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Research Article

Studies on Exhaust Emissions of Direct Injection Diesel Engine with Different Low Heat Rejection Combustion Chambers Fuelled with Tobacco Seed Oil Biodiesel

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Abstract

Experiments were conducted to determine exhaust emissions of direct injection diesel engine with different versions of low heat rejection (LHR) combustion chambers of air gap insulated piston and air gap insulated liner (LHR–2); air gap insulated piston, air gap insulated liner and ceramic coated cylinder head (LHR–3) with different operating conditions [normal temperature and pre-heated temperature] of tobacco seed oil biodiesel with varied injection timing and injector opening pressure. Comparative studies on exhaust emissions were made between different versions of the LHR combustion chamber with biodiesel operation with varied engine parameters. The optimum injection timing was found to be 29° bTDC (before top dead centre) with engine with LHR–2 combustion chamber, while it was 28° bTDC for LHR-3 combustion chamber and 31°bTDC for conventional engine (CE). Particulate emissions decreased, while nitrogen oxide levels increased with different versions of the LHR combustion chamber when compared with CE with mineral diesel operation .Advanced injection timing and increase of injector opening pressure reduced exhaust emissions from LHR engine with biodiesel operation.

Keywords: *Alternative Fuels, Vegetable Oils, Biodiesel, LHR combustion chamber, Exhaust emissions*

1. Introduction

The world is presently confronted with the twin crises of fossil fuel depletion and environmental degradation. The fuels of bio origin can provide a feasible solution of this worldwide petroleum crisis (Matthias Lamping *et al,* 2008, Agarwal, A.K. *et al*, 2006).

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. Rudolph Diesel, the inventor of the diesel engine that bears his name, experimented with fuels ranging from powdered coal to peanut oil. Several researchers experimented the use of vegetable oils as fuel on diesel engine and reported that the performance was poor, citing the problems of high viscosity, low volatility and their polyunsaturated character (Avinash Kumar Agarwal *et al,* 2009, Misra, R.D. *et al*, 2010 Avinash Kumar Agarwal *et al,* 2013).

Experiments were conducted 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 and decreased pollution levels of smoke and NOx emissions. The problems of crude vegetable oils can be solved, if these oils are chemically modified to bio-diesel. (Agarwal, D., *et al,* 2007,Hanbey Hazar . *et al*, 2010 Agarwal A.K. *et al,* 2010).

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 with bio-diesel on direct injection diesel engine and it was reported that particulate emissions decreased, when compared with neat diesel operation on conventional engine. However biodiesel operation increased NO_x levels. (Murugesan *et al,* 2009, Anirudh Gautam. *et al,* 2013 Durga prasada Rao *et al,* 2014,Venkateswara Rao,N. *et al*, 2013).

By controlling the injector opening pressure and the injection rate, the spray cone angle is found to depend on injector opening pressure. Few investigators reported that injector opening pressure has a significance effect on the performance and formation of pollutants inside the direct injection diesel engine combustion (Heywood,J.B. *et al,* 1988, Celikten,I.. *et al*, 2003 Cingur,Y., *et al,* 2003, Avinash Kumar Agarwal ., *et al*, 2013).

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The drawbacks associated with biodiesel for use in diesel engine call for low heat rejection (LHR) diesel engine.

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

Creating an air gap in the piston involved the complications of joining two different metals in medium grade LHR engines. Though it was observed effective insulation provided by an air gap, the bolted design employed by them could not provide complete sealing of air in the air gap. (Parker,D.A *et al,* 1987).

Later, It was made a successful attempt 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. (Rama Mohan, K., *et al,* 1999). However, low degree of insulation provided by these researchers was not able to burn high viscous fuels of vegetable oils. (Rama Mohan, K., *et al,* 1999). Studies were made on engine with LHR-2 combustion chamber 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 biodiesel with varied injection timing and injection pressure (Murali Krishna,M.V.S *et al,* 2004, Janardhan,N. *et al*, 2013).

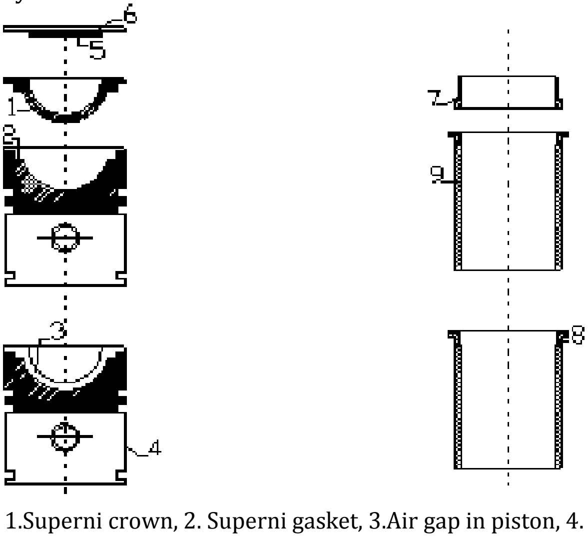
They reported from their investigations that particulate emissions reduced, while NO_x emissions increased with engine with LHR–2 combustion chamber with biodiesel, when compared with neat diesel operation on CE. Advanced injection timing and increase of injection pressure improved pollution levels.

Investigations were carried out on engine with LHR–3 combustion chamber with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head with biodiesel with varied injection timing and injection pressure. (Ratna Reddy, T. *et al,* 2009, Venkateswara Rao,N. *et al*, 2013 Subba Rao,B., *et al*, 2013). They reported from their investigations that particulate emissions reduced, while NO_x emissions drastically increased with engine with LHR–3 combustion chamber with biodiesel, when compared with neat diesel operation on CE. Advanced injection timing and increase of injection pressure improved pollution levels.

Little literature was available on comparative studies of exhaust emissions with engine with LHR-2 and LHR-3 combustion chambers with different operating conditions of the biodiesel with varied injection timing and pressure. Hence it was attempted here to study exhaust emissions with tobacco seed oil biodiesel with different versions of the combustion chamber with varied injector opening pressure and injection timing.

2. Materials and Methods

Engine with LHR-3 combustion chamber contained a two-part piston (Fig.1); 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 for improved performance of the engine with diesel as fuel. . (Rama Mohan, K., *et al,* 1999). 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. Low thermal conductivity materials of superni, air and PSZ offer thermal resistance in the path of heat flow to the coolant, thus resulting LHR combustion chamber. At $500^{o}C$ the thermal conductivities of superni-90,air and PSZ are 20.92, 0.057 and 2.01 W/m-K. Engine with LHR–2 combustion chamber contained air gap insulated piston and air gap insulated liner only.



1.Superni crown, 2. Superni gasket, 3.Air gap in piston, 4. Body of the piston, 5. Ceramic coating on inside portion of cylinder head, 6. Cylinder head, 7. Superni insert, 8. Air gap in liner and 9. Body of liner

Fig.1 Schematic diagram of assembly the insulated piston, insulated liner and ceramic coated cylinder head of the engine with LHR-3 combustion chamber

The chemical conversion of esterification reduced viscosity four fold. Tobacco seed oil contains up to 72.9 % (wt.) free fatty acids (Velikovic,V.B. *et al,* 2006,

Table.1 Properties of Test Fuels

Property	Units	Diesel	Biodiesel	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	4.2	1.9-6.0
Sulfur	%	0.25	0.0	0.05
Oxygen	%	0.3	11	11
Air fuel ratio (stochiometric)	--	14.86	13.8	13.8
Lower calorific value	kJ/kg	42 000	37500	37 518
Flash point (Open cup)	°C	66	174	130
Molecular weight	--	226	261	292
Preheated temperature	°C	--	60	--
Colour	--	Light yellow	Yellowish orange	---

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

Tapasvi D, *et al*, 2005). The methyl ester was produced by chemically reacting the tobacco seed oil with an alcohol (methyl), in the presence of a catalyst (KOH). A two-stage process was used for the esterification [40-42] of the waste fried vegetable oil. The first stage (acid-catalyzed) of the process is to reduce the free fatty acids (FFA) content in tobacco seed oil by esterification with methanol (99% pure) and acid catalyst (sulfuric acid-98% 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 is purified by the process of water washing with air-bubbling. The methyl ester (or biodiesel) produced from tobacco seed oil was known as tobacco seed oil biodiesel (TSOBD). The physical-chemical properties of the crude tobacco seed oil and biodiesel in comparison to ASTM biodiesel standards are presented in Table-1

The schematic diagram of the experimental setup with biodiesel operation is shown in Fig.2

The specifications of the experimental engine are shown in Table-2. Experimental setup used for study of exhaust emissions on low grade LHR diesel engine with cottonseed biodiesel in Fig.3 The specification of the experimental engine (Part No.1) is shown in Table.2 The engine was connected to an electric dynamometer (Part No.2. Kirloskar make) for measuring its brake power. Dynamometer was loaded by loading rheostat (Part No.3). The combustion chamber consisted of a direct injection type with no special arrangement for swirling motion of air. Burette (Part No.9) method was used for finding fuel consumption of the engine with the help of fuel tank (Part No7) and three way valve (Part No.8).

Air-consumption of the engine was measured by air-box method consisting of an orifice meter (Part No.4), U–tube water manometer (Part No.5) and air box (Part No.6) assembly. The naturally aspirated engine was provided with water-cooling system in \

Table.3 Specifications of the Smoke Opacimeter (AVL, India, 437) and NO_x Analyzer (Netel India, (4000 VM))

Pollutant	Measuring Principle	Range	Least Count	Repeatability
Particulate Emissions	Light extinction	1–100%	0.1% of Full Scale (FS)	0.1% for 30 minutes
NO_x	Chemiluminiscence	1–5000 ppm	0.5% of FS	≤0.5% F.S

which outlet temperature of water is 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. The naturally aspirated engine was provided with water-cooling system in which outlet temperature of water is maintained at 80°C by adjusting the water flow rate, which was measured by water flow meter (Part No.14). Exhaust gas temperature (EGT) and coolant water outlet temperatures were measured with thermocouples made of iron and iron-constantan attached to the exhaust gas temperature indicator (Part No.10) and outlet jacket temperature indicator (Part No.13). 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. Change of injector opening pressure from 190 bar to 270 bar (in steps of 40 bar) was made using nozzle testing device. The maximum injector opening pressure was restricted to 270 bar due to practical difficulties involved.

Exhaust emissions of particulate matter and nitrogen oxides (NO_x) were recorded by smoke opacity meter (AVL India, 437; Part No.11) and NO_x Analyzer (Netel India ; 4000 VM; Part No.12) at various values of brake mean effective pressure of the engine. Table 3 shows the measurement principle, accuracy and repeatability of raw exhaust gas emission analyzers/ measuring equipment for particulate emissions and NO_x levels. Analyzers were allowed to adjust their zero point before each measurement. To ensure that accuracy of measured values was high, the gas analyzers were calibrated before each measurement using reference gases.

2.1 Operating Conditions

Fuel used in experiment was biodiesel. Various injection timings attempted in the investigations were 27–34°bTDC, while injection pressures were 190, 230 and 270 bar. Different operating conditions of biodiesel were normal temperature and preheated temperature (where its viscosity was matched to diesel fuel, 90° C)

3. Results and Discussion

3.1 Performance

The optimum injection timing was 31° bTDC with CE, while it was 28° bTDC for engine with LHR–3 combustion chamber, which consisted of air gap insulated piston, air gap insulated liner and ceramic coated cylinder head (Venkateswara Rao,N. *et al*, 2013).

Fig.3 indicates variation of brake thermal efficiency with brake mean effective pressure (BMEP) of biodiesel with engine with LHR–2 combustion chamber, which contained air gap insulated piston and air gap insulated liner with various injection timings. From Fig, it is observed that engine with LHR–2 combustion chamber at recommended injection timing showed the improved performance at all loads compared with CE with neat diesel operation. High cylinder temperatures helped in improved 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–2 engine improved heat release rates and efficient energy utilization. The optimum injection timing was found to be 29° bTDC with LHR-2 combustion chamber with different operating conditions of biodiesel operation. Since the hot combustion chamber of LHR–2 engine reduced ignition delay and combustion duration and hence the optimum injection timing was obtained earlier with LHR–2 engine when compared to CE with the biodiesel operation.

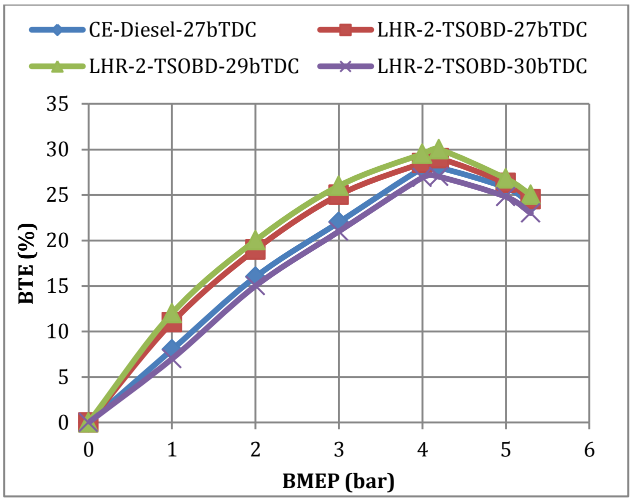


Fig.3 Variation of brake thermal efficiency with brake mean effective pressure (BMEP) in engine with LHR–2 combustion chamber with various injection timings with tobacco seed oil biodiesel (TSOBD) at an injector opening pressure of 190 bar.

The effect of varied injection timing on exhaust emissions and combustion characteristics was discussed with the help of bar charts while the effect of injector opening pressure and preheating was discussed with the help of Tables.

3.2 Exhaust Emissions

Particulate emissions and nitrogen oxide (NOx) levels are the emissions from diesel engine cause health hazards like inhaling of these pollutants cause severe headache, tuberculosis, lung cancer, nausea, respiratory problems, skin cancer, hemorrhage, etc. (Fulekar, M .H. *et al,* 1999, Khopkar,S.M. *et al*, 2010 Sharma,B.K. *et al,* 2010).

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.

Fig.4 indicates that bar charts showing the variation of particulate emissions at full load operation with engine with different versions of the combustion chamber with biodiesel operation at recommended and optimized injection timing at an injector opening pressure of 190 bar. At manufacturer's recommended injection timing of 27^{o} bTDC, CE with biodiesel showed marginal reduction of particulate emissions at full load operation with CE with mineral diesel operation. This was because of presence of oxygen in its composition with which combustion improved leading to reduce particulate emissions with biodiesel operation. Particulate emissions decreased with advanced injection timing at all loads with engine with both versions of the combustion chamber.

This was due to increase of contact period with fuel with air and thus improving atomization characteristics in different versions of the combustion chamber. Particulate emissions decreased with increase of degree of insulation with biodiesel operation. This was due to improved combustion of biodiesel in hot environment provided by LHR engine. Engine with LHR–2 combustion chamber decreased particulate emissions by 11% at 27^{o} bTDC and 12% at 29^{o} bTDC in comparison with CE at 27^{o} bTDC and 31^{o} bTDC. Engine with LHR-3 combustion chamber decreased particulate emissions by 22% at 27^{o} bTDC and 25% at 28^{o} bTDC in comparison with CE at 27^{o} bTDC and 31^{o} bTDC.

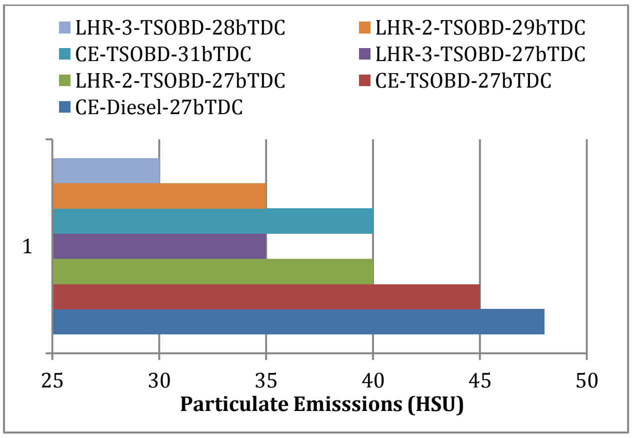


Fig.4 Bar charts showing the variation of particulate emissions in Hartridge smoke unit (HSU) at peak load operation with biodiesel with various configurations of the combustion chambers at recommended and optimized injection timings at an injector opening pressure of 190 bar.

Data from Table 4 shows a decrease in particulate emissions with increase of injector opening pressure, with different versions of the combustion chamber with different operating conditions of the biodiesel. This was due to improvement in the fuel spray characteristics at higher injector opening pressure causing lower particulate emissions. Even though viscosity of biodiesel was higher than diesel, high injector opening pressure improves 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 fast combustion. This will enhance the performance.

Preheating of the biodiesel reduced particulate emissions, when compared with normal temperature of the biodiesel. This was due to i) the reduction of density of the biodiesel, as density was directly related to particulate emissions ii) the reduction of the diffusion combustion proportion with the preheated biodiesel, iii) the reduction of the viscosity of the biodiesel with which the fuel spray does not impinge on the combustion chamber walls of lower temperatures rather than it directed into the combustion chamber**.**

Temperature and availability of oxygen are two favorable conditions to form NOx levels. Fig.5 indicates bar charts showing the variation of nitrogen oxide levels in engine with various configurations of the combustion chambers at full load operation with engine with biodiesel operation at recommended and optimized injection timing. CE with biodiesel gave higher NO_x levels than CE with mineral diesel operation. The tobacco seed oil based biodiesel having long carbon chain (C_{20}–C_{32}) recorded more NOx than that of fossil diesel having both medium (C_8–C_{14}) as well as long chain (C_{16}–C_{28}). The increase in NOx emission might be 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 are mainly responsible for higher levels of NO_x emission Another reason for higher NOx levels is the oxygen (10%) present in the methyl ester. The presence of oxygen in normal biodiesel leads to improvement in oxidation of the nitrogen available during combustion. This will raise the combustion bulk temperature responsible for thermal NO_x formation.

Many researchers reported that oxygen and nitrogen content of biodiesel can cause an increase in NO_x emissions. (Ghattamaneni, L. N.. *et al,* 2008, Jindal, S,. *et al*, 2010 Gamus, M. A. *et al,* 2010,Rao, P. V. *et al*, 2011, Venkanna,B.K.. *et al,* 2013). The production of higher NOx with biodiesel fueling is also attributable to an inadvertent advance of fuel injection timing due to higher bulk modulus of compressibility, with the in-line fuel injection system. NOx levels at full load operation increased with increase of degree of insulation. Engine with LHR-2 combustion chamber

Table.4 Data of exhaust emissions at full load operation

Injection Timing (° bTDC) Version of Combustion chamber	Test Fuel	Smoke Levels (Hartridge Smoke Unit)						NO$_x$ Levels (ppm)					
		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	48	--	38	--	34	--	850	----	900	----	950	---
	TSOBD	45	40	40	35	35	30	900	825	950	875	1000	925
27(LHR-2)	TSOBD	40	35	35	30	30	25	1300	1250	1250	1200	1200	1150
27(LHR-3)	TSOBD	35	30	30	25	25	20	1400	1350	1350	1300	1300	1250
28(LHR-3)	TSOBD	30	25	25	20	20	15	1300	1250	1250	1200	1200	1150
29(LHR-2)	TSOBD	35	30	30	25	25	20	1250	1200	1200	1150	1150	1100
31 (CE)	TSOBD	40	35	45	40	50	45	1200	1100	1250	1150	1300	1250

increased NOx levels by 44% at 27° bTDC and 4% at 29° bTDC in comparison with CE at 27° bTDC and 31° bTDC. Engine with LHR-3 combustion chamber increased NO$_x$ levels by 55% at 27° bTDC and 8% at 28° bTDC in comparison with CE at 27° bTDC and 31° bTDC. Increase of combustion temperatures with the faster combustion and improved heat release rates in the engine with different versions of the LHR combustion chamber caused higher NO$_x$ levels in comparison with CE with biodiesel operation.

From the Table.4, it was observed that Increasing the injection advance resulted in higher combustion temperatures and increase of resident time leading to produce more NO$_x$ concentration in the exhaust of CE with biodiesel. However, NOx levels decreased marginally with advanced injection timing with both versions of the insulated combustion chambers. This was due to decrease of combustion temperatures with improved air fuel ratios.

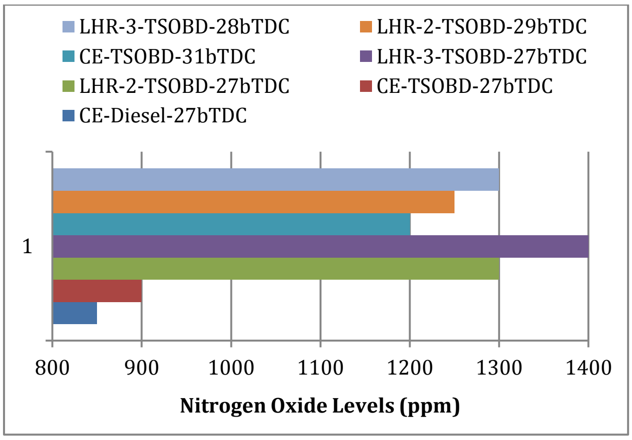


Fig.5 Bar charts showing the variation of nitrogen oxide levels in engine with various configurations of the combustion chambers at full load operation with biodiesel at recommended and optimized injection timings at an injector opening pressure of 190 bar.

From Table 4, it is noted that these levels increased with an increase of injector opening pressure with different operating conditions of biodiesel in CE. This was due to increase of peak pressures in CE with increase of injector opening pressure. However, NO$_x$ levels decreased marginally with an increase of injector opening pressure with different versions of the insulated combustion chamber with biodiesel operation. This was due to reduction of peak pressures with improved combustion and air fuel ratios.

NO$_x$ levels decreased with preheating of the biodiesel as noticed from the Table.4. The fuel spray properties may be altered due to differences in viscosity and surface tension. The spray properties affected may include droplet size, droplet momentum, degree of mixing, penetration, and evaporation. The change in any of these properties may lead to different relative duration of premixed and diffusive combustion regimes. Since the two burning processes (premixed and diffused) have different emission formation characteristics, the change in spray properties due to preheating of the biodiesel are lead to reduction in NO$_x$ formation. As fuel temperature increased, there was an improvement in the ignition quality, which will cause shortening of ignition delay. A short ignition delay period lowers the peak combustion temperature which suppresses NO$_x$ formation Lower levels of NO$_x$ is also attributed to retarded injection, improved evaporation, and well mixing of preheated biodiesel due to their viscosity at preheated temperatures.

Conclusions

1. Particulate emissions decreased, while increasing NOx levels with increase of degree of insulation.
2. When compared with conventional engine, with biodiesel operation, at recommended and optimized injection timings, different versions insulated engines decreased particulate emissions and increased NO$_x$ levels,
3. Different configurations of the insulated engines decreased particulate emissions and NO$_x$ levels with an increase of an injection pressure and with advanced injection timing. .
4. Different versions of the insulated engines decreased particulate emissions and NO$_x$ levels with preheated biodiesel in comparison with normal biodiesel.

4.1 Future Scope of Studies

Different versions of the LHR combustion chamber recorded higher NO$_x$ levels with biodiesel. Hence suitable catalytic converter is to be designed to reduce NOx emissions. The emission levels of NOx in LHR engine were controlled by means of the selective catalytic reduction technique using lanthanum ion exchanged zeolite (catalyst-A) and urea infused lanthanum ion exchanged zeolite (catalyst-B) with different versions of the engine at peak load operation of the engine (Janardhan,N. *et al*, 2012).

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