A R C H I V E O F M E C H A N I C A L E N G I N E E R I N G

VOL. LXI 2014 Number 4

10.2478/meceng-2014-0036

Key words: alternate fuels, vegetable oil, biodiesel, LHR engines, fuel performance, emissions, combustion characteristics

M.V.S. MURALI KRISHNA [*], *N. DURGA PRASADA RAO* [**], *B. ANJENEYA PRASAD* [***], *P.V.K. MURTHY* [****]

COMPARATIVE PERFORMANCE WITH DIFFERENT VERSIONS OF LOW HEAT REJECTION COMBUSTION CHAMBERS WITH CRUDE RICE BRAN OIL

It has been found that the vegetable oils are promising substitute, because of their properties are similar to those of diesel fuel and they are renewable and can be easily produced. However, drawbacks associated with crude vegetable oils are high viscosity, low volatility call for low heat rejection combustion chamber, with its significance characteristics of higher operating temperature, maximum heat release, and ability to handle lower calorific value (CV) fuel etc. Experiments were carried out to evaluate the performance of an engine consisting of different low heat rejection (LHR) combustion chambers such as ceramic coated cylinder head-LHR-1, air gap insulated piston with superni (an alloy of nickel) crown and air gap insulated liner with superni insert – LHR-2; and ceramic coated cylinder head, air gap insulated piston and air gap insulated liner – LHR-3 with normal temperature condition of crude rice bran oil (CRBO) with varied injector opening pressure. Performance parameters (brake thermal efficiency, brake specific energy consumption, exhaust gas temperature, coolant load, and volumetric efficiency) and exhaust emissions [smoke levels and oxides of nitrogen [NOx]] were determined at various values of brake mean effective pressure of the engine. Combustion characteristics [peak pressure, time of occurrence of peak pressure, maximum rate of pressure rise] were determined at full load operation of the engine.

Conventional engine (CE) showed compatible performance and LHR combustion chambers showed improved performance at recommended injection timing of 27°bTDC and recommend injector opening pressure of 190 bar with CRBO operation, when compared with CE with pure diesel operation. Peak brake thermal efficiency

[*] *Mechanical Engineering Department, Chaitanya Bharathi Institute of Technology, Gandipet, Hyderabad-500 075, Andhra Pradesh, India;*

[**] *Production Department, Hindustan Aeronautics Limited, Bangalore-560017;*

[***] *Mechanical Engineering Department, J.N.T. U. College of Engineering, Hyderabad-500 085, Karnataka, India;*

[****] *Jaya Prakash Narayan Educational Society Group of Institutions, Mahabubnagar-509001, Andhra Pradesh, India; E-mail: Krishnamurthy_venkata@yahoo.co.in*

increased relatively by 7%, brake specific energy consumption at full load operation decreased relatively by 3.5%, smoke levels at full load decreased relatively by 11% and NOx levels increased relatively by 58% with LHR-3 combustion chamber with CRBO at an injector opening pressure of 190 bar when compared with pure diesel operation on CE.

1. Introduction

Dramatic increase in vehicular population and environmental concerns renewed interest of scientific community to look for alternative fuels of bio-origin such as vegetable oils. Vegetable oils can be produced from forests, vegetable oil crops, and oil bearing biomass materials. Vegetable oils have high-energy content. It has also been found that the vegetable oil is a promising fuel, because of its properties are similar to those of diesel fuel.

Rudolph Diesel, the inventor of the engine that bears his name, experimented [1] with fuels ranged from powdered coal to peanut oil. Several researchers [2-5] 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. The different fatty acids present in the vegetable oil are [5] palmic, steric, lingoceric, oleic, linoleic and fatty acids. These fatty acids increase smoke emissions and also lead to incomplete combustion due to improper air-fuel mixing. These problems can be solved, if neat vegetable oils are chemically modified to biodiesel.

These problems can be solved, if neat vegetable oils are chemically modified to biodiesel. Biodiesels derived from vegetable oils present a very promising alternative to diesel fuel since biodiesels have numerous advantages compared to fossil fuels as they are renewable, biodegradable, provide energy security and foreign exchange savings besides addressing environmental concerns and socio-economic issues. Experiments were carried out [6-9] with biodiesel on CE and reported performance was compatible with pure diesel operation on CE. However, biodiesel operation increased NOx emissions.

By controlling the injector opening pressure and the injection rate, the spray cone angle is found [10] to depend on injector opening pressure. Few investigators [11-15] reported that injector opening pressure has a significance effect on the performance and formation of pollutants inside the direct injection diesel engine combustion. Venkanna et al. [15] used honne/diesel blend in DI diesel engine with increased injector opening pressure and increased injection rate. It was reported from their investigations that performance and emissions with increase of injector opening pressure.

The drawbacks of crude vegetable oil and biodiesel call for different combustion chambers known as low heat rejection (LHR) combustion chambers with its significance characteristics of higher operating temperature, maximum heat release, and ability to handle lower calorific value (CV) fuel etc.

The concept of LHR combustion chamber is to reduce heat flow to the coolant by providing thermal insulation in the path of heat flow to the coolant and increase thermal efficiency of the engine. Several methods adopted for achieving LHR to the coolant are i) (LHR-1) using ceramic coatings on piston, liner and cylinder head ii) (LHR-2) creating air gap in the piston and other components with low-thermal conductivity materials like superni, cast iron and mild steel etc.iii) (LHR-3) providing ceramic coating on engine components and air gap insulation.

Ceramic coatings provided adequate insulation and improved brake specific fuel consumption (BSFC) in the range of 3-5% at full load operation with pure diesel operation, which was reported by various researchers [16-20]. However, previous studies revealed that the thermal efficiency variation of LHR combustion chamber not only depended on the heat recovery system, but also depended on the engine configuration, operating condition and physical properties of the insulation material. Investigations were carried out on LHR-1 combustion chamber with ceramic coating on engine components with biodiesel operation [21-24]. It was revealed from their investigations that biodiesel operation improved thermal efficiency in the range of 2-5%, decreased smoke levels by 30% and increased NOx levels by 50%.

Creating an air gap in the piston involved the complications of joining two different metals of LHR-2 and LHR-3 combustion chambers. Though one observed [25] effective insulation provided by an air gap, the bolted design employed by them could not provide complete sealing of air in the air gap. It was made a successful attempt [26] of screwing the crown, made of low thermal conductivity material, Nimonic (an alloy of nickel) to the body of the piston, by keeping a gasket, made of Nimonic, in between these two parts. Studies were made with this type of combustion chamber (LHR-2) with pure diesel operation and reported that BSFC at full load increased by 7% at an injection timing of 29.5°bTDC (before top dead centre). However, low degree of insulation provided by these researchers [32] was not able to burn high viscous fuels of vegetable oils. Studies were made [27-30] with combustion chamber (LHR-2) with air gap insulated piston with Superni (an alloy of nickel whose thermal conductivity is $\frac{1}{16}$ of that of aluminium alloy) crown and air gap insulated liner with Superni insert with vegetable oils with varied injection timing and injector opening pressure. It was reported that thermal efficiency increased by 4-6%, smoke levels decreased by 40% and NOx levels increased by 50% with this type of combustion chamber when compared with pure diesel operation on CE.

Experiments were conducted [31-33] with LHR-3 combustion chamber which contained air gap insulated piston with Superni crown with threaded design, air gap insulated liner with Superni insert with threaded design and ceramic coated cylinder head with vegetable oils with varied injection timing and injector opening pressure. It was reported that performance deteriorated with vegetable oils in CE and improved with LHR-3 combustion chamber. However, this combustion chamber drastically increased NOx levels by 60%. It was further reported that performance improved further with increase of injector opening pressure.

Comparative performance on different versions of combustion chambers was also made [34-36] with vegetable oil operation with varied injector opening pressure. It was revealed from their investigations that performance of the engine improved with degree of insulation and increase of injector opening pressure.

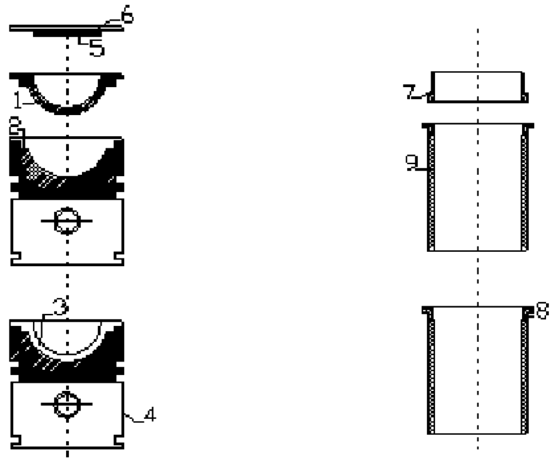
Little literature was available in evaluating the performance of different versions of the combustion chambers with varied injection pressure. The present paper attempted to evaluate the performance of the engine with different combustion chambers, with crude rice bran oil (CRBO) with varied injector opening pressure and compared with pure diesel operation on conventional engine.

2. Materials and Methods

This section contains different configurations of combustion chambers (LHR-1, LHR-2 and LHR-3), fabrication of combustion chamber (LHR-3), description of experimental set up, experimental conditions, properties of vegetable oil, definitions of used values.

Combustion chamber LHR-1 – combustion chamber with ceramic coated cylinder head; Combustion chamber LHR-2 – air gap insulated piston with Superni (an alloy of nickel) crown and air gap insulated liner with 3 mm air gap; Combustion chamber LHR-3 – air gap insulated piston with superni crown, air gap insulated liner with Superni insert with 3 mm air gap and ceramic coated cylinder head.

The LHR-3 combustion chamber (Fig. 1) contained a two-part piston – the top crown made of low thermal conductivity material, Superni-90 was screwed to aluminum body of the piston, providing a 3 mm air gap in between the crown and the body of the piston. The optimum thickness of air gap in the air gap piston was found [26] to be 3 mm for improved performance of the engine with 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 3 mm was maintained between the insert and the liner body. Partially stabilized zirconium (PSZ) of thickness 500 microns was coated on inside portion of cylinder head by means of plasma spray technique.



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: 1 – crown; 2 – gasket; 3 – air gap; 4 – body; 5 – ceramic coating; 6 – cylinder head; 7 – insert; 8 – air gap; 9 – liner

The schematic diagram of the experimental setup used for the investigations on different combustion chambers with CRBO was shown in Fig. 2. The specifications of the experimental engine are shown in Table 1. The combustion chamber consisted of a direct injection type with no special arrangement for swirling motion of air. The speed of the engine was maintained constant at 1500 rpm. 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°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. Injector opening pressure was varied from 190 bar to 270 bar (in steps of 40 bar) using nozzle testing device. The maximum injector opening

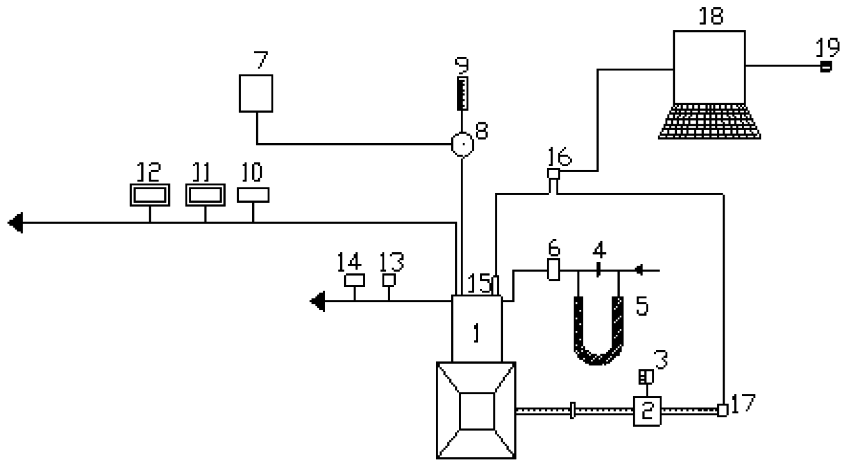


Fig. 2. Experimental set-up: 1 – engine, 2 – electical dynamometer, 3 – load box, 4 – orifice flow meter, 5 – U-tube water manometer, 6 – air box, 7 – fuel tank, 8 – pre-heater, 9 – burette, 10 – exhaust gas temperature indicator, 11 – AVL smoke meter, 12 – netel chromatograph NOx analyzer, 13 – outlet jacket water temperature indicator, 14 – outlet-jacket water flow meter, 15 – Piezo-electric pressure transducer, 16 – console, 17 – TDC encoder, 18 – Pentium Personal Computer, 19 – printer

Table 1.

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

pressure was restricted to 270 bar due to practical difficulties involved. Setting of injector opening pressure is constant for different test fuels with nozzle testing device. Usually fuel final pressure during injection increases highly above nozzle opening pressure. Final fuel pressure depends on viscosity, surface tension and other fuel properties. But data on fuel rail pressure is not available. Exhaust gas temperature was measured with thermocouples made of iron and iron-constantan. The specifications of the analyzers were given in Table 3.

Smoke levels and NOx levels were measured with AVL (Company Trade name) smoke meter and Netel (Company trade name) Chromatograph NOx analyzer respectively. The specification of the measuring instruments were shown in Table 2.

Table 2.
Specifications of Analyzers

Name of the analyzer	**Measuring Range**	**Precision**	**Resolution**
AVL Smoke meter	0-100 HSU	1 HSU	1 HSU
Netel Chromatograph NOx analyzer	0-2000 ppm	2 ppm	1 ppm

Piezoelectric transducer, fitted on the cylinder head to measure pressure in the combustion chamber was connected to a console, which in turn was connected to Pentium personal computer. TDC (top dead centre) encoder provided at the extended shaft of the dynamometer was connected to the console to measure the crank angle of the engine. A special pressure-crank angle (P-θ) software package evaluated the combustion characteristics such as peak pressure (PP), time of occurrence of peak pressure (TOPP) and maximum rate of pressure rise (MRPR) from the signals of pressure and crank angle at the full load operation of the engine. Pressure-crank angle diagram was obtained on the screen of the personal computer.

Experimental conditions:

Test fuels were pure diesel and crude rice bran. Different injector opening pressures attempted in the experimentation were 190 bar, 230 bar and 270 bar. The recommended injection timing specified by the manufacturer was 27°bTDC. Various combustion chambers used in the experimentation were LHR-1, LHR-2 and LHR-3.

Rice bran oil obtained during milling of rice is gaining commercial importance in the world as it has many beneficial nutritive and biological effects. Rice bran oil can be extracted from rice bran by solvent extraction technique or solvent-free process or by superficial fluid extraction technology [37]. India is the second largest producer of paddy after China. But unfortunately in India, the potential of rice bran oil as cooking oil still remains largely untapped. Hence crude rice bran oil can be conveniently used as IC engine fuel, as its properties are similar to those of diesel fuel. The properties of the crude rice bran (CRBO) and the diesel used in this work were presented in Table 3.

Table 3.

Properties of test fuels

Test Fuel	Viscosity at 25°C (Centi-poise)	Specific gravity at 25°C	Cetane number	Calorific value (kJ/kg)
Diesel	12.5	0.84	55	42000
CRBO	80	0.91	45	39000

Few definitions of IC engine parameters:

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.

$$BTE = \frac{BP}{m_f \times c_v}$$

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 $V_a = \sqrt{2gh_a}$; Actual discharge of air = $c_d a \sqrt{2gh_a}$, where a = area of an orifice flow meter, c_d = coefficient of discharge.

3. Results and Discussion

This section contains performance parameters, exhaust emissions and combustion characteristics.

3.1. Performance Parameters

Figure 3 indicates that brake thermal efficiency (BTE) increased up to 80% of the full load (4.2 bar, BMEP at full load = 5.3 bar) due to increase of fuel conversion efficiency and beyond that load, it decreased due to reduction of air fuel ratios [27] and volumetric efficiency. CE with CRBO showed the deterioration in the performance for entire load range when compared with the pure diesel operation on CE at recommended injection timing. Although carbon accumulations [27] on the nozzle tip might play a partial role for the general trends observed, the difference of viscosity between the diesel and CRBO provided a possible explanation for the deterioration in the performance of the engine with CRBO operation. In addition, less air entrainment by the fuel spray suggested that the fuel spray penetration might increase and resulted in more fuel reaching the combustion chamber walls. Furthermore, droplet mean diameters (expressed as Sauter mean) were larger [15] for CRBO leading to reduce the rate of heat release [38] as compared with die-

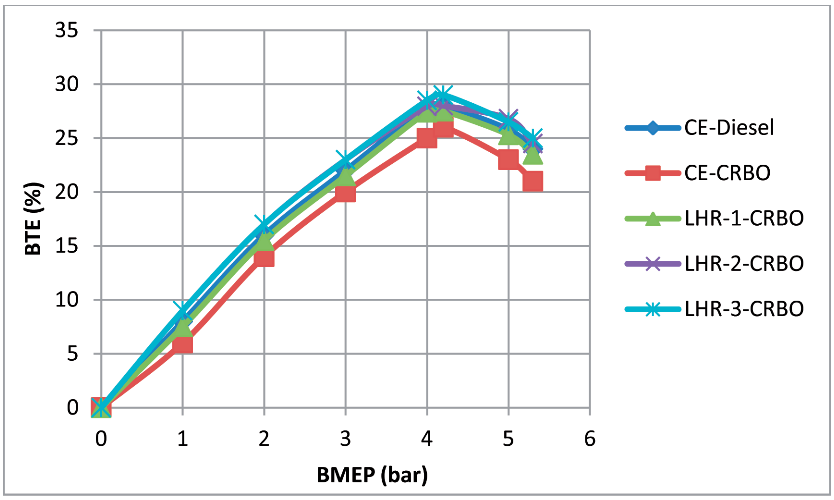


Fig. 3. Variation of BTE with BMEP in different versions of the engine with test fuels operation at an injector opening pressure of 190 bar

sel fuel. This also contributed the higher ignition (chemical) delay of the CRBO due to lower cetane number. According to the qualitative image of the combustion under the CRBO operation with CE, the lower BTE was attributed to the relatively retarded and lower heat release rates [27].

Curves from the same Figure indicate that LHR-1 and LHR-2 combustion chambers of the engine showed compatible performance, while LHR-3 combustion chamber showed improved performance for entire load range compared with CE with pure diesel 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 CRBO in the hot environment of the combustion chamber of LHR improved heat release rates [27] and efficient energy utilization. LHR-3 combustion chamber showed improved performance when compared with LHR-2 and LHR-3 combustion chambers of the engine. This was due to hot environment provided by LHR-3 combustion chamber which caused efficient burning of high viscous fuel.

The variation of injection opening pressure was carried out with a nozzle-testing device. Performance of the engine was evaluated with varying injector opening pressure from 190 to 270 bar for CE and different types of combustion chambers.

From Table 4, it is evident that with pure diesel operation, peak BTE decreased by 4% with LHR-3 combustion chamber in comparison with CE. It was expected that high combustion temperatures would be prevalent in LHR-3 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.

Table 4.

Data of Peak BTE

Peak Brake Thermal Efficiency (%)						
Engine Version	Pure Diesel operation			CRBO operation		
	Injector opening pressure (bar)			Injector opening pressure (bar)		
	190	230	270	190	230	270
CE	28	29	30	26	27	28
LHR-1	28.5	29	29.5	27.5	28.5	29.5
LHR-2	29	30	30.5	28	29	30
LHR-3	27	27.5	28	29	30	31

From the same Table, it is observed that with vegetable oil operation, peak BTE increased by 11% with LHR-3 combustion chamber in comparison with CE. This is due to improved evaporation rate of CRBO with the hot environment provided by LHR-3 combustion chamber, as CRBO has high duration of combustion and high viscous fuel.

Peak BTE increased with increase of injector opening pressure with both test fuels with different configurations of the combustion chambers. Poor performance at lower injector opening pressure indicated slow mixing probably because of insufficient spray penetration with consequent slow mixing during diffusion burning.

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. Hence an optimum mean diameter of the droplet should be attempted as a compromise.

LHR-3 combustion chamber registered higher value of peak BTE with CRBO operation when compared with other configurations of the combustion chambers.

From the Table, it is observed that with pure diesel operation, brake specific energy consumption (BSEC) increased by 8% with LHR-3 combustion chamber in comparison with CE. This was because of reduction of ignition delay. 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.

From the Table 5, it is observed that with vegetable oil operation, brake specific energy consumption (BSEC) decreased by 25% with LHR-3 combustion chamber in comparison with CE. BSEC was higher with conventional engine due to due to higher viscosity, poor volatility and reduction in heating value of vegetable oil lead to their poor atomization and combustion characteristics. BSEC improved with LHR-3 combustion chamber with lower substitution of energy in terms of mass flow rate.

It is also observed from the same Table, BSEC at full load operation decreased with increase of injector opening pressure in different combustion chambers with different test fuels. This was due to increase of air entrainment [27] in fuel spray giving lower BSEC.

LHR-3 combustion chamber gave lower BSEC when compared with other versions of LHR combustion chamber because of provision of higher degree of insulation and energy was effectively utilized in converting heat into work.

Table 5.

Data of Peak BSEC at full load operation

Brake Specific Energy Consumption (kW/kW)						
Type of combustion chamber	Pure Diesel operation			CRBO operation		
	Injector opening pressure (bar)			Injector opening pressure (bar)		
	190	230	270	190	230	270
CE	4.0	3.92	3.84	5.2	5.0	4.8
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	3.90	3.86	3.82

Figure 4 indicates that CE with CRBO operation at the recommended injection timing recorded higher value of exhaust gas temperature (EGT) at all loads when compared with CE with pure diesel operation. Though the calorific value (or heat of combustion) of fossil diesel is more than those of vegetable oil, density of the vegetable oil was higher. Therefore, greater amount of heat was released in the combustion chamber leading to higher exhaust gas temperature. Also, there was an advanced combustion of diesel due to its cetane number (55), when compared to vegetable oil (45). Therefore, the heat released [38] by vegetable oil combustion was late by few degrees and thus more heat gets exhausted.

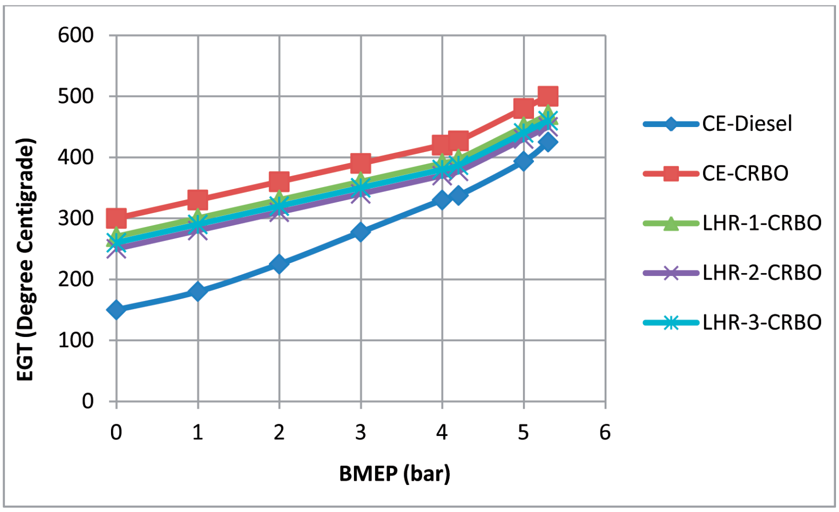


Fig. 4. Variation of EGT with BMEP in different versions of the engine with CRBO operation at an injector opening pressure of 190 bar

LHR combustion chambers recorded lower value of EGT when compared with CE with CRBO operation. This was due to reduction of ignition delay in the hot environment with the provision of the insulation in LHR combustion chamber, which caused the gases expand in the cylinder giving higher work output and lower heat rejection

From Table, it was observed that exhaust gas temperature with LHR-3 combustion chamber with pure diesel operation was higher by 75°C when compared with CE.

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

From the same Table, it is noticed that exhaust gas temperature with LHR-3 combustion chamber with vegetable oil operation decreased by 40°C, in comparison with CE.

From Table 6, is observed that the value of exhaust gas temperature decreased with increase in injector opening pressure with test fuels. This was due to improved spray characteristics of the fuel with improved air fuel ratios [27] with increase of injector opening pressure.

Table 6.

Data of Exhaust Gas Temperature at full load operation

Engine Version	Pure Diesel operation			CRBO operation		
	Injector opening pressure (bar)			Injector opening pressure (bar)		
	190	230	270	190	230	270
CE	425	410	395	500	475	450
LHR-1	450	425	400	470	450	430
LHR-2	475	460	445	450	420	390
LHR-3	500	480	460	460	430	400

It is observed from Fig. 5 that coolant load (CL) increased at all loads with CE with vegetable oil operation when compared with CE with diesel operation. This was because of un-burnt fuel concentration at the walls of the combustion chambers.

Coolant load was lower with different configurations of combustion chambers with CRBO operation when compared with CE with pure diesel operation. This was due to the provision of insulation in the path of coolant.

As it is obvious, LHR-3 combustion chamber registered lower value of coolant loss, as it was provided with high degree of insulation.

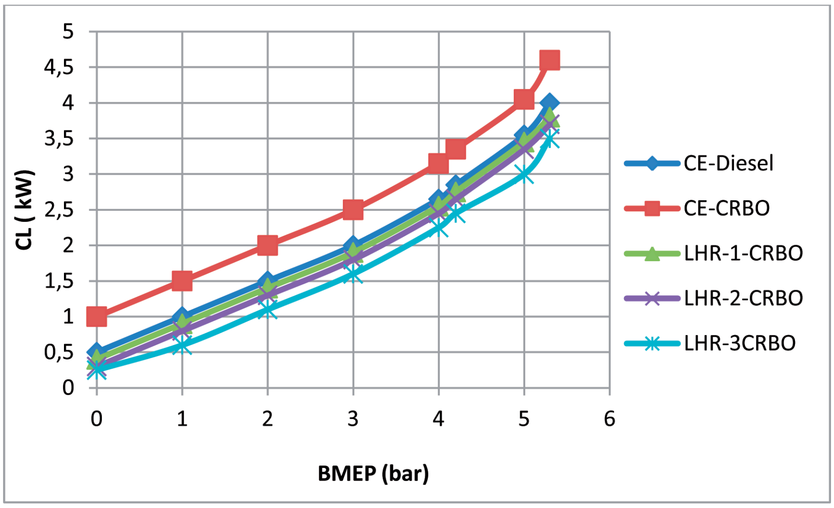


Fig. 5. Variation of coolant load (CL) with BMEP in different versions of the engine with CRBO operation at an injector opening pressure of 190 bar

With pure diesel operation, LHR-3 combustion chamber decreased coolant load by 5% at peak load operation in comparison with CE.

With vegetable oil operation, LHR-3 combustion chamber of decreased coolant load by 24% at peak load operation, when compared with CE.

From Table 7, with increase of injector opening pressure, coolant load increased marginally in CE and decreased in different versions of combustion chambers with test fuels. This was due to the fact with an increase of injector opening pressure with CE, nominal fuel spray velocity increased, resulting in better fuel-air mixing with which gas temperatures increased. The reduction of coolant load in different LHR combustion chambers was not only due to the provision of the insulation but also it was due to better fuel spray characteristics, increase of air-fuel ratios causing decrease of gas temperatures and hence the coolant load.

Table 7.

Data of coolant load at full load operation

Coolant Load (kW)						
Engine Version	Pure Diesel operation			CRBO operation		
	Injector opening pressure (bar)			Injector opening pressure (bar)		
	190	230	270	190	230	270
CE	4.0	4.2	4.4	4.6	4.8	5.0
LHR-1	4.1	3.6	3.1	3.8	3.6	3.4
LHR-2	4.5	4.0	3.40	3.7	3.5	3.3
LHR-3	3.8	3.7	3.2	3.5	3.3	3.2

Volumetric efficiency depends on density of the charge which in turn depends on temperature of combustion chamber wall. Figure 6 indicates that at the recommended injection timing, volumetric efficiency with vegetable oil operation decreased at all loads, when compared with pure diesel operation. This was due to increase of combustion chamber wall temperatures with vegetable oil operation due to accumulation of un-burnt fuel concentration with vegetable oil operation. This was also because of increase of combustion chamber wall temperature as exhaust gas temperatures increased with vegetable oil operation in comparison with pure diesel operation.

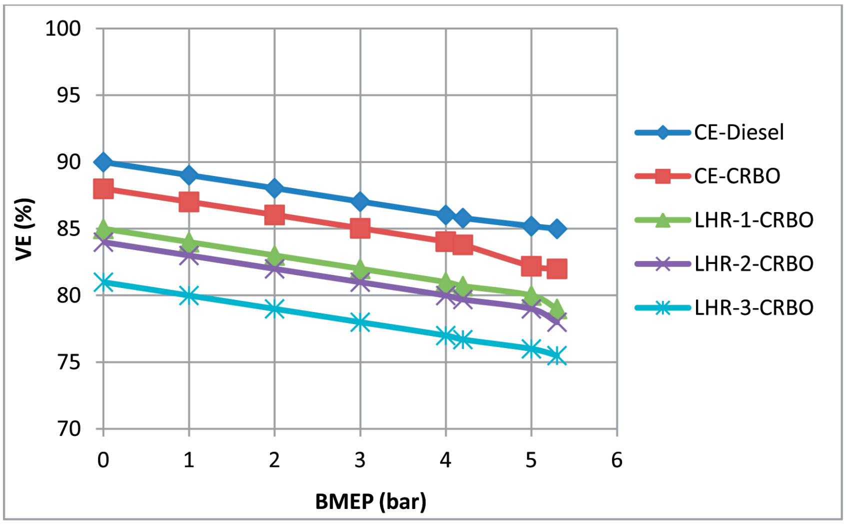


Fig. 6. Variation of volumetric efficiency (VE) with BMEP in different versions of the engine with CRBO operation at an injector opening pressure of 190 bar

Volumetric efficiency in LHR combustion chamber decreased at all loads with vegetable oil operation when compared with conventional engine on CE. 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 [26] also observed the similar trends in the value of volumetric efficiency.

From Table 8, 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

With pure diesel operation, volumetric efficiency decreased by 12% with LHR-3 combustion chamber, in comparison with CE.

With vegetable operation, volumetric efficiency decreased by 8% with LHR-3 combustion chamber in comparison with CE.

Table 8.

Data of volumetric efficiency at full load

Volumetric Efficiency (%)						
Engine Version	Pure Diesel operation			CRBO operation		
	Injector opening pressure (bar)			Injector opening pressure (bar)		
	190	230	270	190	230	270
CE	85	86	87	82	83	84
LHR-1	80	82	84	79	80	81
LHR-2	78	80	82	78	79	80
LHR-3	75	76	77	75.5	76.5	77.5

3.2. Exhaust Emissions

Curves from Fig. 7 indicate that the value of smoke intensity increased from no load to full load in both versions of the engine wit test fuels. During the first part, smoke level was more or less constant, as there was always excess air present. However, in the higher load range, there was an abrupt rise in smoke levels due to less available oxygen, causing the decrease of air-fuel ratio, leading to incomplete combustion, producing more soot density.

It is also observed from the same Figure that smoke levels were higher with CE at all loads with CRBO operation when compared with pure diesel operation on CE. This is due to the higher value of the ratio of C/H of CRBO (0.7) when compared with pure diesel (0.45). The increase of smoke levels was also due to decrease of air-fuel ratios [27] and volumetric efficiency with CRBO compared with pure diesel operation. Smoke levels are related to the density of the fuel. CRBO has higher smoke levels due to its high density compared with diesel fuels.

LHR combustion chambers with vegetable oil operation decreased smoke levels due to efficient combustion, with improved air fuel ratios [27] and less amount of fuel accumulation on the hot combustion chamber walls of the LHR combustion chamber compared with CE. LHR-3 combustion chamber

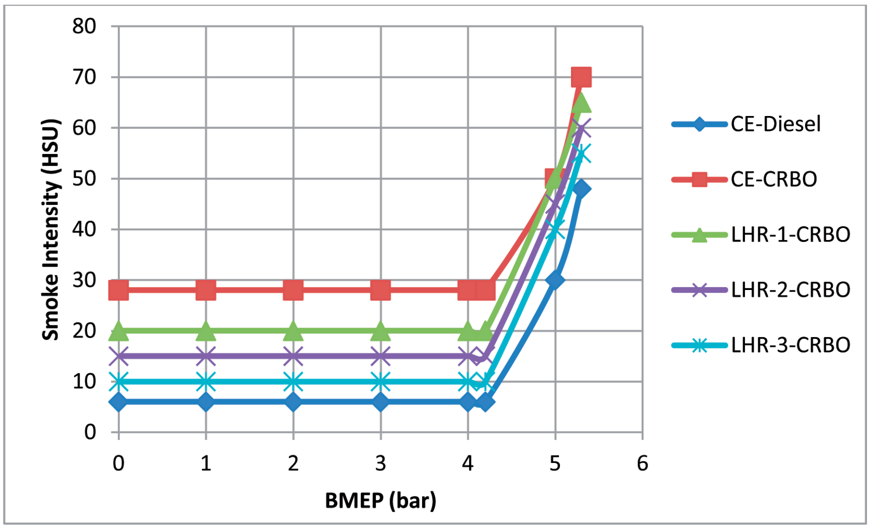


Fig. 7. Variation of smoke levels with BMEP in different versions of the engine with CRBO operation at an injector opening pressure of 190 bar

registered lower value of smoke levels in comparison with other versions of combustion chambers due to efficient combustion in LHR-3 engine.

With pure diesel operation, LHR-3 combustion chamber increased smoke levels by 25% when compared with CE as noticed from the Table 9.

Table 9.

Data of smoke levels at full load

Smoke Levels (Hartridge Smoke Unit)						
Engine Version	Pure Diesel operation			CRBO operation		
	Injector opening pressure (bar)			Injector opening pressure (bar)		
	190	230	270	190	230	270
CE	48	38	34	70	65	63
LHR-1	52	45	40	65	60	55
LHR-2	55	50	45	60	55	50
LHR-3	60	55	50	55	45	40

With pure diesel operation, smoke levels were higher at full load in LHR-3 engine when compared with other versions of the LHR engine. This was due to fuel cracking at higher temperatures in LHR-3 combustion chamber. This was also due to the decreased oxidation rate of soot in relation to soot formation. Higher surface temperatures of LHR-3 combustion chamber aided this process. LHR-3 combustion chamber shorten the delay period, which increases thermal cracking, responsible for soot formation. Higher temperature of LHR-3 combustion chamber produced increased rates of both soot formation and burn up. The reduction in volumetric efficiencies air-fuel ratios [27] were responsible factors for increasing smoke levels in LHR-3 combustion chamber near full load operation of the engine. As expected, smoke increased in LHR-2 combustion chamber because of higher temperatures and improper utilization of the fuel consequent upon predominant diffusion combustion. LHR-1 combustion chamber registered marginally higher value of smoke intensity when compared with CE. It followed the same trend as followed by LHR-2 combustion chamber.

With pure diesel operation, LHR-3 combustion chamber increased smoke levels by 25% when compared with CE.

With vegetable oil operation, LHR-3 combustion chamber decreased smoke levels by 22% when compared with CE. This showed that combustion chamber of high degree of insulation decreased smoke levels effectively with vegetable oil operation.

Smoke levels decreased with increase of injector opening pressure with test fuels. This was due to improvement in the fuel spray characteristics at higher injector opening pressure causing lower smoke levels.

Temperature and availability of oxygen are responsible factors for formation of NOx levels. Figure 8 indicates that NOx concentrations raised steadily as the fuel/air ratio increased with increasing BMEP, at constant injection timing with CRBO operation. From the Figure, it is seen that NOx levels were marginally higher with CE while they were drastically higher in

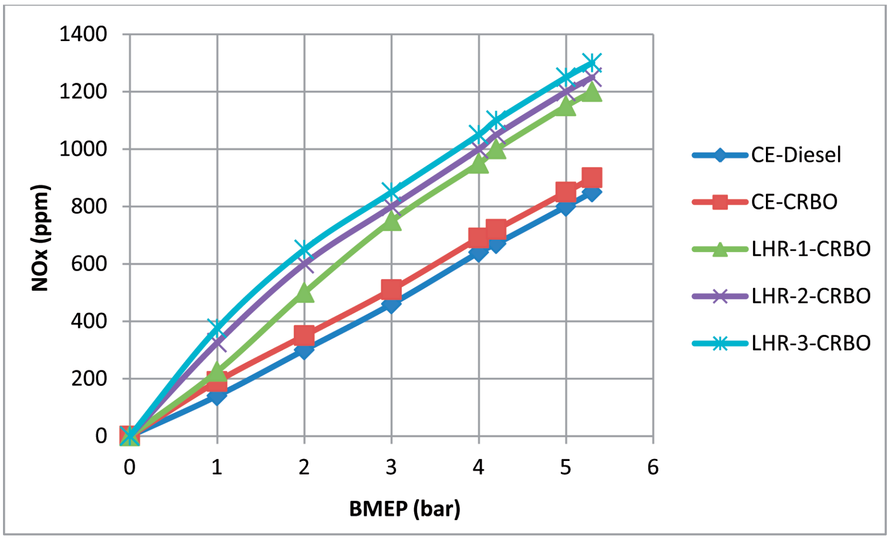


Fig. 8. Variation of NOx levels with BMEP with test fuels in different versions of the engine with CRBO operation at an injector opening pressure of 190 bar

different LHR combustion chambers with CRBO operation, when compared with diesel operation. This was due to lower heat release rate because of high duration of combustion causing lower gas temperatures with the CRBO operation on CE, which caused marginally higher NOx levels.

NOx levels were higher with LHR-3 combustion chamber when compared with other versions of combustion chamber. This was due to high degree of insulation provided with combustion chamber of LHR-3.

From the Table 10, it is observed that that increase of injector opening pressure increased NOx emissions in CE and decreased the same in different versions of LHR combustion chambers with test fuels.

Table 10.

Data of NOx emissions at full load

NOx Levels (ppm)						
Engine Version	Pure Diesel operation			CRBO oil operation		
	Injector opening pressure (bar)			Injector opening pressure (bar)		
	190	230	270	190	230	270
CE	850	900	950	900	950	1000
LHR-1	1100	1050	1000	1200	1150	1100
LHR-2	1150	1100	1050	1250	1200	1150
LHR-3	1200	1150	1100	1300	1250	1200

With the increase of injection pressure, fuel droplets penetrate [38] and find oxygen counterpart easily. Turbulence of the fuel spray increased the spread of the droplets thus leading to increase of gas temperatures in CE. As seen from the Table 4, that peak brake thermal efficiency increased as injector opening pressure increased. The increase in peak brake thermal efficiency was proportional to increase in injector opening pressure. Normally, improved combustion causes higher peak brake thermal efficiency due to higher combustion chamber pressure (Table 11), temperature and leads to higher NOx formation. This is an evident proof of enhanced spray characteristics, thus improving fuel air mixture preparation and evaporation [38] process.

Different versions of LHR combustion chambers decreased NOx levels. This was due to decrease of gas temperatures with increase of injection pressure with improved [27] air fuel ratios.

With pure diesel operation, LHR-3 combustion chamber increased NOx levels by 41% when compared with CE.

With vegetable oil operation, LHR-3 combustion chamber increased NOx levels by 44% when compared with CE. This showed that combustion chamber of LHR-3 drastically increased NOx levels.

3.3. Combustion Characteristics

From Table 11, it is observed that peak pressures (PP) were lower in different versions of the combustion chambers with pure diesel operation in comparison with CE. This was because combustion chamber of LHR engine exhibited higher temperatures of combustion chamber walls leading to continuation of combustion, giving peak pressures away from TDC.

With vegetable oil operation, peak pressures were lower in conventional engine when compared with pure diesel operation on CE. This was due to increase of ignition delay, as CRBO requires large duration of combustion, mean while the piston started making downward motion thus increasing volume when the combustion takes place in CE.

Peak pressures were higher with different configurations of LHR combustion chambers as they increased the mass-burning rate of the fuel in the hot environment leading to produce higher peak pressures. The advantage of using LHR combustion chambers for vegetable oil operation was obvious as it could burn high viscous fuels.

Table 11.
Data of Peak Pressure at full load operation

PP (bar)						
Engine Version	Pure Diesel operation			CRBO operation		
	Injector opening pressure (bar)			Injector opening pressure (bar)		
	190	230	270	190	230	270
CE	50.4	51.7	53.5	47.9	48.1	48.8
LHR-1	49.4	52.2	54.3	57.8	58.8	60.1
LHR-2	48.1	51.1	53.0	59.8	60.3	61.1
LHR-3	46.1	48.4	51.1	60.8	61.4	62.1

The value of PP increased with the increase of injector opening pressures in CE and different types of combustion chamber of LHR. This may be due to smaller sauter mean diameter [37] shorter breakup length, better dispersion, and better spray and atomization characteristics. This improves combustion rate in the premixed combustion phase.

Table 12 denotes that maximum rate of pressure rise (MRPR) was highest for normal diesel followed by crude vegetable oil. With vegetable oil operation, as injector opening pressure increased, spray characteristic improved and in turn burned fuel increased again and in turn combustion rate increased in the premixed combustion phase [38] The trend followed by MRPR was similar to PP in different versions of the combustion chambers as shown in Table 10.

Table 12.
Data of Maximum Rate of Pressure Rise (MRPR) at full load operation

MRPR (bar/deg)						
Engine Version	Pure Diesel operation			CRBO operation		
	Injector opening pressure (bar)			Injector opening pressure (bar)		
	190	230	270	190	230	270
CE	5.4	5.7	6.0	2.6	2.8	3.0
LHR-1	3.0	3.3	3.4	3.6	3.8	4.0
LHR-2	2.9	3.2	3.3	3.8	4.0	4.2
LHR-3	2.7	2.8	2.9	4.0	4.2	4.4

From Table 13, it is evident that the value of time of occurrence of peak pressure (TOPP) decreased with the increase of injector opening pressure in different versions of the engine, with vegetable oil operation, from the Table, it can be noticed that the value of TOPP decreased (shifted towards TDC) with the increasing of injector opening pressure in all versions of the engine. This was confirmed that different versions of LHR combustion chambers showed improvement in performance, when the injection pressures increased. TOPP was higher with vegetable oil operation on CE when compared with pure diesel operation. This was due to higher ignition delay with vegetable oil

Table 13.
Data of Time of occurrence of Peak Pressure (TOPP) at full load operation

TOPP (bar/deg)						
Engine Version	Pure Diesel operation			CRBO operation		
	Injector opening pressure (bar)			Injector opening pressure (bar)		
	190	230	270	190	230	270
CE	9	9	8	11	11	11
LHR-1	9	9	9	10	10	9
LHR-2	10	10	9	10	9	9
LHR-3	11	10	9	9	9	8

operation, when compared with 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 with pure diesel operation on CE.

4. Conclusions

Comparing LHR-3 Combustion Chamber with CE on vegetable oil operation:

1. Peak BTE increased by 11%.
2. Brake specific energy consumption (BSEC) decreased by 25% at peak load operation.
3. Exhaust gas temperature decreased by 40°C at peak load operation.
4. LHR-3 combustion chamber of decreased coolant load by 24% at peak load operation, when compared with CE.
5. Volumetric efficiency decreased by 8% at peak load operation.
6. Smoke levels decreased by 22% at peak load operation.
7. NOx levels increased levels by 44% at peak load operation.
8. Peak pressures increased by 27% at peak load operation.
9. Maximum rate of pressure rise increased by 54% at peak load operation.

Performance parameters exhaust emissions and combustion characteristics improved with increase of injector opening pressure.

However, performance deteriorated with pure diesel with different versions of LHR combustion chambers, in comparison with CE.

5. Research Findings and Future Scope of Work

Vegetable oil operation on three different versions of LHR combustion chambers was performed with varied injector opening pressure.

LHR combustion chambers increased NOx emissions drastically with vegetable oil operation. Hence further work on reduction of NOx levels is necessary.

Performance can be improved further with varied injection timing and compression ratio.

Acknowledgments

Authors thank authorities of Chaitanya Bharathi Institute of Technology, Hyderabad for providing facilities for carrying out this research work.

Financial assistance provided by All India Council for Technical Education (AICTE), New Delhi, was greatly acknowledged.

Manuscript received by Editorial Board, September 22, 2012;
final version, October 09, 2014.

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Porównanie osiągów różnych wersji komór spalania o małych stratach ciepła przy wykorzystaniu surowego oleju roślinnego z otrąb ryżowych

Streszczenie

Jak wiadomo, oleje roślinne są obiecującym substytutem paliw ropopochodnych, ponieważ ich właściwości są podobne do oleju dieslowskiego, są odnawialne i łatwe do wyprodukowania. Niemniej, surowe oleje roślinne wykazują wady, takie jak wysoka lepkość i mała lotność, co wymaga komory spalania o małych stratach ciepła, której istotnymi cechami są m.in. wyższa temperatura robocza, maksymalne wydzielanie ciepła i zdolność do wykorzystania paliwa o mniejszej wartości kalorycznej (CV). Przeprowadzono eksperymenty mające na celu ocenę osiągów silnika z różnymi komorami spalania o małych stratach ciepła (LHR), takich jak głowica cylindra o pokryciu ceramicznym (LHR-1), tłok izolowany szczeliną powietrzną z denkiem ze stopu Superni (superstop niklu) i tuleją cylindra z wkładką z Superni izolowaną szczeliną powietrzną (LHR-2) oraz głowica cylindra z pokryciem ceramicznym, tłok i tuleja cylindra izolowane szczelinami powietrznymi (LHR-3). Badania prowadzono przy normalnej temperaturze oleju roślinnego (surowy olej z otrąb ryżowych, CRBO) i zmiennym ciśnieniu w otworze wtryskiwacza. Parametry osiągów silnika (użyteczna sprawność termiczna, użyteczny współczynnik zużycia energii, temperatura gazu wydychanego, obciążenie obiegiem chłodziwa i współczynnik napełnienia) oraz emisje wydechowe [poziomy dymu i tlenków azotu, NOx] zostały wyznaczone przy różnych wartościach średniego użytecznego ciśnienia w silniku. Charakterystyki spalania [ciśnienie szczytowe, czas występowania ciśnienia szczytowego, maksymalna szybkość wzrostu ciśnienia] zostały wyznaczone w warunkach pracy silnika z pełnym obciążeniem.

W porównaniu z silnikiem napędzanym olejem diesla, silnik konwencjonalny (CE) wykazał podobne osiągi przy pracy z olejem roślinnym (CRBO), a w komorach spalania o małych stratach ciepła (LHR) uzyskano lepsze osiągi przy zalecanym kącie wtrysku 27°bTDC (przed górnym punktem zwrotnym) i zalecanym ciśnieniu w otworze wtryskiwacza równym 190 bar. Szczytowa użyteczna sprawność cieplna wzrosła relatywnie o 7%, użyteczny współczynnik zużycia energii zmalał o 3,5% przy pracy z pełnym obciążeniem, poziomy dymu przy pełnym obciążeniu zmalały o 11%, a poziom tlenków NOx wzrósł relatywnie o 58% w przypadku komory spalania typu LHR-3 napędzanej olejem roślinnym CBRO przy ciśnieniu w otworze wtryskiwacza 190 bar, w porównaniu z parametrami uzyskanymi przy pracy z czystym olejem diesla.