Comparative Investigations on the Pollution Levels of Tobacco Seed Oil Biodiesel in A Low Heat Rejection Diesel Engine

N. Janardhan[1] and M. V. S. Murali Krishna[2]
[1,2] Mechanical Engineering Department, Chaitanya Bharathi Institute of Technology,
Gandipet, Hyderabad-500 075. Telangana State, India,

Abstract: -
Aim: To determine the exhaust emissions of a single cylinder, four–stroke, water cooled, 3.68 kW direct–injection diesel engine at a speed of 1500 rpm with different versions of the combustion chamber with tobacco seed oil biodiesel and to make comparative studies with data of pure diesel operation working on similar conditions.
Study Design: Different versions of the low heat rejection (LHR) combustion chamber such as LHR–1 (ceramic coated cylinder head), LHR–2 (air gap insulated piston and air gap insulated liner) and LHR–3 (ceramic coated cylinder head, air gap insulated piston and air gap insulated liner); Various injector opening pressures such as 190 bar, 230 bar and 270 bar.
Methodology; Exhaust emissions of particulate emissions and nitrogen oxide levels were measured with AVL Smoke meter and Netel Chromatograph NOx analyzer at different values of BMEP of the engine,
Brief Results: At recommended injection timing of 27^{o}bTDC and recommended injector opening pressure of 190 bar, conventional engine (CE) showed comparable performance, while different versions of LHR combustion chamber showed reduction in pollution levels with biodiesel operation, when compared with conventional engine with pure diesel operation (standard diesel operation).

Keywords: LHR combustion chamber; Vegetable oil; Biodiesel; LHR, Fuel Performance; Exhaust Emissions; .

1.INTRODUCTION

In the context of depletion of fossil fuels, the search for alternative fuels has become pertinent. Vegetable oils are promising substitutes for diesel fuels as they are renewable in nature and their properties are similar to those of diesel fuel. Rudolph Diesel the inventor of the diesel engine that bears his name experimented with fuels ranging from powdered coal to peanut oil and hinted that vegetable oil would be the future fuel. Several researchers experimented the use of vegetable oils as fuel on conventional engines and reported that the performance was poor, citing the problems of high viscosity and low volatility [1–5]. 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 presence of the fatty acid components greatly affects the viscosity of the oil, which in turn affect the wear of engine components, oil consumption, fuel economy, hot starting, cold starting, low temperature pumpability, noise and shear stability. The limitation of unsaturated fatty acids is necessary due to the fact heating higher unsaturated fatty acids results in polymerization of glycerides. This can leads to formation of deposits or to deterioration of lubricating oil. The different fatty acids present in the vegetable oil are palmic, steric, lingoceric, oleic, linoleic and fatty acids [1]. These fatty acids increase particulate emissions and also lead to incomplete combustion due to improper air–fuel mixing.

The above mentioned problems were solved to some extent by converting crude vegetable oil into biodiesel by the process of esterifiction, 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. These biodiesels have lower viscosity, density, molecular weight and ratio of carbon to hydrogen than crude vegetable oils.

Several researchers conducted experiments with biodiesel with four–stroke, medium speed, direct–injection diesel engine and concluded that at manufacturer's recommended injection timing, brake thermal efficiency marginally improved, particulate emissions marginally decreased and NO_x levels drastically increased with biodiesel operation when compared with pure diesel operation.[6–9]. Comparative studies were made between crude waste fried vegetable oil operation and its biodiesel with single cylinder, four-stroke, water cooled direct–injection diesel engine of 3. 68 kW at a speed of 1500 rpm and compression ratio of 16:1 with varied injection timing and injector opening pressure [19]. The optimum injection timing was found out to be 31^o bTDC with biodiesel, while it was 32^o bTDC with crude vegetable oil. It was reported from their investigations that at optimum injection timings, brake thermal efficiency increased by 5–8%, particulate emissions were comparable, NO_x levels increased by 35–40% with biodiesel operation, while brake thermal efficiency was comparable, particulate emissions were comparable and NO_x levels marginally increased by 5–10% with crude vegetable oil, when compared with pure diesel operation at manufacturer's recommended injection timing of 27^{o}bTDC.

Increased injector opening pressure may also result in efficient combustion in compression ignition engine. It has a significance effect on the performance and formation of pollutants inside the direct injection diesel engine combustion. it was reported that performance of the engine improved with an increase of injector opening pressure. [4–5]. It marginally increased NO_x levels by 15–20% and decreased particulate matter emissions by 15–20% with vegetable oil operation with increase of injector opening pressure by 80 bar.

The drawbacks (high viscosity and low volatility) of the vegetable oils call for engine with LHR combustion chamber. The concept of engine with LHR combustion chamber is to provide thermal insulation in the path of heat flow to the coolant so as to increase thermal efficiency of the engine. Hence classification of the LHR combustion chambers is made on basis of the degree of insulation. Engine with LHR-1 combustion chamber consisted of ceramic coatings on engine components of piston, liner and cylinder head, while LHR–2 combustion chamber contained an air gap insulation provided for piston and liner. The combination of LHR–1 and LHR–2 combustion chambers resulted in engine with LHR–3 combustion chamber.

Investigations were carried out with single cylinder, four–stroke, water cooled, 3.68 kW diesel engine at a speed of 1500 rpm with LHR–1 combustion chamber with ceramic coating on inside portion of cylinder head with biodiesel operation with varied injector opening pressure and injection timing. [11–14]. Thermal efficiency marginally increased by 2–6%, particulate emissions decreased by 15–20% and nitrogen oxide levels increased by 20–30% with engine with LHR–1 combustion chamber, when compared with pure diesel operation on conventional engine. Advanced injection timing and increase of injector opening pressure improved performance and reduced pollution levels with engine with LHR–1 combustion chamber.

In case of air gap insulation, though effective insulation was provided by an air gap, the welded, bolted and stud design employed by the researchers in assembling the crown and body of the piston could not provide complete sealing of air and gases in the air gap of the piston.[15]. The top portion of the piston, crown made of low thermal conductivity material superni–90 (an alloy of nickel) was screwed to aluminum body of the piston, providing a 3mm air gap in between the crown and the body of the piston by inserting a gasket made of superni–90 in between them [16]. The optimum thickness of air gap in the air gap piston was found to be 3 mm for improved performance of the engine with superni inserts with diesel as fuel [16]. The air gap insulated piston with superni–90 crown with an injection timing of 27° bTDC gave lower brake specific fuel consumption (BSFC) up to 80% of full load in comparison with the conventional piston. Beyond 80% of full load BSFC for the insulated piston increased over and above that of the conventional piston. The drawback of higher BSFC at full load with air gap piston disappeared with advanced injection timing of 29.5° bTDC. The air gap insulated piston engine with superni–90 crown and 3 mm air gap at an injection timing of 29.5° bTDC with diesel operation decreased BSFC by 4% at full load and 12% at part loads in comparison with the conventional engine operating at 27° bTDC [17-20].

Experiments were conducted on single cylinder four–stroke, direct– injection diesel engine of 3.68 kW at a speed of 1500 rpm with a compression ratio of 16:1 with LHR–2 combustion chamber consisting of air gap insulated piston with low thermal conductivity material superni (an alloy of nickel) crown assembled with body of the piston by means of threads and air gap insulated liner with superni insert with biodiesel operation with varied injector opening pressure and injection timing [17–19]. Thermal efficiency increased by 5–12%, particulate emissions decreased by 20–25% and nitrogen oxide levels increased by 35–45% with engine with LHR–2 combustion chamber, when compared with pure diesel operation on conventional engine. Advanced injection timing and increase of injector opening pressure improved performance and reduced pollution levels with engine with LHR–2 combustion chamber.

Studies were made with engine as mentioned in Ref 17-19 with LHR–3 combustion chamber consisting of air gap insulated piston with low thermal conductivity material superni (an alloy of nickel) crown assembled with body of the piston by means of threads, air gap insulated liner with superni insert and ceramic coated cylinder head with biodiesel operation with varied injector opening pressure and injection timing [20–22]. Thermal efficiency increased by 12–15%, particulate emissions decreased by 20–25% and nitrogen oxide levels increased by 45–55% with engine with LHR–3 combustion chamber, when compared with pure diesel operation on conventional engine. Advanced injection timing and increase of injector opening pressure improved performance and reduced pollution levels with engine with LHR–3 combustion chamber .

Comparative studies were made for LHR–1, LHR–2 and LHR–3 combustion chambers with biodiesel operation and reported that performance improved with increase in degree of insulation. [23]. However, comparative studies were not made with respect to diesel fuel operation on similar conditions.

The present paper attempted the comparative studies with different versions of the insulated combustion chambers with tobacco seed oil based biodiesel at normal temperature with varied injector opening pressure. Data was compared with the data of diesel operation on similar working conditions.

2.MATERIALS AND METHODS

2.1 Preparation of Biodiesel

Tobacco seeds, a by–product of leaves production contain oil in a wide range of 33-40% of the total seed weight. It contains fatty acids of 65% by weight. This is used in soap production, as well as in paint and varnish industries. Recent studies have suggested that tobacco seed oil as a renewable source of energy may be an appropriate substitute for diesel fuel in both crude form and biodiesel form. [4].

Since crude vegetable oil contains up to 65 % (wt.) free fatty acids and has high viscosity, it is to be chemically converted in to biodiesel [24]. The chemical conversion of esterification reduced viscosity four fold. The methyl ester was produced by chemically reacting the crude vegetable oil with methanol in the presence of a catalyst (KOH). A two–stage process was used for the esterification of the crude vegetable oil [24]. The first stage (acid–catalyzed) of the process was used to reduce the free fatty acids (FFA) content in tobacco seed oil by esterification with methanol (99% pure) and acid catalyst (sulfuric acid–98%

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pure) in one hour time of reaction at 55°C. In the second stage (alkali–catalyzed), the triglyceride portion of the tobacco seed oil reacts with methanol and base catalyst (sodium hydroxide–99% pure), in one hour time of reaction at 65°C, to form methyl ester and glycerol. To remove un-reacted methoxide present in raw methyl ester, it was purified by the process of water washing with air-bubbling. The methyl ester (or biodiesel) produced from crude tobacco seed oil is known as tobacco seed oil based biodiesel. The properties of the test fuels along with diesel fuel used in the experiment were presented in Table-1.

Table 1
Properties of Test Fuels

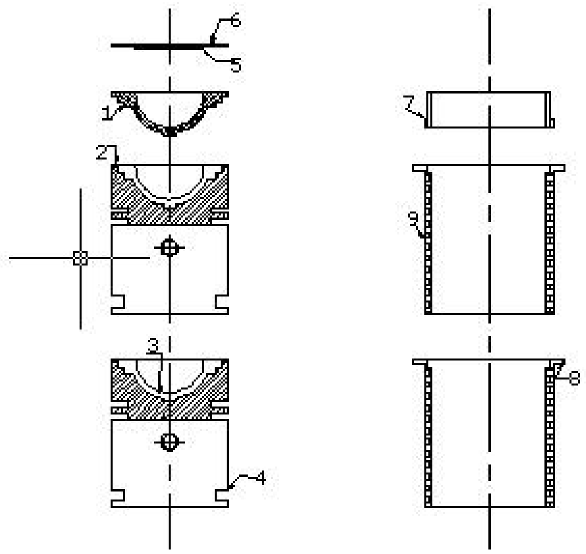
Test Fuel	Viscosity at 40°C (centi-Poise)	Specific gravity at 25°C	Cetane number	Lower Calorific value (kJ/kg)
Diesel	12.0	0.84	55	42000
Tobacco Seed Oil (crude)	24.0	0.91	45	38438
ASTM Standard	ASTM D 445	ASTM D 4809	ASTM D 613	ASTM D 7314

2.2 Fabrication of Insulated Combustion Chambers:

Engine with LHR–1 combustion chamber contained ceramic coated cylinder head as mentioned in Ref. [11–14]. Engine with LHR–2 combustion chamber contained air gap insulated piston and air gap insulated liner given in Ref [17–19]. Engine with LHR–3 combustion chamber consisted of air gap piston, air gap liner and ceramic coated cylinder head as mentioned in Ref [20–22].

Fig.1 shows assembly details of engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head (LHR–3 combustion chamber).

The top portion of the piston, 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. 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 by means of plasma coating technique. The combination of low thermal conductivity materials of air and superni–90 provide sufficient insulation for heat flow to the coolant thus resulted in LHR combustion chamber.

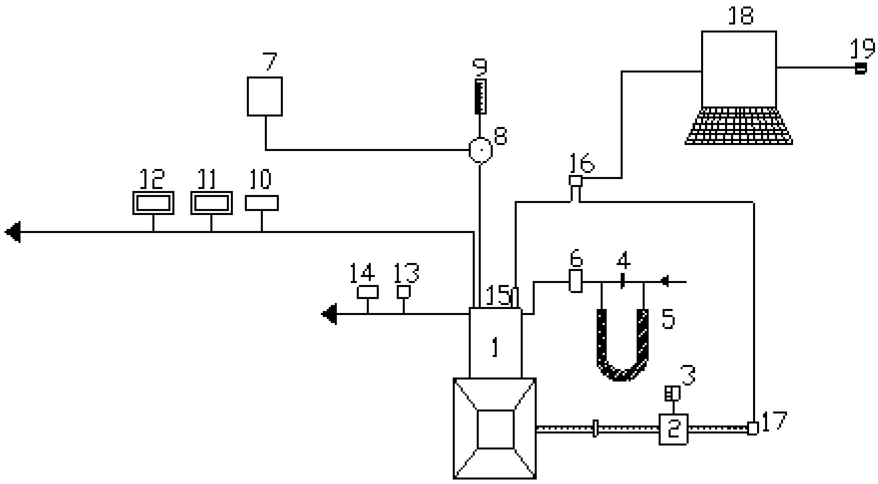


1. Crown with threads,2. Gasket, 3. Air gap in piston, 4. Body of piston, 5. Ceramic coating on inside portion of cylinder head, 6. Cylinder head, 7. Superni insert for liner, 8 Air gap in liner, 9. Liner

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

2.3. Experimental Set-Up:

The schematic sketch of experimental setup used for the investigations of different versions of LHR combustion chambers with crude tobacco seed oil is shown in Fig. 2. Conventional engine had an aluminum alloy piston with a bore of 80 mm and a stroke of 110 mm. The rated output of the engine was 3.68 kW at a speed of 1500 rpm. The compression ratio was 16:1 and manufacturer’s recommended injection timing and injector opening pressure were 27° bTDC (before top dead center) and 190 bar. The fuel injector had 3 holes of size 0.25-mm. The combustion chamber consisted of a direct injection type. No special arrangement was made for swirling motion of air.



1.Engine, 2.Electical Dynamo meter, 3.Load Box, 4.Orifice meter, 5.U-tube water manometer, 6.Air box, 7.Fuel tank, 8, Three-way valve, 9.Burette, 10. Exhaust gas temperature indicator, 11.AVL Smoke meter, 12.Netel Chromatograph NOx Analyzer, 13.Outlet jacket water temperature indicator, 14. Outlet-jacket water flow meter, 15.Piezo-electric pressure transducer, 16.Console, 17.TDC encoder, 18.Pentium Personal Computer and 19. Printer.

Fig.2. Schematic diagram of Experimental Set-up

The engine was connected to an electric dynamometer for measuring its brake power. Burette method was used for finding fuel consumption of the engine. Air-consumption of the engine was measured by air box method (with assembly of U–tube water manometer, orifice meter air box).

The naturally aspirated engine was provided with water–cooling system in which outlet temperature of water was maintained at 80^o 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 changed 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 (EGT) was measured with thermocouples made of iron and iron–constantan.

2.3.1.Exhaust Emissions: Exhaust emissions of smoke and nitrogen oxide (NO_x) were recorded by AVL smoke meter and Netel Chromatograph NOx analyzer at different values of brake mean effective pressure (BMEP).

2.5.Methodology:

Brake power (BP) of the engine was calculated by knowing voltmeter signal (V), ammeter signal (I) and efficiency of dynamometer (η_d) (generally assumed as 0.85) from the equation (1). Brake mean effective pressure (BMEP) was determined by a standard equation, knowing bore diameter, stroke of cylinder and speed of the engine. Particulate emissions were determined by AVL Smoke meter , while oxides of nitrogen were found out by multi gas Netel Chromatograph analyzer at different values of BMEP of the engine.

3.RESULTS AND DISCUSSION

3.1 Exhaust Emissions

The major pollutants emitted from diesel engine are particulate emissions and NO_x levels. Inhaling of these pollutants causes health hazards like severe headache, tuberculosis, lung cancer, dizziness, nausea, respiratory problems, skin cancer, hemorrhage [25–26]. The contaminated air containing carbon dioxide released from automobiles reaches ocean in the form of acid rain, there by polluting water. Hence control of these emissions is an immediate task and important. Hence globally, stringent regulations are made for permissible pollutants in the exhaust of the engines.

Curves in Fig.3 indicate that particulate emissions increased from no load to full load in engine with different versions of the combustion chambers with test fuels. During the first part, the particulate emissions were more or less constant, as there was always excess air present. However, in the higher load range there was an abrupt rise in particulate emissions due to less available oxygen, causing the decrease of oxygen–fuel ratio, leading to incomplete combustion, producing more particulate emissions.

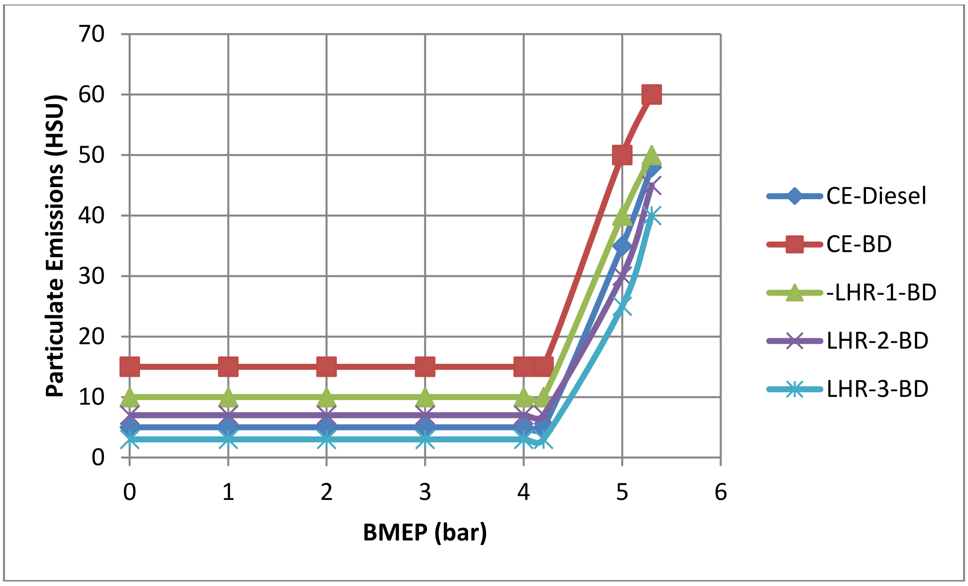


Fig. 3. Variation of particulate emissions with brake mean effective pressure (BMEP) an injector opening pressure of 190 bar.

It is also observed from same figure, particulate emissions were higher with conventional engine at all loads with biodiesel operation when compared with standard diesel operation. This is due to the higher value of C/H (C=Number of carbon atoms, H=Number of hydrogen atoms in fuel composition) (0.83) when compared to pure diesel (0.45). The increase of particulate emissions was also due to decrease of oxygen–fuel ratios and volumetric efficiency with biodiesel operation compared to standard diesel operation. Particulate emissions are related to the density of the fuel. Since biodiesel has higher density compared to diesel fuels, particulate emissions were higher with biodiesel operation. However, different configurations of LHR combustion chamber decreased particulate emissions due to efficient combustion, improved air fuel ratios and less amount of fuel accumulation on the hot combustion chamber walls with vegetable oil operation compared with conventional engine.
From Fig.4, it is noticed that particulate emissions decreased marginally with increase of degree of insulation with biodiesel operation. This was due to improved combustion with increase of degree of insulation.

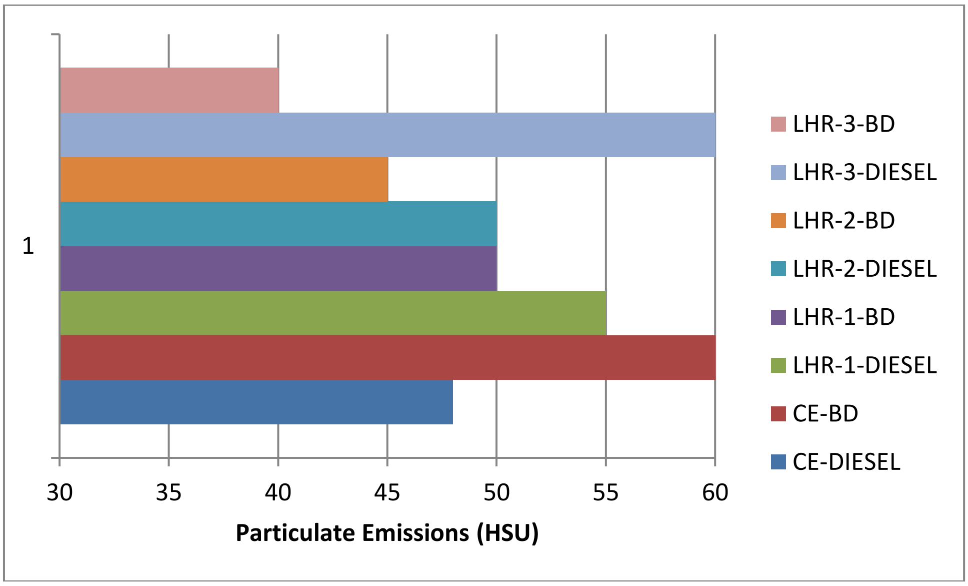


Fig.4 Bar charts showing the variation of particulate emissions at full load operation with engine at an injector opening pressure of 190 bar and injection timing of 27°bTDC

From same figure, it is noticed that LHR–1, LHR–2 and LHR–3 combustion chambers with biodiesel operation decreased particulate emissions by 9%, 10% and 33% at full load when compared with similar working conditions with pure diesel operation. LHR-3 combustion chamber was more suitable for alternative fuel, as combustion improved with its hot environment.

From Table.2, it is noticed that particulate emissions at full load operation decreased marginally with increase of injector opening pressure in different versions of the insulated combustion chambers with biodiesel operation. This was due to improved spray characteristics of fuel with improved oxygen–fuel ratios at higher injector opening pressure. Even though viscosity of biodiesel was higher than that of diesel, high injector opening pressure improved spray characteristics, hence leading to a shorter physical delay period. The improved spray also leads to better mixing of fuel and air resulting in turn in improved combustion, which directly influences pollutant formation leading to reduce particulate emissions. At higher injector opening pressure, total particulate number concentration in the exhaust decreased due to relatively superior fuel–air mixing. [27]. The main reason for this trend is improvement in fuel atomization due to increase of fuel injector opening pressure, which leads to finer droplet size distribution in the spray because higher fuel pressure differential causes the fuel to be discharged from injection nozzle in the form of smaller droplets and its size is proportional to ΔP^n, where ΔP is the pressure difference between the fuel injection pressure and the spray chamber pressure. Therefore, an increase in fuel injector opening pressure induces improvement in spray atomization, combustion and particulate emissions.[27]

Table-2
Data of Exhaust Emissions

Fuel	Combustion chamber Version	Particulate Emissions at full load operation (Hartridge Smoke Unit)			Nitrogen oxide levels at full load operation (ppm)		
		Injector opening pressure (bar)			Injector opening pressure (bar)		
		190	230	270	190	230	270
Diesel	CE	48	38	34	850	900	950
BD	CE	60	55	50	900	950	1000
Diesel	LHR-1	55	50	45	1100	1050	1000
BD	LHR-1	50	45	40	1200	1150	1100
Diesel	LHR-2	50	45	40	1150	1100	1050
BD	LHR-2	45	40	35	1250	1225	1200
Diesel	LHR-3	60	55	50	1300	1250	1200
BD	LHR-3	40	35	30	1350	1300	1250

Particulate emissions decreased by 18–22% with increase of injector opening pressure of 80 bar with vegetable oil operation with different versions of the insulated combustion chambers.

Fig.5. indicates that nitrogen oxide levels (NO_x) increased with an increase of brake mean effective pressure for different configurations of the combustion chambers with biodiesel operation.

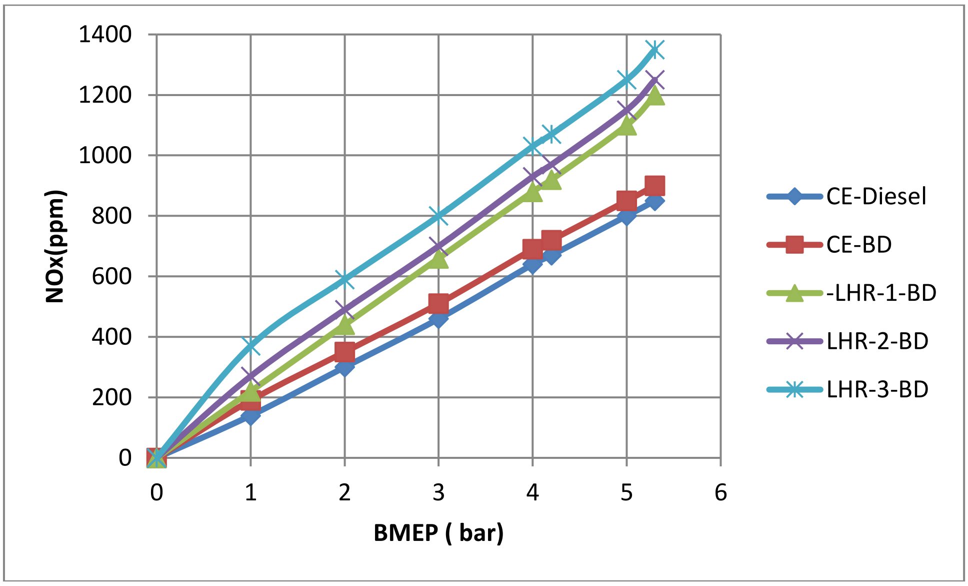


Fig.5 Variation of NOx levels with brake mean effective pressure (BMEP) at an injector opening pressure of 190 bar.

This was due to increase of gas temperatures with increased fuel consumption with the load. Conventional engine decreased NO_x levels by 6% at full load operation with biodiesel operation, when compared with standard diesel operation. Tobacco see oil based biodiesel having long carbon chain (C_{20}–C_{32}) recorded comparable or marginally higher NO_x levels in conventional engine than those of fossil diesel having both medium (C_8–C_{14}) as well as long chain (C_{16}–C_{28}). This was due to an inherent characteristic of biodiesel due to the presence of 54.9% of mono–unsaturated fatty acids (MUFA) and 18% of poly-unsaturated fatty acids (PUFA). That means, the long chain unsaturated fatty acids (MUFA and FUPA) such as oleic C18:1 and linoliec

C18:2 fatty acids were mainly responsible for comparable or marginally higher levels of NO_x emission [28-29]. Another reason for comparable or marginally higher NOx levels with biodiesel operation is the presence of oxygen (10%) in the methyl ester, which leads to improvement in oxidation of the nitrogen available during combustion. This will raise the combustion bulk temperature responsible for thermal NO_x formation. The production of higher NO_x with biodiesel fueling was also attributable to an inadvertent advance of fuel injection timing due to higher bulk modulus of compressibility, with the in–line fuel injection system.

NO_x levels were drastically higher in engine with different configurations of insulated combustion chamber with biodiesel operation, when compared with standard diesel operation. Increase of combustion temperatures with the faster combustion and improved heat release rates in engine with LHR combustion chambers caused drastically higher NO_x levels.

From Fig.6, it is noticed that nitrogen oxide levels increased with increase of degree of insulation. It was due to the reduction of fuel-air equivalence ratio with LHR combustion chamber, which was approaching to the stochiometric ratio, causing more NOx concentrations.

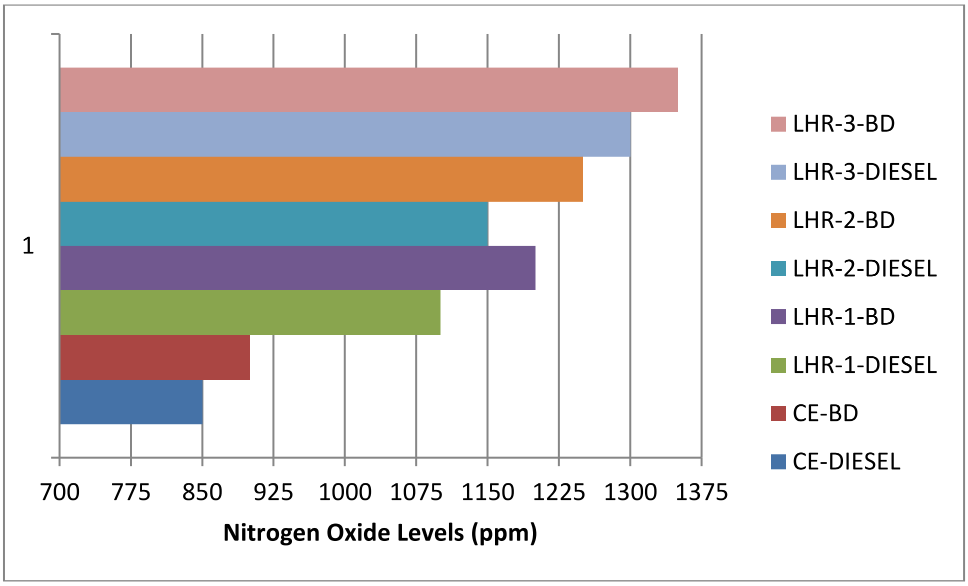


Fig.6 Bar charts showing the variation of nitrogen oxide levels at full load operation at an injector opening pressure of 190 bar and injection timing of 27° bTDC

From same figure, it is noticed that LHR–1, LHR–2 and LHR–3 combustion chambers increased NO_x levels by 9%, 9% and 4% at full load with biodiesel when compared with similar working conditions with pure diesel operation.

From Table.2, it is noticed that NO_x levels at full load operation decreased marginally with increase of injector opening pressure in different versions of the insulated combustion chambers with vegetable oil operation. This was due to reduction of gas temperatures with improved oxygen–fuel ratios at higher injector opening pressure. NO_x levels decreased by 7–8% with increase of injector opening pressure of 80 bar with biodiesel operation with different versions of the insulated combustion chambers.

4.CONCLUSIONS

1. Conventional engine with biodiesel increased particulate emissions by emissions by 25%, and nitrogen oxide levels by 6, when compared with conventional engine with neat diesel operation (standard diesel operation)
2. Engine with LHR–3 combustion chamber with biodiesel showed decreased particulate emissions by 17%, it drastically increased nitrogen oxide levels by 59%], combustion characteristics, when compared with conventional engine with diesel operation.
3. Engine with LHR–3 combustion chamber with biodiesel operation decreased particulate emissions by 33%, increased nitrogen oxide levels by 50%, when compared with conventional engine with biodiesel operation.
4. The performance of the engine with LHR-3 combustion chamber with biodiesel increased with increase of degree of insulation. Pollution levels at full load operation– decreased by 20%, nitrogen oxide levels increased by 11%) Performance parameters, pollution levels and combustion characteristic of the
5. engine with different versions of the insulated combustion chamber improved marginally with increase of injector opening pressure with biodiesel operation.

4.2 Highlights

- Engine performance was affected by change of combustion chamber design.
- Engine performance was influenced by degree of insulation.
- Engine performance was influenced by fuel composition.

- Engine performance was affected by nature of fuel
- Fuel injection pressure affect performance, exhaust emissions and combustion characteristics.

4.3.Scientific Significance:

The drawbacks associated with biodiesel (high viscosity and low volatility, low calorific value), though it is renewable in nature and important substitute for diesel fuel call for low heat rejection (LHR) combustion chamber with its significance characteristics of higher operating temperature, maximum heat release, higher brake thermal efficiency (BTE) and ability to handle the lower calorific value (CV) fuel.

4.4. Social Significance:

Tobacco seed oil in biodiesel form can be reused as fuel in internal combustion engines, particularly in diesel engines in order to combat economy problem in importing crude petroleum, so as to save foreign exchange which otherwise can be spent for important sectors like poverty, health, agriculture, education, industry and defense.

4.5 Novelty:

Performance of the engine which includes the study of performance parameters, pollution levels and combustion characteristic was evaluated with different versions of the LHR combustion chambers with varied injector opening pressure and compared with similar operating conditions with pure diesel operation.

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