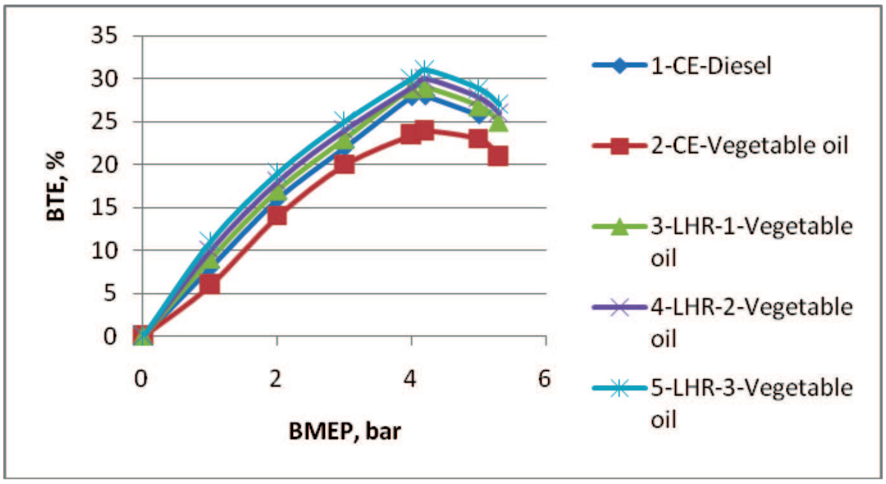


Fig. 8. Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in different versions of the engine with vegetable oil operation

In addition, less air entrainment by the fuel spay 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) were 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 engine operation. This also, contributed to 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.

Table 11 repre sents the variation of peak brake thermal efficiency in different versions of the engine with injection pressure with vegetable oil operation.

Table 11.

(Peak Brake Thermal Efficiency (%)						
Engine Version	Pure Diesel operation			Crude Linseed Oil		
	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	29.5	30
LHR-2	29	30	30.5	30	30.5	31
LHR-3	27	27.5	28	31	31.5	32

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 the increase in 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 12 presents the variation of brake specific energy consumption (BSEC) at peak load operation in different versions of the engine with injection pressure with vegetable oil operation.

Table 12.

Brake Specific Energy Consumption (kW/kW)						
Engine Version	Pure Diesel operation			Crude Linseed Oil operation		
	Injection Pressure (bar)			Injection Pressure (bar)		
	190	230	270	190	230	270
CE	4.0	3.92	3.84	5.00	4.80	4.70
LHR-1	4.12	4.04	3.96	3.98	3.94	3.90
LHR-2	4.16	4.08	4.00	3.94	3.90	3.86
LHR-3	4.3	4.1	4.05	3.82	3.78	3.76

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.

BSEC at peak load operation decreased with increase in 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.

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. 9. 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 an 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.

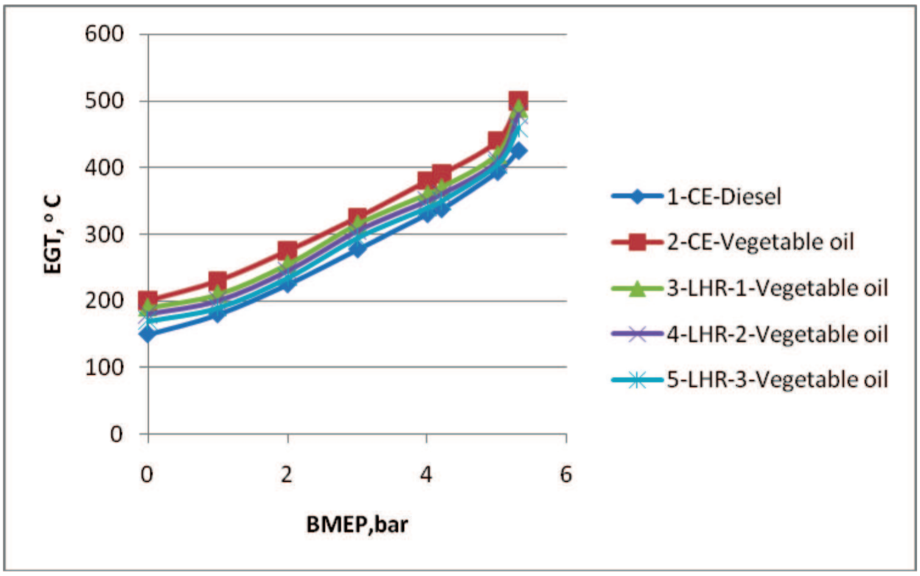


Fig. 9. Variation of exhaust gas temperature (EGT) with brake mean effective pressure (BMEP) in different versions of the engine with vegetable oil operation

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.

Table 13 presents the variation of exhaust gas temperature (EGT at peak load operation in different versions of the engine with injection pressure with vegetable oil operation.

Table 13.

Exhaust Gas Temperature (°C)						
Engine Version	Pure Diesel operation			Crude Linseed 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	490	465	450
LHR-2	475	460	445	480	460	440
LHR-3	500	480	460	460	440	420

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 the increase in injection pressure in both versions of the engine with vegetable oil. This is due to improved atomization characteristics of the fuel.

The variation of coolant load with BMEP in CE, LHR-1, LHR-2 and LHR-3 engine, with crude vegetable oil at 27°bTDC and at an injection pressure of 190 bars, is shown in Fig. 10.

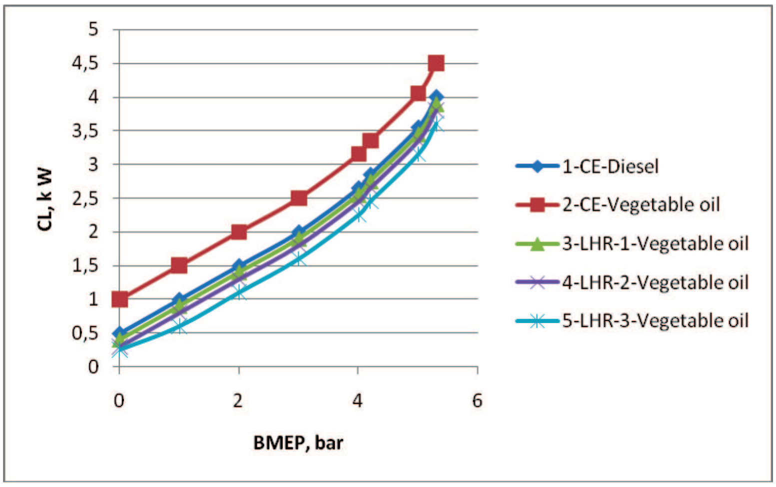


Fig. 10. Variation of coolant load (CL) with brake mean effective pressure (BMEP) in different versions of the engine with vegetable oil operation

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.

Table 14 presents the variation of coolant load (CL) at peak load operation in different versions of the engine with injection pressure with vegetable oil operation.

Table 14.

Coolant Load (kW)						
Engine Version	Pure Diesel operation			Crude Linseed 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	**3.9**	**3.7**	**3.5**
LHR-2	4.5	4.0	3.40	**3.8**	**3.6**	**3.4**
LHR-3	4.2	3.7	3.2	**3.6**	**3.4**	**3.2**

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.

The magnitude of coolant load at peak load decreased with the increase in injection pressure in LHR versions of the engine, however, it increases with CE with vegetable oil. This is due to a decrease in gas temperatures in LHR versions of the engine and increase of the same with CE.

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.11.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. 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.

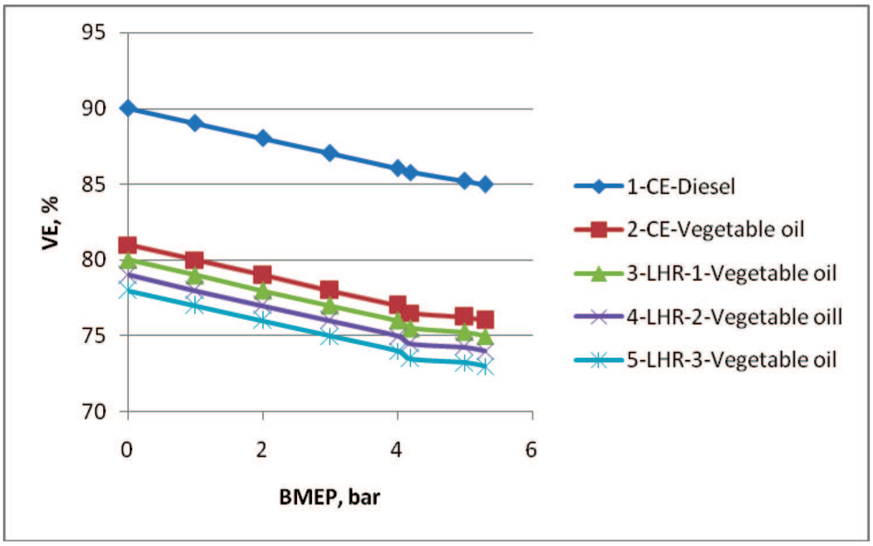


Fig. 11. Variation of volumetric efficiency (VE) with brake mean effective pressure (BMEP) in different versions of the engine with vegetable oil operation

Table 15 presents the variation of volumetric efficiency (VE) at peak load operation in different versions of the engine with injection pressure with vegetable oil operation.

Table 15.

Volumetric Efficiency (%)						
Engine Version	Pure Diesel operation			Crude Linseed 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 the increase in injection pressure in both versions of the engine with different test fuels. Volumetric efficiency increased with the increase in injection pressure and at optimum injection pressure in both versions of the engine. Fuel air ratios improved with the increase in injection pressures leading to an increase in 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

Barsic et al. [21] reported that fuel physical properties, such as density and viscosity, could have a greater influence on smoke emission than the fuel chemical.

The variation of smoke levels 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. 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(0.60) when compared to pure diesel (0.45). The increase in smoke levels is also due to the decrease in air-fuel ratios and volumetric efficiency with crude jatropha 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 unsaturated crude vegetable oils are

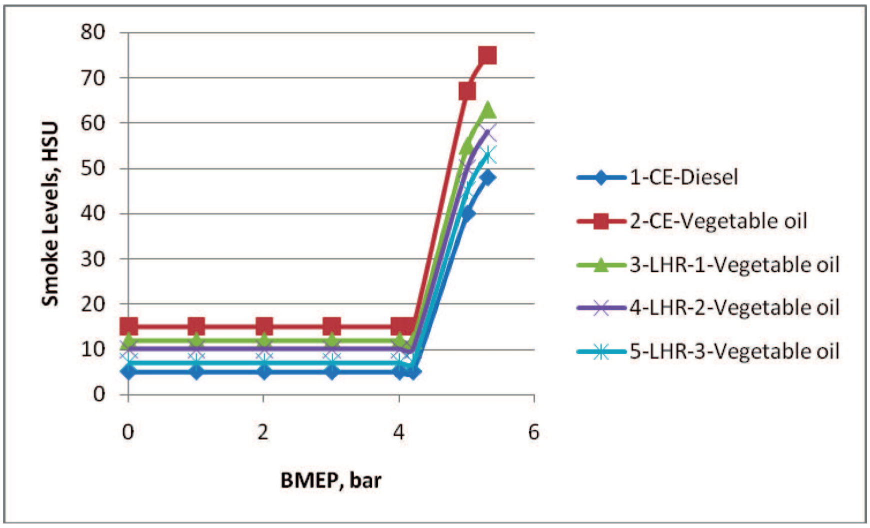


Fig. 12. Variation of smoke levles with brake mean effective pressure (BMEP) in different versions of the engine with vegetable oil operation

inherently more reactive than diesel fuels, in results of which they are more susceptible to oxidation and thermal polymerization reactions leading to produce higher smoke levels. However, LHR engines provide 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.

Table 16 presents the variation of smoke levels at peak load operation in different versions of the engine with injection pressure with vegetable oil operation.

Table 16.

Smoke Levels (HSU)						
Engine Version	Pure Diesel operation			Crude jatropha oil operation		
	Injection Pressure (bar)			Injection Pressure (bar)		
	190	230	270	190	230	270
CE	48	38	34	75	70	65
LHR-1	52	45	40	63	58	53
LHR-2	55	50	45	58	53	48
LHR-3	60	55	50	53	48	43

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.

Smoke levels decreased with the increase in 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 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 Table 17.

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. The increase in 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.

Table 17 presents the variation of NOx levels at peak load operation in different versions of the engine with injection pressure with vegetable oil operation.

Table 17.

NOx Levels (ppm)						
Engine Version	Pure Diesel operation			Crude jatropha oil operation		
	Injection Pressure (bar)			Injection Pressure (bar)		
	190	230	270	190	230	270
CE	850	890	930	**700**	**720**	**730**
LHR-1	1150	1100	1050	**1100**	**1050**	**1000**
LHR-2	1300	1280	1260	**1245**	**1230**	**1180**
LHR-3	1400	1380	1360	**1290**	**1260**	**1210**

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.

NOx levels increased with the increase in injection pressure in CE with vegetable oil. With the increase in injection pressure, fuel droplets penetrate and find oxygen counterpart easily. Turbulence of the fuel spray increased the spread of the droplets thus leading to increase in NOx levels. However, a decrease in NOx levels is observed in LHR engine, due to the decrease in combustion temperatures with increased injection pressure.

C. Combustion Characteristics

Table 18 presents the variation of PP at peak load operation in different versions of the engine with injection pressure with vegetable oil operation. With vegetable oil operation, peak pressures were lower in the conventional engine, 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 the increase in ignition delay, as vegetable oils require large duration of combustion. Meanwhile, 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 higher peak pressures. The advantage of using LHR engine for vegetable oils is obvious, as it could burn low cetane and high viscous fuels. Peak pressures increased with the increase in 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.

Table 18.

PP (bar)						
Engine Version	**Pure Diesel operation**			**Crude jatropha oil operation**		
	Injection Pressure (bar)			**Injection Pressure (bar)**		
	190	**230**	**270**	**190**	**230**	**270**
CE	50.4	51.7	53.5	46.9	49.8	49.9
LHR-1	49.4	52.2	54.3	56.7	59.5	60.5
LHR-2	48.1	51.1	53.0	59.5	62.2	63.6
LHR-3	46.1	48.4	51.1	62.5	64.7	66.6

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 19 presents the variation of MRPR at peak load operation in different versions of the engine with injection pressure with vegetable oil operation. The trend exhibited by MRPR followed the similar characteristics of PP.

Table 19.

MRPR (bar/deg)						
Engine Version	**Pure Diesel operation**			**Crude jatropha 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. This trend of increase in MRPR and decrease in 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 20 presents the variation of TOPP at peak load operation in different versions of the engine with injection pressure with vegetable oil operation.

Table 20.

TOPP (bar/deg)						
Engine Version	Pure Diesel operation			Crude jatropha 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.

The magnitude of TOPP decreased with the increase in injection pressure in different versions of the engine, with vegetable oil operation. TOPP is greater 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.

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Studium porównawcze osiągów silnika o małych stratach ciepła, napędzanego olejem roślinnym, przy trzech różnych poziomach izolacji cieplnej

S t r e s z c z e n i e

Wykonano badania mające na celu ocenę osiągów silnika wysokoprężnego o małych stratach ciepła (Low Heat Rejection, LHR). Badano różne wersje izolacji cieplnej, takie jak głowica cylindra z powłoką ceramiczną (LHR-1), tłok i tuleja cylindra izolowane szczelinami powietrznymi (LHT-2), głowica cylindra z powłoką ceramiczną oraz tłok i tuleja cylindra izolowane szczelinami powietrznymi (LHR-3). Badania wykonano dla różnego stopnia izolacji, w normalnych warunkach temperaturowych, przy różnych ciśnieniach wtrysku paliwa (oleju lnianego). Parametry robocze wyznaczono dla różnych wartości ciśnienia użytecznego. Poziomy zanieczyszczeń dymem i tlenkami azotu (NOx) były mierzone w warunkach szczytowego obciążenia silnika. Przy pomiarze charakterystyk spalania silnika wykorzystano koder TDC (górnego martwego punktu), przetwornik ciśnienia, konsolę i specjalny pakiet programowy do wyznaczania zależności ciśnienie – kąt obrotu wału korbowego. Silnik konwencjonalny (CE), napędzany czystym olejem dieslowskim, wykazywał gorsze działanie. W porównaniu z nim, sinik o małych stratach ciepła (LHR), napędzany olejem roślinnym, miał lepsze parametry robocze przy zalecanym kącie wyprzedzenia wtrysku 27° przed GMP i zalecanym ciśnieniu wtrysku 190 bar. Dla silnika typu LHR z optymalnym kątem wyprzedzenia wtrysku i przy maksymalnym zasysaniu etanolu, szczytowa sprawność cieplna była większa o 18%, poziom zawartości dymu mniejszy o 48%, a zawartość tlenków azotu mniejsza o 38% w porównaniu z silnikiem konwencjonalnym (CE), z czystym paliwem dieslowskim, przy zalecanym przez producenta kącie wyprzedzenia wtrysku.