COMPARATIVE STUDIES ON PERFORMANCE PARAMETERS OF DIRECT INJECTION DIESEL ENGINE WITH HIGH GRADE LOW HEAT REJECTION COMBUSTION CHAMBER WITH LINSEED OIL BASED BIODIESEL

P.V. K. Murthy[1*]and M.V.S. Murali Krishna[2]

[1]*Mechanical Engineering Department, Sagar Institute of Technology, Flame of Forest, Chevella-Urella Road, Urella, Chevella, Hyderabad-501 503, Telangana State, [*]E-mail: Krishnamurthy_venkata@rediffmail.com*

[2]*Mechanical Engineering Department, Chaitanya Bharathi Institute of Technology, Gandipet, Hyderabad-500 075, Telangana State, India,*

ABSTRACT

Experiments were carried out to evaluate the performance of diesel engine with high grade low heat rejection (LHR) combustion chamber consisting of air gap insulated piston with 3-mm air gap, with superni (an alloy of nickel) crown, air gap insulated liner with superni insert and ceramic coated cylinder head with different operating conditions (normal temperature and preheated temperature) of linseed oil based biodiesel (LSOBD) with varied injection timing and injector opening pressure. Performance parameters [brake thermal efficiency, exhaust gas temperature, sound levels, coolant load and volumetric efficiency] were determined at various values of brake mean effective pressure (BMEP) of the engine with biodiesel and compared with conventional engine at similar operating conditions. Biodiesel showed compatible performance with conventional engine (CE), while LHR combustion chamber improved the performance in comparison with pure diesel operation at similar operating conditions. The optimum injection timing was found to be 31°bTDC with CE while it was 28°bTDC for LHR combustion chamber with biodiesel operation. Relatively, with LHR combustion chamber with biodiesel operation, peak brake thermal efficiency increased by 7%, at full load operation- brake specific energy consumption decreased by 5%, exhaust gas temperature decreased by 70°C, coolant load decreased by 6%, sound levels decreased by 16% and volumetric efficiency was compatible in comparison LHR combustion chamber with pure diesel operation at similar operating conditions.

Keywords: Need for Alternate Fuels, Vegetable Oil, Biodiesel, LHR combustion chamber, Performance.

INTRODUCTION

The paper is divided into i) Introduction, ii) Materials and Methods, iii) Results and Discussions, iv) Conclusions, Research Findings and Future scope of studies, v) Acknowledgements followed by References.

This section deals with need and necessity of alternative fuels and various alternative fuels. Investigations carried out by various researchers on crude vegetable oils and biodiesel at normal temperature and preheated temperature in compression ignition engine were mentioned. Conclusions from their investigations were given. Objectives of the investigations were given at the end of the section

In the scenario [1] of i) increase of vehicle population at an alarming rate due to advancement of civilization, ii) use of diesel fuel in not only transport sector but also in agriculture sector leading to fast depletion of diesel fuels iii) increase of pollution levels with these fuels, and iv) increase of fuel prices in International market leading to burden on economic sector of Govt. of India, the search for alternative fuels has become pertinent for the engine manufacturers, users and researchers involved in the combustion research.

Vegetable oils and alcohols are prominent substitutes for diesel fuel. Alcohols have good volatility and low cetane number. Hence engine modification is necessary for use them as fuel in diesel engines. That too, most of the alcohol produced is diverted for Petro-chemical industries in India.

Vegetable oils which are renewable in nature have properties compatible to diesel fuel. Rudolph Diesel, the inventor of the diesel engine that bears his name, experimented [2] with fuels ranging from powdered coal to peanut oil. Several researchers [3-6] experimented the use of vegetable oils as fuel on conventional engines (CE) and reported that the performance was poor, citing the problems of high viscosity, low volatility and their polyunsaturated character. Not only that, the common problems of crude vegetable oils in diesel engines are formation of carbon deposits, oil ring sticking, thickening and gelling of lubricating oil as a result of contamination by the vegetable oils.

Experiments were conducted [7-10] on preheated vegetable oils [temperature at which viscosity of the vegetable oils were matched to that of diesel fuel] and it was reported that preheated vegetable oils improved the performance marginally. The problems of crude vegetable oils can be solved, if these oils are chemically modified to bio-diesel.

The U.S. Department of Energy has stated [11] that, "Raw or refined vegetable oil, that have not been processed into biodiesel, are not biodiesel and should be avoided." The use of raw, unprocessed vegetable oils or animal fats in diesel engines – regardless of blend level – can have significant adverse effects and should not be used as fuel in diesel engines. Raw or refined vegetable oil, or recycled greases have significantly different and widely varying properties that are not acceptable for use in modern diesel engines. For example, the higher viscosity and chemical composition of unprocessed oils and fats have been shown to cause problems in a number of areas: (i) piston ring sticking; (ii) injector and combustion chamber deposits; (iii) fuel system deposits; (iv) reduced power; (v) reduced fuel economy and(vi) increased exhaust emissions vii) dilution of lubricating oil, viii) reduced engine life, ix) increased maintenance cost, xi) stress on fuel injection system. The above mentioned problems are reduced if crude vegetable oils are converted [11] into biodiesel, which have low molecular weight, low dense and low viscosity when compared with crude vegetable oils.

Investigations were carried out [12-16] with biodiesel with CE and reported that biodiesel operation improved the performance, reduced smoke emissions and increased NOx emissions. The drawbacks

associated with biodiesel and crude vegetable oils for use in diesel engines call for LHR hot combustion chamber.

The concept of LHR combustion chamber is to reduce coolant losses by providing thermal resistance in the path of heat flow to the coolant, there by gaining thermal efficiency. Several methods adopted for achieving LHR to the coolant are ceramic coated engines and air gap insulated engines with creating air gap in the piston and other components with low-thermal conductivity materials like superni, cast iron and mild steel etc.

LHR combustion chambers were classified as low degree, medium grade and high grade LHR combustion chambers depending on degree of insulations.

Investigations were carried out by various researchers [17-19] on low degree LHR combustion chambers- ceramic coated engines with pure diesel operation. It was reported from their investigations that brake specific fuel consumption (BSFC) improved in the range 5-9% and pollution levels decreased with ceramic coated combustion chamber. Studies were also made [20-22] ceramic coated LHR combustion chamber with biodiesel operation and reported that performance improved, decreased smoke emissions and increased NOx emissions.

The technique of providing an air gap in the piston involved the complications of joining two different metals. Investigations were carried out [23] on medium grade LHR combustion chamber-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 [24] were carried out with LHR combustion chamber with air gap insulated piston with nimonic crown threaded with the body of the piston fuelled with pure diesel with varied injection timing and reported brake specific fuel consumption improved by 5%. Experiments were conducted with medium grade LHR combustion chamber- air gap insulated piston with superni crown and air gap insulated liner with superni insert with varied injection timing and injector opening pressure with different alternate fuels like crude vegetable oils [25-27] and biodiesel [28]. It was reported that medium grade LHR combustion chamber improved the performance with alternate fuels.

Investigations were carried out [29-30] on higher degree of insulation-with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head with biodiesel varied injection timing and injector opening pressure. It was reported that biodiesel increased the efficiency of the engine.

Sound levels determine the phenomena of combustion in engine whether the performance was improving or deteriorating. Studies were made [25-27] on sound levels with convention engine with vegetable oils and it was reported from the studies, that performance deteriorated with vegetable oil operation on conventional engine leading to produce high sound levels.

Change of injection timing affected the performance of the engine. Investigations were carried out [31-33] on conventional engine with tobacco seed oil with varied injection timing and reported that advanced injection timing increased efficiency and NOx emissions.

The present paper attempted to evaluate the performance of high grade LHR combustion chamber, which consisted of air gap insulated piston, air gap insulated liner and ceramic coated cylinder head. This high grade LHR combustion chamber was fuelled with linseed oil based biodiesel (LSOBD) with varied vied injector opening pressure and injection timing. Comparative performance studies were made between high grade LHR combustion chamber and CE with biodiesel operation.

MATERIALS AND METHOD

This part deals with preparation of biodiesel, properties of biodiesel along with diesel fuels, fabrication of air gap insulated piston, air gap insulated liner and ceramic coated cylinder head,

brief description of experimental set-up, specification of experimental engine, operating conditions and definitions of used values.

Due to very high free fatty acid, linseed oil was converted into methyl ester by the two stage process [34]. In the first stage linseed oil was reacted with CH3OH in presence of an acid catalyst (H2SO4) to convert free fatty acid into fatty ester. A specified amount 1000g of linseed oil was taken in a round bottom flask and heated up to 60-65°C. In a separate flasks CH3OH (950 g) and H2SO4 (22 g) were taken and properly mixed and then stirred for 4 h and maintained at 60°C.It was allowed to cool overnight without stirring. When acid number of the mixture reaches to less than 1, the second stage was started. During this stage, a mixture 1000g obtained from the first stage was taken in around bottom flask and heated up to 60°C. Methanol (200ml) and KOH 4.5g were properly mixed in other flask and then introduced into the round bottom flask containing the mixture from first stage. The mixture stirred vigorously for 2h and then allowed to cool overnight. Glycerol was separated by adding warm water at 60°C to the mixture. Glycerol and soap formed during the process settled down the bottom. Top layer containing linseed oil methyl ester 91% was removed with the help of a separating funnel and wasted two times with water and dried.

The physic-chemical properties of the crude vegetable oil and biodiesel in comparison to ASTM biodiesel standards are presented in Table-1.

Table.1. Properties of Test Fuels

Property	Units	Diesel	Biodiesel (ERBO)	ASTM D 6751-02
Carbon chain	--	C_8-C_{28}	C_{16}-C_{24}	C_{12}-C_{22}
Cetane Number		55	55	48-70
Density	gm/cc	0.84	0.87	0.87-0.89
Bulk modulus @ 20Mpa	Mpa	1475	1850	NA
Kinematic viscosity @ 40°C	cSt	2.25	4.5	1.9-6.0
Sulfur	%	0.25	0.0	0.05
Oxygen	%	0.3	10	11
Air fuel ratio (stochiometric)	--	14.86	14.2	13.8
Lower calorific value	kJ/kg	42 000	38000	37 518
Flash point (Open cup)	°C	66	180	130
Molecular weight	--	226	280	292
Preheated temperature	°C	--	60	--
Colour	--	Light yellow	Yellowish orange	---

LHR diesel engine (Figure.1) 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 3-mm air gap in between the crown and the body of the piston. The optimum thickness of air gap in the air gap piston was found to be 3-mm [24], for improved performance of the engine with diesel as fuel. The height of the piston was maintained such that compression ratio was not altered. Partially stabilized zirconium of thickness 500 microns was applied on inner side of cylinder head by plasma technique.

A superni-90 insert was screwed to the top portion of the liner in such a manner that an air gap of 3-mm was maintained between the insert and the liner body. At $500^{\circ}C$ the thermal conductivity of superni-90 and air are 20.92 and 0.057 W/m-K respectively
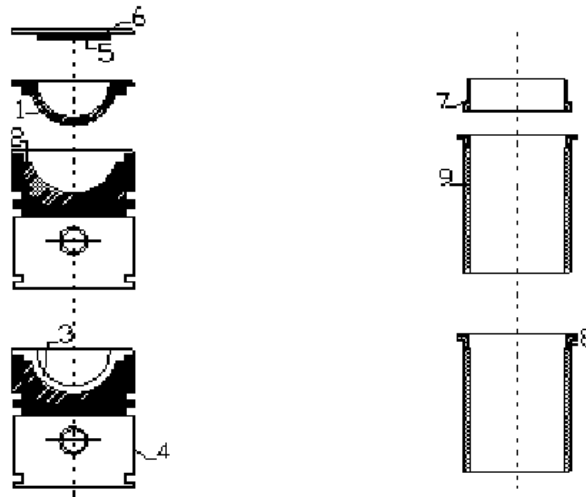
1. Crown   7 Insert

2. Gasket   8. Air gap

3. Air gap   9. Liner

4. Body

5. Ceramic coating

6. Cylinder head

Insulated piston   Insulated liner   Ceramic coated cylinder head

Fig.1 Assembly details of air gap piston liner, air gap insulated liner and ceramic coated cylinder head

Schematic diagram of experimental setup used for the investigations on compression ignition diesel engine and LHR combustion chamber with biodiesel (ERBO) is shown in Figure 2.

The test fuels used in the experimentation were pure diesel and linseed oil biodiesel. The schematic diagram of the experimental setup with test fuels is shown in Figure 2. The specifications of the experimental engine are shown in Table-2. 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 an air-box method (Air box was provided with an orifice flow meter and U-tube water manometer). The naturally aspirated engine was provided with water-cooling system in which inlet temperature of water was maintained at $80^{\circ}C$ by adjusting the water flow rate. Engine oil was provided with a pressure feed system. No temperature control was incorporated, for measuring the lube oil temperature. Copper shims of suitable size were provided in between the pump body and the engine frame, to vary the injection timing and its effect on the performance of the engine was studied, along with the change of injector opening pressure from 190 bar to 270 bar (in steps of 40 bar) using nozzle testing device. The maximum injector opening pressure was restricted to 270 bar due to practical difficulties involved. Exhaust gas temperature was measured with thermocouples made of iron and iron-

constantan. Sound at full load operation was measured with sound analyzer. The specifications of the sound analyzer were given in Table-3. The accuracy of sound analyzer was 0.1%.

Table.2. Specifications of the Test Engine

Description	Specification
Engine make and model	Kirloskar (India) AV1
Maximum power output at a speed of 1500 rpm	3.68 kW
Number of cylinders ×cylinder position× stroke	One × Vertical position × four-stroke
Bore × stroke	80 mm × 110 mm
Method of cooling	Water cooled
Rated speed (constant)	1500 rpm
Fuel injection system	In-line and direct injection
Compression ratio	16:1
BMEP @ 1500 rpm	5.31 bar
Manufacturer's recommended injection timing and pressure	27°bTDC × 190 bar
Dynamometer	Electrical dynamometer
Number of holes of injector and size	Three × 0.25 mm
Type of combustion chamber	Direct injection type
Fuel injection nozzle	**Make: MICO-BOSCH** **No- 0431-202-120/HB**
Fuel injection pump	**Make: BOSCH: NO- 8085587/1**

Table 3. Specifications of sound Analyzer

Name of the analyzer	Measuring Range	Precision	Resolution
Sound Analyzer	0-150 Decibels	1 decibel	1 decibel
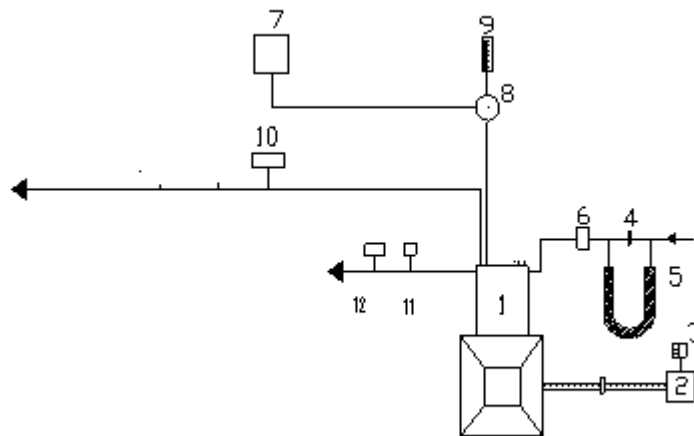
1.Engine, 2.Electical Dynamometer, 3.Load Box, 4.Orifice flow meter, 5.U-tube water manometer, 6.Air box, 7.Fuel tank, 8, Pre-heater, 9.Burette, 10. Exhaust gas temperature indicator, 11.Outlet jacket water temperature indicator, 12. Outlet-jacket water flow meter,

Fig.3 Schematic Diagram of Experimental Set-up

Various test fuels used in experimentation were pure diesel and linseed oil based biodiesel. Different operating conditions of the biodiesel were normal temperature and preheated temperature. Different injector opening injector opening pressures attempted in this experimentation were 190 bar, 230 bar and 270 bar. Various injection timings attempted in the investigations were 27-34°bTDC.

Definitions of used values:

Brake thermal efficiency (BTE); It is the ratio of brake power of the engine to the energy supplied to the engine. Brake power was measured with dynamometer. Energy supplied to the engine is the product of rate of fuel consumed (m_f)and calorific value (c_v)of the fuel. Higher the efficiency better the performance of the engine is.

$$BTE = \frac{BP}{m_{f \times CV}}$$

Brake specific energy consumption (BSEC): It is measured at full load operation of the engine. Lesser the value, the better the performance of the engine. It is defined as energy consumed by the engine in producing 1 kW brake power. When different fuels having different properties are tested in engine, brake specific fuel consumption is not the criteria to evaluate the performance of the engine. Peak BTE and BSEC at full load are important parameters to be considered to evaluate the performance of the engine.

$$BSEC = \frac{1}{BTE}$$

Coolant load: Product of mass flow rate of coolant, specific heat of coolant, rise of temperature of the coolant between inlet conditions and outlet conditions.
Volumetric efficiency: It is the ratio of the volume of air drawn into a cylinder to the piston displacement.

Recommended injection timing: It is the injection timing of the engine with maximum efficiency of the engine with minimum pollution levels.

Calculation of actual discharge of air: By means of water tube manometer and an orifice flow meter, head of air (h_a) can be calculated. Velocity of air (V_a) can be calculated using the formula _____ ; Actual discharge of air = _____ , where a= area of an orifice flow meter, c_d =

$$V_a = \sqrt{2gh_a}$$ $$c_d a \sqrt{2gh_a}$$

Coefficient of discharge.

Optimum injection timing: It is injection timing at which maximum thermal efficiency was obtained at all loads and beyond this injection timing, efficiency of the engine decreased.

RESULTS AND DISCUSSION

Data of pure diesel was taken from reference [29]. The optimum injection timing with conventional engine was 31°bTDC, while with LHR combustion chamber it was 28°bTDC.

Performance Parameters

Figure 3 indicates that BTE increased up to 80% of the full load operation (BMEP=4.2 bar) due to conversion of increase of fuel efficiency and beyond that load it decreased due to decrease of air fuel ratios [26] as oxygen was completely used up with both test fuels. Curves from Figure 3 indicate that CE with bio-diesel showed the compatible performance for entire load range when compared with the pure diesel operation on CE at recommended injection timing. Although carbon accumulations on the nozzle tip might play a partial role for the general trends observed, the difference of viscosity between the diesel and bio-diesel provided a possible explanation for the compatible performance of CE with bio-diesel operation.
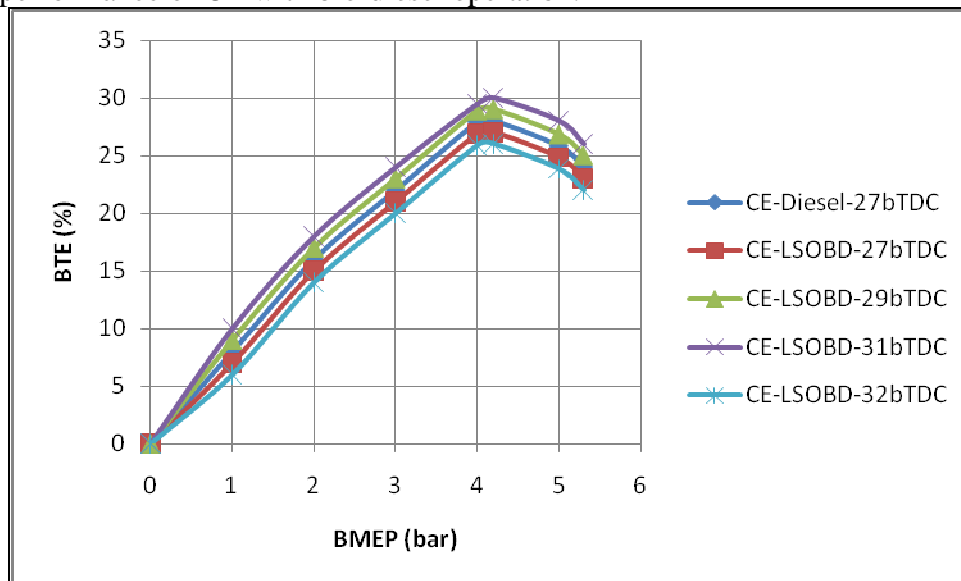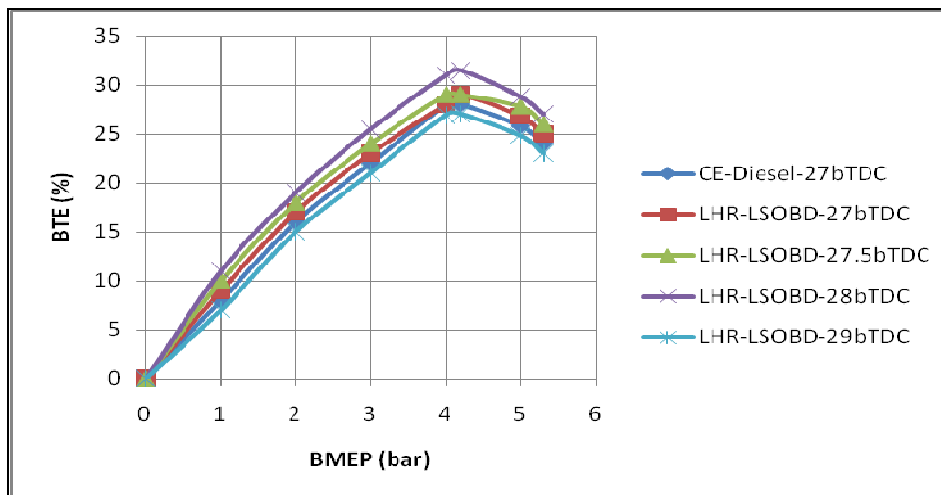

Fig.3 Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in conventional engine (CE) at various injection timings with biodiesel (LSOBD) operation at an injector opening pressure of 190 bar.

BTE increased with the advancing of the injection timing in the CE with the bio-diesel at all loads, when compared with CE at the recommended injection timing and pressure. This was due to initiation of combustion at earlier period and efficient combustion with increase of air entrainment [26] in fuel spray giving higher BTE. BTE increased at all loads when the injection timing was advanced to 31°bTDC in CE at the normal temperature of bio-diesel. Similar trends were observed

with preheated biodiesel also. Preheating of the biodiesel reduced the viscosity, which improved the spray characteristics of the oil.

From Figure 4, it is observed that LHR combustion chamber with biodiesel showed the improved performance for the entire load range compared with CE with pure diesel operation. This was because of efficient combustion of biodiesel in the hot environment provided by LHR combustion chamber. The optimum injection timing was found to be 28°bTDC with LHR combustion chamber with normal bio-diesel and preheated biodiesel operations. Since the hot combustion chamber of LHR combustion chamber reduced ignition delay and combustion duration and hence the optimum injection timing was obtained earlier with LHR combustion chamber when compared with CE with the biodiesel operation.

Fig.4 Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in engine with LHR combustion chamber at various injection timings with biodiesel (LSOBD) operation an injector opening pressure of 190 bar.

Injector opening pressure was varied from 190 bars to 270 bar to improve the spray characteristics and atomization of the vegetable oils and injection timing was advanced from 27 to 34°bTDC for CE and LHR combustion chamber. The improvement in BTE at higher injector opening pressure was due to improved fuel spray characteristics. The optimum injection timing was 31°bTDC at 190 bar, 30°bTDC at 230 bar and 29°bTDC at 270 bar for CE. The optimum injection timing for LHR combustion chamber n engine was 28°bTDC irrespective of injector opening pressure.

Part load variations were very small and minute for the performance parameters and exhaust emissions. The effect of varied injection timing on the performance was discussed with the help of bar charts while the effect of injector opening pressure and preheating was discussed with the help of Tables.

it was noticed (Figure.5) that peak brake thermal efficiency(BTE)with LHR combustion chamber engine with pure diesel operation was lower in comparison with conventional engine at recommended (4%) and optimized injection timings (6%).

LHR combustion chamber [26] with pure diesel operation deteriorated the performance in comparison with conventional engine. As the combustion chamber was insulated to greater extent, it was expected that high combustion temperatures would be prevalent in LHR combustion chamber. It tends 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 peak BTE decreased. More over at this load, friction and increased diffusion combustion resulted from reduced ignition delay.

Peak BTE with LHR combustion chamber with biodiesel operation was higher in comparison with conventional engine at recommended (7%) and optimized injection timings (5%).

This was due to higher degree of insulation provided in the piston, liner (with the provision of air gap with superni-90 inserts) and cylinder head reduced the heat rejection leading to improve the thermal efficiency. This was also because of improved evaporation rate of the biodiesel. 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 combustion chamber improved heat release rates and efficient energy utilization.

From Table 4, it could be noticed that improvement in the peak BTE was observed with the increase of injector opening pressure and with advancing of the injection timing in both versions of the engine. This was due to improved spraying characteristics and efficient combustion as biodiesel has high duration of combustion and hence advancing of injection timing helped efficient energy release from the fuel leading to produce higher BTE.

The performance improved further with the preheated biodiesel when compared with normal biodiesel. Preheating of the biodiesel reduced the viscosity, which improved the spray characteristics of the oil causing efficient combustion thus improving brake thermal efficiency. The cumulative heat release was more for preheated biodiesel [29] than that of biodiesel and this indicated that there was a significant increase of combustion in diffusion mode [26]. This increase in heat release [29] was mainly due to better mixing and evaporation of preheated biodiesel, which leads to complete burning.

LHR combustion chamber with biodiesel operation gave higher BTE than CE, while CE gave higher BTE than LHR combustion chamber with diesel operation.
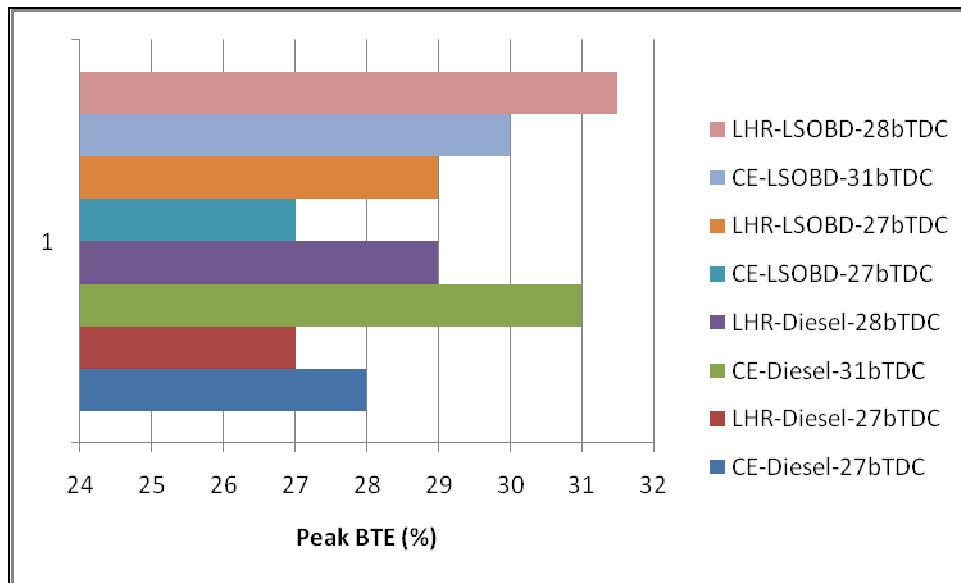
Fig.5 Bar charts showing the variation of Peak brake thermal efficiency with test fuels at recommended and optimized injection timings at an injector opening pressure of 190 bar with different versions of the combustion chamber.

Table 4. Data of Peak BTE and BSEC at full load operation

Injection Timing (° bTDC)	Test Fuel	Peak BTE (%)						BSEC at full load operation (kW/kW)					
		Injector Opening Pressure (Bar)						Injector Opening Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27(CE)	DF	28		29		30		4.00	--	3.92	--	3.84	--
	LSOBD	27	27.5	27.5	28	28.5	29	4.02	3.96	3.96	3.94	3.94	3.96
27(LHR)	DF	27	--	27.5	--	28	--	4.16	---	4.08	--	4.00	--
27(LHR)	LSOBD	29	29.5	29.5	30	30	30.5	3.96	3.92	3.92	3.88	3.88	3.84
28(LHR)	LSOBD	31.5	32	32	32.5	32.5	33	3.68	3.64	3.64	3.60	3.60	3.56
28(LHR)	DF	29	--	30	--	32	--	3.76	-	3.72	-	3.68	-
31(CE)	DF	31	--	31	--	30	--	3.6	--	3.7	--	3.8	---
	LSOBD	30	30.5	30.5	31	30	30.5	3.82	3.78	3.86	3.82	3.90	3.86

Generally brake specific fuel consumption, is not used to compare the two different fuels, because their calorific value, density, chemical and physical parameters are different. Performance parameter, BSEC, is used to compare two different fuels by normalizing brake specific energy consumption, in terms of the amount of energy released with the given amount of fuel.

From Table 4, it is evident that brake specific energy consumption (BSEC) at full load decreased with the increase of injector opening pressure and with the advancing of the injection timing at different operating conditions of the biodiesel. This was because of improved spray characteristics with increase of injector opening pressure. This was also due to initiation of combustion at early period with advanced injection timing.

From Figure.6, it was evident that brake specific energy consumption with LHR combustion chamber with pure diesel operation was higher in comparison with conventional engine at recommended (4%)and optimized injection timings (4%).
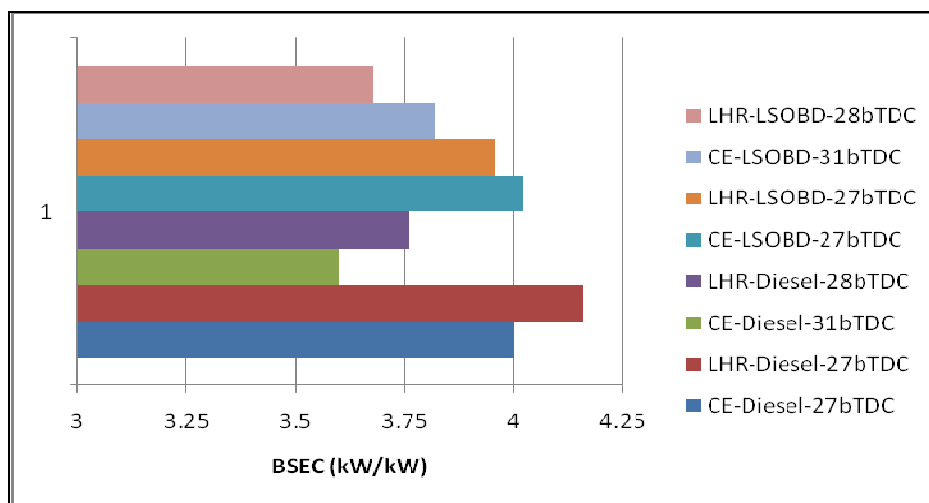
Fig.6 Bar charts showing the variation of brake specific energy consumption (BSEC) at full load operation with test fuels at recommended and optimized injection timings at an injector opening pressure of 190 bar with different versions of the combustion chamber.

This was due to reduction of ignition delay with pure diesel operation with LHR combustion chamber as hot combustion chamber was maintained by it.

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BSEC was lower with LHR combustion chamber with biodiesel operation in comparison with conventional engine with biodiesel operation at recommended injection timing (1%) and optimum injection timing (4%).

BSEC was higher with conventional engine due to due to higher viscosity, poor volatility and reduction in heating value of biodiesel lead to their poor atomization and combustion characteristics. The viscosity effect, in turn atomization was more predominant than the oxygen availability [35] in the blend leads to lower volatile characteristics and affects combustion process. BSEC was improved with LHR combustion chamber with lower substitution of energy in terms of mass flow rate.

BSEC decreased with advanced injection timing with test fuels. This was due to initiation of combustion and substitution of lower energy as seen From the Figure.6i.

BSEC of biodiesel is almost the same as that of neat diesel fuel as shown in Figure.6. Even though viscosity of biodiesel is slightly higher than that of neat diesel, inherent oxygen of the fuel molecules improves the combustion characteristics. This is an indication of relatively more complete combustion [35].

BSEC decreased with the preheated biodiesel at full load operation when compared with normal biodiesel. Preheating of the biodiesel reduced the viscosity, which improved the spray characteristics of the oil.

From Figure.7, it was observed that exhaust gas temperature (EGT) with LHR combustion chamber with pure diesel operation was higher in comparison with conventional engine at recommended (18%) and optimized injection timings (13%).

This was due to reduction of ignition delay with pure diesel operation with LHR engine as hot combustion chamber was maintained by LHR combustion chamber. This indicated that heat rejection was restricted through the piston, liner and cylinder head, thus maintaining the hot combustion chamber as result of which the exhaust gas temperature increased.

EGT *with* LHR combustion chamber with biodiesel operation was marginally lower in comparison with conventional engine at recommended (4%)and optimized injection timings (6%). This was due to reduction of ignition delay in the hot environment with the provision of the insulation in the LHR combustion chamber, which caused the gases expand in the cylinder giving higher work output and lower heat rejection.

EGT decreased with advanced injection timing with test fuels as seen from the Figure. This was because, when the injection timing was advanced, the work transfer from the piston to the gases in the cylinder at the end of the compression stroke was too large, leading to reduce in the value of EGT.

Though the calorific value (or heat of combustion) of fossil diesel is more than that of biodiesel ; the density of the biodiesel was higher therefore greater amount of heat was released in the combustion chamber leading to higher exhaust gas temperature with conventional engine, which confirmed that performance was compatible with conventional engine with biodiesel operation in comparison with pure diesel operation. Similar findings were obtained by other studies [27].

From the Table.5, it is noticed that the exhaust gas temperatures of preheated biodiesel were higher than that of normal biodiesel, which indicates the increase of diffused combustion [32] due to high rate of evaporation and improved mixing between methyl ester and air. Therefore, as the fuel temperature increased, the ignition delay decreased and the main combustion phase (that is, diffusion controlled combustion) increased [35], which in turn raised the temperature of exhaust gases. The value of exhaust gas temperature decreased with increase in injector opening pressure with test fuels as it is evident from the Table.5. This was due to improved spray characteristics of the fuel with increase of injector opening pressure.

Exhaust gas temperature was lower with diesel operation with conventional engine when compared with biodiesel operation, while EGT was lower with LHR combustion chamber with biodiesel

operation in comparison with diesel operation. Hence conventional engine was more suitable for diesel operation, while LHR combustion chamber was suitable for biodiesel operation.
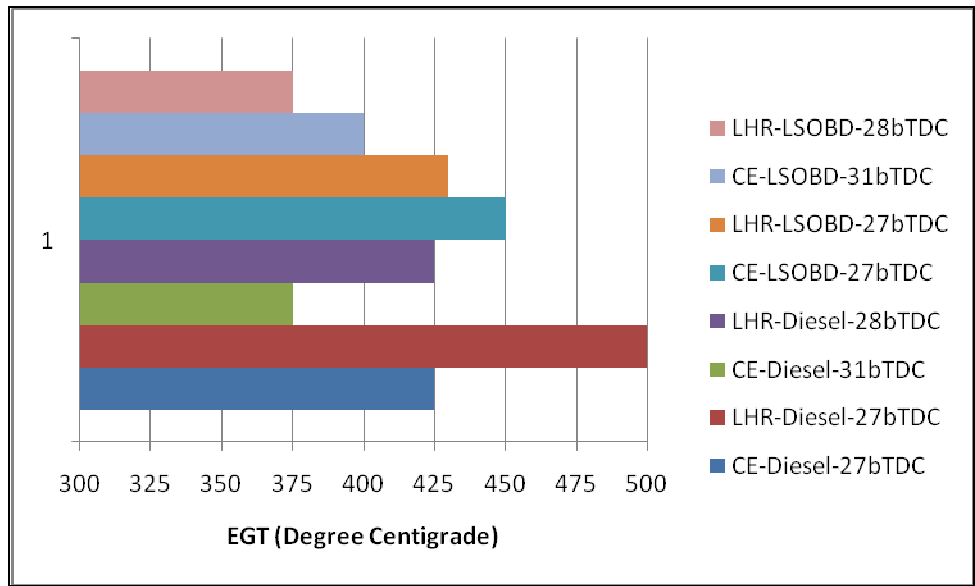
Fig.7 Bar charts showing the variation of exhaust gas temperatures (EGT) at full load with test fuels at recommended and optimized injection timings at an injector opening pressure of 190 bar with different versions of the combustion chamber.

Table. 5. Data of EGT and Coolant Load at full load operation

Injection Timing (° bTDC)	Test Fuel	EGT (degree centigrade) at full load operation						Coolant Load at full load operation (kW)					
		Injector Opening Pressure (Bar)						Injector Opening Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27(CE)	DF	425	--	410	---	395	--	4.0	---	4.2	--	4.4	---
	LSOBD	450	490	410	450	370	410	4.2	4.0	4.4	4.2	4.6	4.4
27(LHR)	DF	500	--	475	--	450	--	3.4		3.2		3.0	
27(LHR)	LSOBD	430	400	400	370	370	340	3.2	3.0	3.0	2.8	2.8	2.6
28(LHR)	LSOBD	375	350	350	325	325	300	3.0	2.8	2.8	2.6	2.6	2.4
28(LHR)	DF	425	--	400	--	375	--	3.2		3.0		2.8	
31(CE)	DF	375	---	350	---	325	--	4.2	--	4.4	--	4.6	---
	LSOBD	400	440	420	460	440	420	4.4	4.2	4.6	4.4	4.8	4.6

Figure 8 indicates that coolant load with LHR combustion chamber with pure diesel operation was lower (15% and 23%) at recommended and optimized injection timings respectively in comparison with conventional engine. This was due insulation provided with LHR combustion chamber.
Coolant load with LHR combustion chamber with biodiesel operation was lower (23% and 14%) at recommended and optimized injection timings respectively in comparison with conventional engine. This was due insulation provided with LHR combustion chamber.

In case of conventional engine, un-burnt fuel concentration reduced with effective utilization of energy, released from the combustion, coolant load with test fuels increased marginally at full load operation, due to un-burnt fuel concentration reduced with effective utilization of energy, released from the combustion, with increase of gas temperatures, when the injection timing was advanced to the optimum value. However, the improvement in the performance of the conventional engine was due to heat addition at higher temperatures and rejection at lower temperatures, while the improvement in the efficiency of the engine with LHR combustion chamber was due to recovery from coolant load at their respective optimum injection timings with test fuels. Rama Mohan [24] noticed the similar trend at optimum injection timing with his LHR combustion chamber.

From Table.5, it is seen that coolant load increased marginally in the conventional engine while it decreased in the LHR combustion chamber with increasing of the injector opening pressure with test fuels. This was due to the fact with increase of injector opening pressure with conventional engine, increased nominal fuel spray velocity resulting in better fuel-air mixing with which gas temperatures increased. The reduction of coolant load in the LHR combustion chamber was not only due to the provision of the insulation but also it was due to better fuel spray characteristics and increase of air-fuel ratios causing decrease of gas temperatures and hence the coolant load.
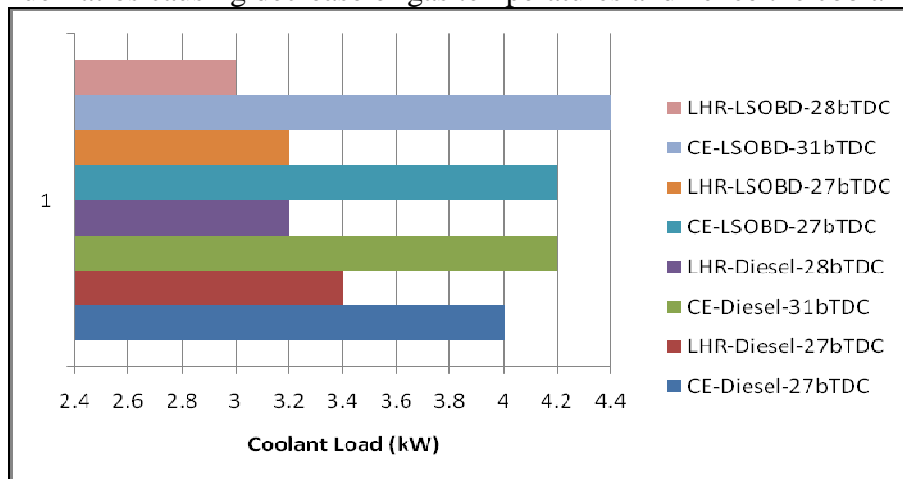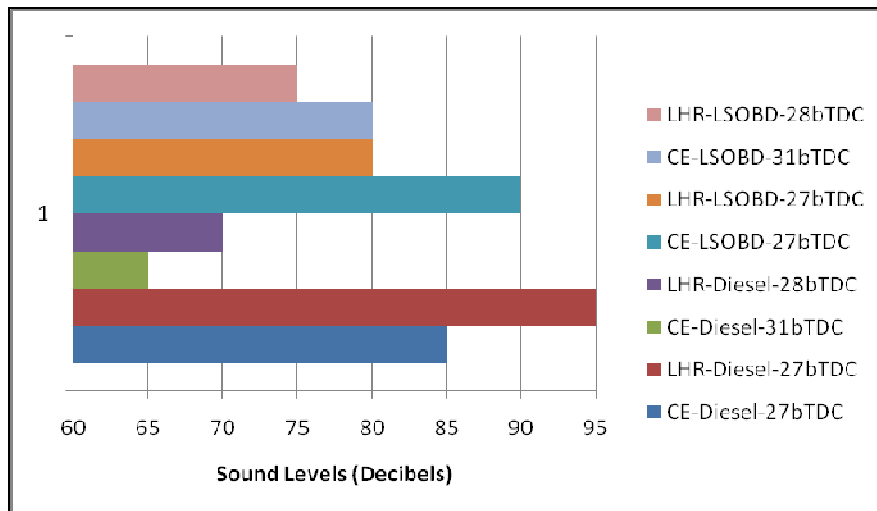

Fig.8 Bar charts showing the variation of coolant load at full load operation with test fuels at recommended and optimized injection timings at an injector opening pressure of 190 bar with different versions of the combustion chamber.

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Coolant load decreased marginally with preheating of biodiesel. This was due to improved air fuel ratios [26] with improved spray characteristics.

Figure 9 denotes that sound levels were higher (12% and 8%) with LHR combustion chamber with pure diesel operation at recommended and optimized injection timings respectively in comparison with conventional engine. This showed that performance deteriorated with LHR combustion chamber with pure diesel operation. This was due to reduction of ignition delay.

Sound levels were lower (11% and 9%) with LHR combustion chamber with biodiesel operation at recommended and optimized injection timings respectively in comparison with conventional engine. This showed that performance improved with LHR combustion chamber with biodiesel operation.

Fig.9 Bar charts showing the variation of sound levels at full load operation with test fuels at recommended and optimized injection timings at an injector opening pressure of 190 bar.

With advanced injection timings, air fuel ratios improved with early initiation of combustion hence sound levels got reduced with both versions of the engine with test fuels.

Table 6 denotes that the Sound levels decreased with increase of injector opening pressure with the test fuels. This was due to improved spray characteristic of the fuel, with which there was no impingement of the fuel on the walls of the combustion chamber leading to produce efficient combustion.

Sound intensities were lower at preheated condition of preheated biodiesel when compared with their normal condition. This was due to improved spray characteristics, decrease of density and viscosity of the fuel.

**Table. 4. Data of sound levels and volumetric efficiency at full load operation**

Injection Timing (° bTDC)	Test Fuel	Sound Levels at full load operation (Decibels)						Volumetric Efficiency at full load operation (%)					
		Injector Opening Pressure (Bar)						Injector Opening Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27(CE)	DF	85	--	80	--	95	--	85	--	86	--	87	--
	LSOBD	90	85	85	80	80	70	83	82	84	83	85	84
27(LHR)	DF	95		90		85		78		79		80	
27(LHR)	LSOBD	80	75	75	70	70	65	77	78	78	79	79	80
28(LHR)	LSOBD	75	70	70	65	65	60	78	79	79	80	80	81
28(LHR)	DF	70		65		60		79		80		81	
31(CE)	DF	65	--	60	--	55	--	89	--	90	--	91	--
	LSOBD	80	75	85	80	90	85	87	88	87	89	88	87

Volumetric efficiency depends on density of the charge which intern depends on temperature of combustion chamber wall.

Figure 10 denotes that volumetric efficiency were lower (8% and 11%) with LHR combustion chamber with pure diesel operation at recommended and optimized injection timings respectively in comparison with conventional engine.

Volumetric efficiencies were lower (7% and 10%) with LHR combustion chamber with biodiesel operation at recommended and optimized injection timings respectively in comparison with conventional engine.

Volumetric efficiency in the LHR combustion chamber decreased at full load operation when compared to the conventional engine at recommended and optimized injection timing with test fuels. This was due increase of temperature of incoming charge in the hot environment created with the provision of insulation, causing reduction in the density and hence the quantity of air. However, this variation in volumetric efficiency is very small between these two versions of the engine, as volumetric efficiency mainly depends [16] on speed of the engine, valve area, valve lift, timing of the opening or closing of valves and residual gas fraction rather than on load variation. Rama Mohan [24] also observed the similar trends in the value of volumetric efficiency.
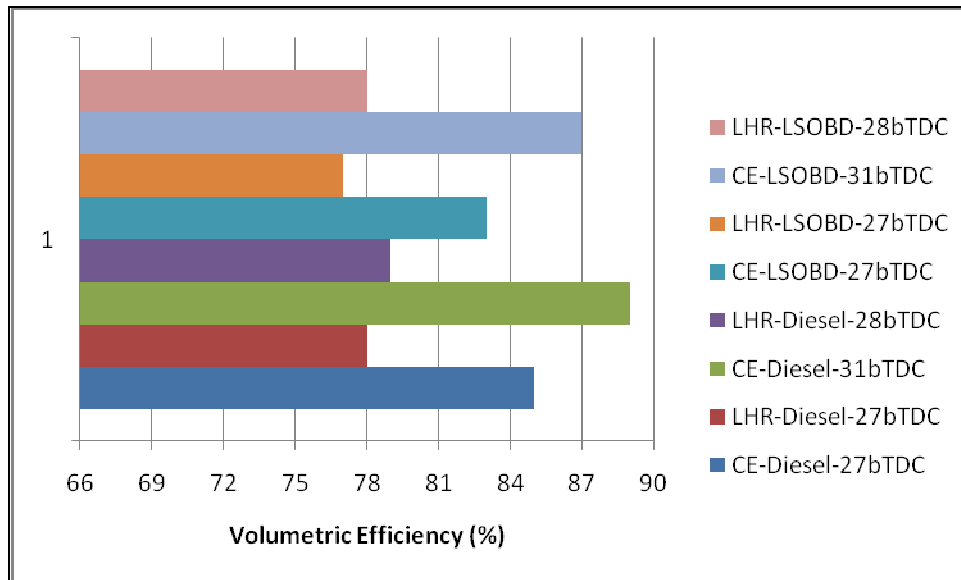
Fig.10 Bar charts showing the variation of volumetric efficiency at full load operation with test fuels at recommended and optimized injection timings at an injector opening pressure of 190 bar with different versions of the combustion chamber.

Volumetric efficiency was higher with pure diesel operation at recommended and optimized injection timing with conventional engine in comparison with biodiesel operation. This was due to increase of combustion chamber wall temperatures with biodiesel operation due to accumulation of un-burnt fuel concentration. This was also because of increase of combustion chamber wall temperature as exhaust gas temperatures increased with biodiesel operation in comparison with pure diesel operation.

Volumetric efficiency increased marginally with both versions of the engine with test fuels with advanced injection timing. This was due to decrease of combustion chamber wall temperatures with improved air fuel ratios [29].

From Table-6, it is evident that volumetric efficiency increased with increase of injector opening pressure with test fuels. This was due to improved fuel spray characteristics and evaporation at higher injection pressures leading to marginal increase of volumetric efficiency. This was also because of decrease of exhaust gas temperatures and hence combustion chamber wall temperatures. This was also due to the reduction of residual fraction of the fuel, with the increase of injector opening pressure.

Preheating of the biodiesel marginally decreased volumetric efficiency, when compared with the normal temperature of biodiesel, because of reduction of bulk modulus, density of the fuel and increase of exhaust gas temperatures.

CONCLUSION

At recommended and respective optimized injection timings with biodiesel operation,

1. Peak BTE with LHR combustion chamber with biodiesel operation was higher in comparison with conventional engine at recommended (7%) and optimized injection timings (5%).
2. BSEC was lower with LHR combustion chamber with biodiesel operation in comparison with conventional engine with biodiesel operation at recommended injection timing (1%) and optimum injection timing (4%).
3. EGT *with* LHR combustion chamber with biodiesel operation was marginally lower in comparison with conventional engine at recommended (4%)and optimized injection timings (6%).
4. Coolant load with LHR combustion chamber with biodiesel operation was lower (23% and 14%) at recommended and optimized injection timings respectively in comparison with conventional engine.
5. Sound levels were lower (11% and 9%) with LHR combustion chamber with biodiesel operation at recommended and optimized injection timings respectively in comparison with conventional engine.
6. Volumetric efficiencies were lower (7% and 10%) with LHR combustion chamber with biodiesel operation at recommended and optimized injection timings respectively in comparison with conventional engine.

Increase of the injection pressure with both versions of the engine with test fuels.

Peak brake thermal efficiency increased. At full load operation- brake specific energy consumption decreased, exhaust gas temperature decreased, volumetric efficiency increased, coolant load increased and sound levels decreased.

With preheating of biodiesel with both versions of the engine

Peak brake thermal efficiency increased, at full load operation- brake specific energy consumption decreased, exhaust gas temperature increased, volumetric efficiency decreased, coolant load decreased, sound levels decreased.

LHR combustion chamber was more suitable for biodiesel operation than pure diesel operation
Research Findings and Suggestions

Comparative studies on performance parameters with direct injection diesel engine with high grade low heat rejection combustion chamber and conventional combustion chambers were determined at varied injector opening pressure and injection timing with different operating conditions of the biodiesel. Experimental results were compared with pure diesel operation at similar operating conditions.

Hence further work on the effect of injector opening pressure and injection timing on exhaust emissions and combustion characteristics with LHR combustion chamber with biodiesel operation is necessary.

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