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Research Article

Experimental Investigations on Low Grade Low Heat Rejection Diesel Engine with Crude Cottonseed Oil Blended with Butanol

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Abstract

In the scenario of fast depletion of fossil fuels, search for alternative fuels has become pertinent. Alcohols and vegetable oils are important substitutes for diesel fuel as they are renewable in nature. However, drawbacks of alcohols (low cetane number and low energy content) and vegetable oils (high viscosity and low volatile in nature) cause combustion problems in diesel engine and hence call for low heat rejection (LHR) engine, which can burn low calorific value fuel and give high heat release rate. They are many methods to induct alcohol in diesel engine out of which blending of alcohol with vegetable oil is simple technique. Neat vegetable oils produce high particulate emissions in diesel engine as they contain fatty acids. Neat alcohol causes combustion problems as it has low cetane number. Hence blending of alcohol with vegetable oils is a promising technique. Butanol has higher calorific value than ethanol and methanol. Hence use of butanol is finding favor in diesel engine. Investigations were carried out to evaluate the performance parameters of a low grade low heat rejection (LHR) diesel engine or LHR–1 engine consisting of ceramic coated cylinder head with crude cottonseed oil blended with butanol with varied injector opening pressure. Performance parameters of brake thermal efficiency (BTE), exhaust gas temperature (EGT), coolant load and volumetric efficiency (VE) were determined at various values of brake mean effective pressure (BMEP). Conventional engine (CE) showed deteriorated performance, while LHR engine showed compatible performance with crude cottonseed oil. (CSO) operation when compared with neat diesel operation at recommended injection timing and pressure. The performance of both version of the engine improved with vegetable oil blended with butanol with varied injector opening pressure.

Keywords: *Vegetable oil, Injector opening pressure, LHR engine, Classification, Fuel Performance.*

1. Introduction

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

Vegetable oils and alcohols are promising substitutes for diesel fuel as they are renewable in nature. Out of many techniques available, blending is simple technique, to induct alcohol into diesel engine [Wang *et al,* 2008; Lalit Kumar *et al*, 2012; Satish Kumar *et al*, 2013]. Alcohols have low cetane number and hence engine modification is necessary for use as fuel in diesel engine [Murali Krishna *et al*, 2014; Murali Krishna *et al,* 2015]. On the other hand, vegetable oils have comparable properties in comparison with diesel fuel. The idea of using vegetable oil as fuel has been around from the birth of diesel engine. Rudolph diesel, the inventor of the engine that bears his name, experimented with fuels ranging from powdered coal to peanut oil. [Cummins, 1993]. Several researchers experimented the use of vegetable oils as fuel on

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*Corresponding author's ORCID ID: 0000-0002-2165-8106 conventional engines (CE) and reported that the performance was poor, citing the problems of high viscosity, low volatility and their polyunsaturated character [Pugazhvadivu, *et al*, 2005; Deepak Agarwal *et al,* 2008; Baiju et al, 2009; Hanbey Hazar *et al,* 2010]. 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. The performance of the engine improved along with reduction of particulate emissions by an increase of injector opening pressure [Jindal *et al,* 2010; Venkanna *et al,* 2010; Avinash Kumar *et al,* 2013].

The concept of LHR engine is to reduce heat loss to coolant by providing thermal insulation in the path of heat flow to the coolant. LHR engines are classified depending on degree of insulation such as low grade or LHR–1, medium grade or LHR–2 and high grade insulated engines or LHR–3 engine. Several methods adopted for achieving low grade LHR engines are using ceramic coatings on piston, liner and cylinder head, while air gap insulation is provided in the piston and other components with low-thermal conductivity materials like superni, cast iron and mild steel etc and high grade LHR engine is the combination of low grade and medium grade engines.

Experiments were conducted on low grade LHR engines with diesel and reported that diesel operation with LHR–1 engine improved performance and reduced smoke levels. [Parlak *et al,* 2005; Ekrem *et al,* 2006; Ciniviz *et al,* 2008]. However, they increased nitrogen oxide levels (NO_x) levels.

Investigations were carried out with low grade LHR engines with vegetable oil and reported that vegetable oil operation with LHR-1 engine improved performance and reduced smoke levels, however, they increased NO_x levels. [Murali Krishna *et al,* 2012; Kesava Reddy *et al,* 2012; Ratna Reddy *et al*, 2012; Murali Krishna *et al,* 2012]. However, little reports are available with LHR–1 engine with vegetable oil blended with butanol. Hence this paper reported the performance parameters with LHR–1 engine which contained ceramic coated cylinder head with varied injector opening pressure and compared with neat diesel operation on conventional engine (CE).

2. Materials and Method

Cottonseed oil is extracted from cottonseed. **Cottonseed oil** has a 2:1 ratio of polyunsaturated to saturated fatty acids. Its fatty acid profile generally consists of 70% unsaturated fatty acids including 18% monounsaturated (oleic) and 52% polyunsaturated (linoleic) and 26% saturated (primarily palmitic and stearic). **Cottonseed oil** is described by scientists as being "naturally hydrogenated" because of the levels of oleic, palmitic, and stearic acids which it contains. These make it a stable frying oil without the need for additional processing or the formation of trans fatty acids. Because **Cottonseed oil** is America's original vegetable oil, it has been the standard to which other oils are compared. [Srikanth *et al,* 2013] LHR diesel engine contained a cylinder head with ceramic coating of thickness 500 microns, by spray coating. The photographic view of ceramic coated cylinder head is shown in Fig.1

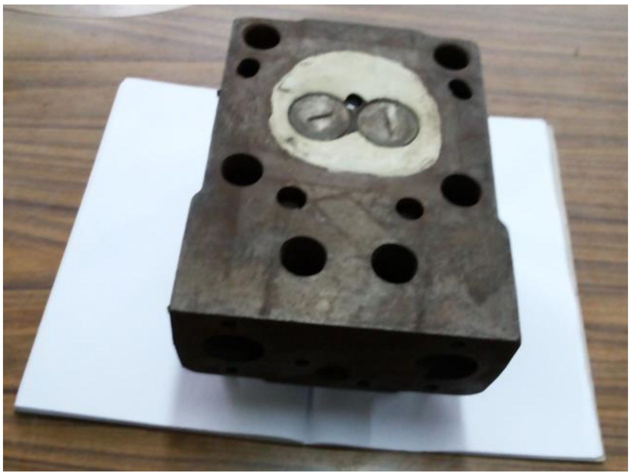


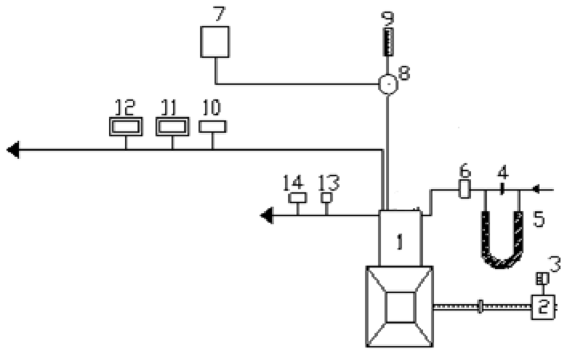
Fig.1 Photographic view of ceramic coated cylinder head

The properties of vegetable oil along with diesel fuel are given in Table-1

Table 1 Properties of Test Fuels [Srikanth et al, 2013]

Test Fuel	Kinematic viscosity at 25°C (centi-Stoke)	Density at 25° C	Cetane number	Calorific value (kJ/kg)
Diesel	2.5	0.84	55	42000
Cottonseed oil (CSO)	4.0	0.90	45	41200

Butanol is manufactured from municipal waste. butanol is produced commercially from fossil fuels. The most common process starts with propene (propylene), which is put through a hydroformylation reaction to form butyraldehyde, which is then reduced with hydrogen to 1-butanol and/or 2-butanol. Butanol can also be produced by fermentation of biomass by bacteria. Butanol is not mixable with cottonseed oil. Hence a binder is required. Here soap solution (2%) was used a binder. These solutions were mixed by using mechanical stirrer. Experimental setup used for the investigations of LHR diesel engine with crude cottonseed oil (CSO) blended with butanol operation is shown in Fig.2. CE had an aluminum alloy piston with a bore of 80 mm and a stroke of 110mm. The rated output of the engine was 3.68 kW at a speed of 1500 rpm. The compression ratio was 16:1. The manufacturer's recommended injection timing and injection pressures were 27°bTDC and 190 bar respectively.



1.Engine, 2.Electical Dynamo meter, 3.Load Box, 4.Orifice meter, 5.U-tube water manometer, 6.Air box, 7.Fuel tank, 8, Pre-heater, 9.Burette, 10. Exhaust gas temperature indicator, 11.AVL Smoke meter, 12.Netel Chromatograph NOx Analyzer, 13.Outlet jacket water temperature indicator, 14. Outlet-jacket water flow meter

Fig.2 Schematic diagram of experimental set-up

The fuel injector had 3-holes of size 0.25-mm. The combustion chamber consisted of a direct injection type with no special arrangement for swirling motion of air. The engine was connected to an electric dynamometer for measuring its brake power. Burette method was used for finding fuel consumption of the engine. Air-consumption of the engine was measured by air-box method.

The naturally aspirated engine was provided with water-cooling system in which inlet temperature of water was maintained at 60°C by adjusting the water flow rate. Engine oil was provided with a pressure feed system. No temperature control was incorporated, for measuring the lube oil temperature. Injection pressure was varied from 190 bar to 270 bar (in steps of 40 bar) using nozzle testing device. The maximum injection pressure was restricted to 270 bar due to practical difficulties involved. Exhaust gas temperature (EGT) was measured with thermocouples made of iron and iron-constantan.

3. Results and Discussion

3.1Performance Parameters

Investigations were carried out with conventional engine and LHR–1 engine with ceramic coated cylinder head with emulsified fuel of butanol and cotton seed oil. As mentioned earlier in previous article, emulsified solution was prepared with 20% of butanol by volume with 78% of cottonseed oil in the presence of 2% soap solution, which was stirred by a mechanical stirrer, so that phase separation should not occur among the solvents. The emulsified solution was tested with conventional diesel engine such that it should give maximum performance and at same time the engine was to be operated with the constant speed of 1500 rpm. The purpose of adding butanol to the vegetable oil was to reduce the viscosity of the vegetable oil, while the purpose of adding soap solution was that it acted as binder and emulsifier.

Investigations were carried out with the objective of determining the factors that would allow maximum use of butanol in diesel engine with best possible efficiency at all loads. These experiments found the basis to bring out the importance of the hot combustion chamber achieved with the LHR–1 engine. The conventional engine with neat diesel operation at the recommended injection timing and pressure was referred as the standard diesel engine. Performance of the convectional engine and LHR–1 engine with emulsified solution of butanol and cottonseed oil was evaluated at the recommended injection timing and injector opening pressure of 190 bar.

Fig.3 shows the variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) with different percentages of emulsified butanol in the conventional engine at the recommended injection timing and pressure. This figure also provided the data with the pure diesel operation for the comparison purpose. BTE increased at all loads with 20% emulsified butanol and with the increase of emulsified butanol beyond 20%, it decreased at all loads in the conventional engine when compared to the standard diesel engine. The reason for improving the efficiency with the 20% emulsified butanol was because of improved homogeneity of the mixture with the presence of butanol, decreased dissociated losses, specific heat losses and cooling losses due to lower combustion temperatures. This was also due to high heat of evaporation of butanol, which caused the reduction the gas temperatures resulting in a lower ratio of specific heats leading to more efficient conversion of heat into work. Blending of butanol resulted in increase of moles of working gas, which caused high pressures in the cylinder.

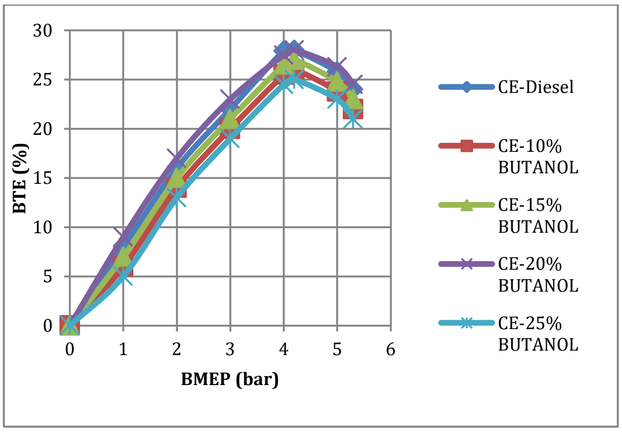


Fig.3 Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) with different percentages of emulsified butanol in the conventional engine at the recommended injection timing and pressure

The observed increased in the ignition delay period would allow more time for fuel to vaporize before ignition started. This means higher burning rates resulted more heat release rate at constant volume, which was a more efficient conversion process of heat into work.

When emulsified butanol was more than 20%, performance deteriorated with increase of ignition delay and reduction of combustion temperatures.

Fig.4 shows the variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) with different percentages of emulsified butanol in the LHR–1 engine at the recommended injection timing and pressure. LHR engine showed an improvement in the performance with the emulsified butanol at all loads when compared to the standard diesel engine.

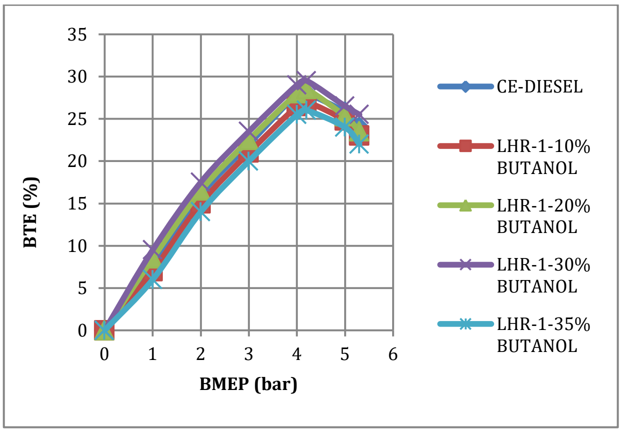


Fig.4 Variation of BTE with BMEP with different percentages of emulsified butanol in LHR-1 engine at the recommended injection timing and pressure

This was due to recovery of heat from the hot insulated components of engine with ceramic coated cylinder head (LHR–1) due to high latent heat of evaporation of the butanol, which lead to increase in thermal efficiency. The maximum blend of butanol was 30% in the LHR-1 engine which showed improvement in the performance at all loads when compared to standard diesel engine. However when emulsified butanol was increased more than 30% in the engine with ceramic coated cylinder head (LHR–1), brake thermal efficiency deteriorated at all loads when compared to the standard diesel engine.

Fig.5 presents bar charts showing the variation of peak BTE with test fuels with different versions of the engine at recommended injection timing and pressure.

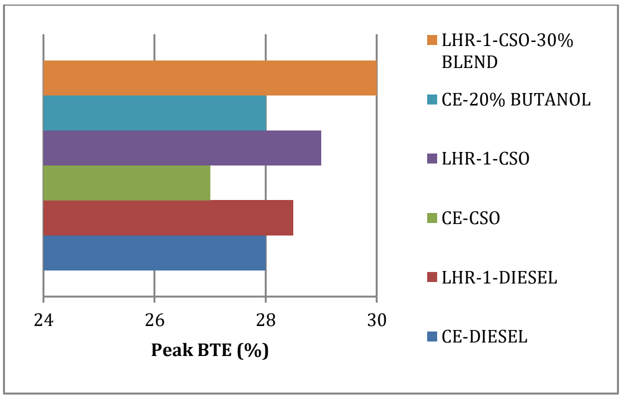


Fig.5 Bar charts showing the variation of peak BTE with test fuels with different versions of the engine at recommended injection timing and pressure

LHR-1 engine with 30% emulsified butanol gave marginally higher thermal efficiency than conventional engine with 20% emulsified butanol in conventional engine due to higher amount of butanol substitution, which improved evaporation characteristics from hot insulated components of the LHR-1 engine. Conventional engine with vegetable oil operation showed deteriorated performance when compared with other versions of the engine. Low calorific value and high viscosity of the vegetable oil might have caused combustion problems. However, LHR version of the engine with vegetable oil improved the performance of the engine with increased heat release rate. The addition of butanol with vegetable oil improved dissociation heat losses and homogeneity of the mixture, taking the process close to constant volume heat addition process.

Table.2 shows variation of peak BTE with conventional engine and LHR-1 engine with test fuels at different injector opening pressure, at recommended injection timing. From Table, it is noticed that peak brake thermal efficiency increased with increase an injector opening pressure in both versions of the combustion chamber at different operating conditions of the test fuel. The improvement in brake thermal efficiency at higher injector opening pressure was due to improved fuel spray characteristics.

Table.2 Data of Peak BTE

Test Fuel	Peak BTE (%)					
	Conventional Engine (CE)			LHR–1 Engine		
	Injector opening pressure (Bar)			Injector opening pressure (Bar)		
	190	230	270	190	230	270
	NT	NT	NT	NT	NT	NT
Diesel	28	29	30	28.5	29	29.5
CSO	27	28	29	29	29.5	30
20% Emulsified CSO	28	29	30	29.5	30	30.5
30% Emulsified CSO	--	--	--	30	30.5	31

Table 3 Data of Brake Specific Energy Consumption (BSEC) at full load operation

Test Fuel	Brake Specific Energy Consumption (kW.h) at full load operation					
	Conventional Engine (CE)			LHR–1 Engine		
	Injector opening pressure (Bar)			Injector opening pressure (Bar)		
	190	230	270	190	230	270
	NT	NT	NT	NT	NT	NT
Diesel	4	3.96	3.92	3.96	3.92	3.88
CSO	4.2	4.0	3.94	3.92	3.88	3.84
20% Emulsified CSO	3.96	3.92	3.88	3.88	3.84	3.80
30% Emulsified CSO	--	---	--	3.84	3.80	3.76

Fig.6 presents bar charts showing the variation of brake specific energy consumption (BSEC) at full load with test fuels with different versions of the engine at recommended injection timing and pressure.

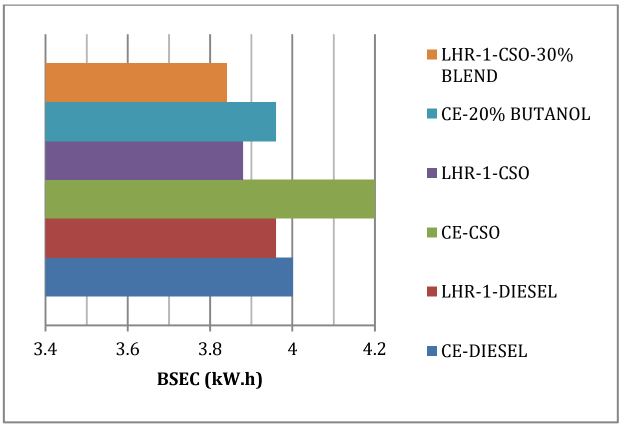


Fig.6 Bar charts showing the variation of brake specific energy consumption (BSEC) at full load with test fuels with different versions of the engine at recommended injection timing and pressure

BSEC at full load operation decreased with 20% emulsified butanol with conventional engine when compared with standard diesel engine. This was due to improved combustion with reduction of viscosity of the crude vegetable oil by blending with butanol. LHR-1 engine with 30% emulsified butanol gave marginally lower BSEC at full load operation when compared with conventional engine with 20% butanol blend. This was due to substitution of higher amount of butanol, which improved combustion with reduction of losses during combustion. CE with vegetable oil showed deteriorated performance in compassion with diesel operation with CE. Low calorific value and high viscosity of the vegetable oil caused deterioration with CE. However, BSEC at full load operation improved combustion with addition of butanol. Reduction of combustion losses and improved homogeneity of the mixture reduced BSEC at full load.

Table.3 shows variation of brake specific energy consumption (BSEC) with conventional engine and LHR-1 engine with test fuels at different operating conditions at different injector opening pressure, at recommended injection timing. BSEC at full load operation decreased with an increase of injector opening pressure with both versions of the engine with test fuels. This was due to efficient combustion with improved oxygen–fuel ratios giving lower value of brake specific energy consumption. Bulk modulus of the fuel increased with increase of injector opening pressure leading to generate higher peak pressure leading to reduce BSEC.

Fig.7 presents bar charts showing the variation of exhaust gas temperature (EGT) at full load with test fuels with different versions of the engine at recommended injection timing and pressure. EGT at full load operation decreased marginally with 20% emulsified butanol with conventional engine when compared with standard diesel engine. This was due to high latent heat of butanol which absorbs temperatures in combustion zone. LHR-1 engine with 30% emulsified butanol gave marginally lower EGT at full load operation when compared with conventional engine with 20% butanol blend. This was due to substitution of higher amount of butanol, which caused reduction of EGT due to its high latent heat. This was also because of increased thermal efficiency and decreased rejection losses with the LHR-1 engine, when compared with standard diesel operation.

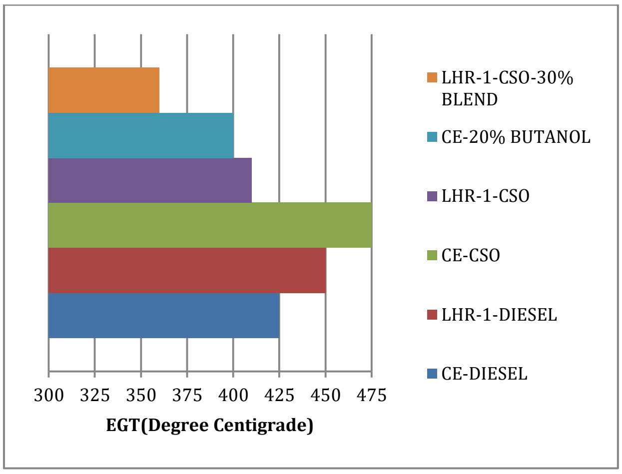


Fig.7 Bar charts showing the variation of exhaust gas temperature (EGT) at full load with test fuels with different versions of the engine at recommended injection timing and pressure

Table 4 Data of Exhaust gas temperature at full load operation

Test Fuel	Exhaust Gas Temperature at full load operation (degree centigrade)					
	Conventional Engine (CE)			LHR–1 Engine		
	Injector opening pressure (Bar)			Injector opening pressure (Bar)		
	190	230	270	190	230	270
	NT	NT	NT	NT	NT	NT
Diesel	425	410	395	450	425	400
CSO	475	440	410	410	390	370
20% Emulsified CSO	400	375	350	380	360	340
30% Emulsified CSO	--	--	--	360	340	320

Table 5 Data of Volumetric efficiency at full load operation

Test Fuel	Volumetric efficiency at full load operation (%)					
	Conventional Engine (CE)			LHR-1 Engine		
	Injector opening pressure (Bar)			Injector opening pressure (Bar)		
	190	230	270	190	230	270
	NT	NT	NT	NT	NT	NT
Diesel	85	86	87	80	81	82
CSO	82	83	84	78	79	80
20% Emulsified CSO	86	87	88	79	80	81
30% Emulsified CSO	--	--	--	80	81	82

Table.4 shows variation of exhaust gas temperature with conventional engine and LHR-1 engine with vegetable oil at different operating conditions at different injector opening pressure, at recommended injection timing. EGT decreased with increase of injector opening pressure with both versions of the combustion chamber with test fuels which confirmed that performance increased with an increase of injector opening pressure. This was due to improved spray characteristics of the fuel with improved oxygen–fuel ratios.

Fig.8 presents bar charts showing the variation of volumetric efficiency at full load with test fuels with different versions of the engine at recommended injection timing and pressure.

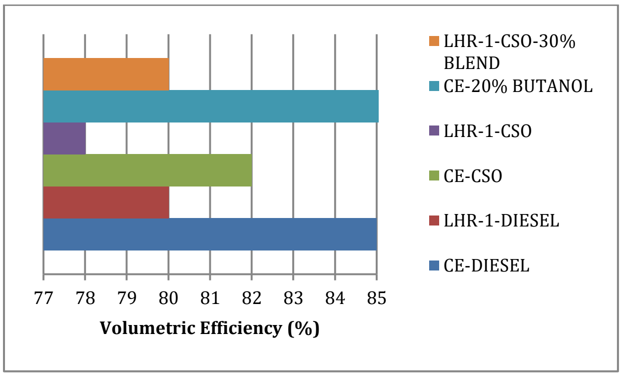


Fig.7 Bar charts showing the variation of volumetric efficiency at full load with test fuels with different versions of the engine at recommended injection timing and pressure

Table 6 Data of Coolant Load at full load operation

Test Fuel	Data of Coolant Load (kW) at full load operation					
	Conventional Engine (CE)			LHR–1 Engine		
	Injector opening pressure (Bar)			Injector opening pressure (Bar)		
	190	230	270	190	230	270
	NT	NT	NT	NT	NT	NT
Diesel	4.0	3.8	3.6	3.8	3.6	3.4
CSO	4.4	4.0	3.8	3.6	3.4	3.2
20% Emulsified CSO	3.8	3.6	3.4	3.4	3.2	3.0
30% Emulsified CSO	--	--	--	3.2	3.0	2.8

Volumetric efficiency at full load operation increased marginally with 20% emulsified butanol with conventional engine when compared with standard diesel engine. This was due to high latent heat of butanol which absorbs temperatures in combustion zone, with which density of charge increased leading to increase of volumetric efficiency. This was also because of decrease of combustion chamber wall temperatures. LHR-1 engine with 30% emulsified butanol gave lower volumetric efficiency at full load operation when compared with conventional engine with 20% butanol blend. This was due to increase of temperatures with hot insulated components of the engine with which density of the air decreased. However, volumetric efficiency of the engine with LHR-1 combustion chamber with 30% emulsified butanol was marginally higher than same configuration of the engine with 20% butanol blend. This was more temperature drop with 30% emulsified butanol than 20% butanol blend. Volumetric efficiency was marginally lower with CE with vegetable oil operation. Increase in EGT and un-burnt fuel concentration at combustion chamber walls might have lowered with volumetric efficiency with CE with vegetable oil operation.

Table.5 shows variation of volumetric efficiency with conventional engine and LHR-1 engine with test fuels at different operating conditions at different injector opening pressures, at recommended injection timing. From Table, it is observed that volumetric efficiency increased marginally with an increase of injector opening pressure in both versions of the engine with test fuels. This was also due to improved fuel spray characteristics and evaporation at higher injector opening pressures leading to marginal increase of volumetric efficiency. This was also due to the reduction of residual fraction of the fuel, with the increase of injector opening pressure. Increase of volumetric efficiency depends on combustion chamber wall temperature, which in turn depends on exhaust gas temperatures. With increase of injector opening pressure, exhaust gas temperatures decreased and hence volumetric efficiency increased.

Fig.9 presents bar charts showing the variation of coolant load at full load with test fuels with different versions of the engine at recommended injection timing and pressure.

CE with vegetable oil increased coolant load at full load in comparison with CE with neat diesel operation. Increase of un-burnt fuel concentration might have increased coolant load with CE with vegetable oil operation.

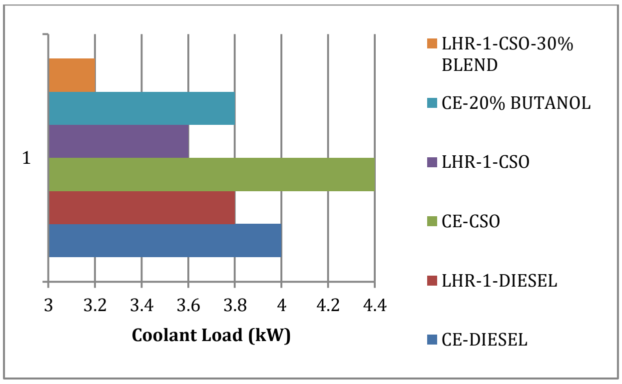


Fig.9 Bar charts showing the variation of coolant load at full load with test fuels with different versions of the engine at recommended injection timing and pressure

Coolant load at full load operation decreased marginally with 20% emulsified butanol with conventional engine when compared with standard diesel engine. This was due to high latent heat of butanol which absorbs temperatures in combustion zone. LHR-1 engine with 30% emulsified butanol gave lower coolant load at full load operation when compared with conventional engine with 20% butanol blend. This was due to provision of insulation in the path of coolant. This was also due to improved combustion with increase of oxygen–fuel ratios. Coolant load of the LHR-1 engine with 30% emulsified butanol was marginally lower with the engine with same configuration of the engine with 20% butanol blend. This was more temperature drop with 30% emulsified butanol than 20% butanol blend.

Table.6 shows variation of coolant load with conventional engine and LHR-1 engine with test fuels at different operating conditions at different injector opening pressure, at recommended injection timing.

It is observed from Table, coolant load increased marginally in the conventional engine while it decreased in LHR-1 engine with increasing of the injector opening pressure with vegetable oil. This was due to the fact with increase of injector opening pressure with conventional engine, increased nominal fuel spray velocity resulting in better fuel-oxygen mixing with which gas temperatures increased. The reduction of coolant load in the LHR-1 engine was not only due to the provision of the insulation but also it was due to better fuel spray characteristics and increase of oxygen-fuel ratios causing decrease of gas temperatures and hence the coolant load.

Conclusions

1) The maximum blend ratio of butanol with cottonseed oil with conventional engine was observed to be 20%, while it was 30% for the LHR-1 engine.
2) Both versions of the engine showed improved performance with emulsified cottonseed oil in comparison with conventional engine with diesel operation.
3) When compared with conventional engine with maximum blend ratio of butanol (20% butanol), LHR-1 engine with its maximum blend ratio (30% of butanol)

a) Increased peak brake thermal efficiency by 7%%
b) Decreased brake specific energy consumption by 3 %
c) Decreased exhaust gas temperatures by 10%
d) Decreased coolant load by 16 %
e) Decreased volumetric efficiency by 7%

Performance parameters improved marginally with an increase of injector opening pressure with both versions of the engine with test fuels.

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