International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 - 5161

Available at http://inpressco.com/category/ijcet

Research Article

# Studies on Exhaust Emissions of Air Gap Insulated Di Diesel Engine Fuelled with Cotton Seed Biodiesel

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Accepted 01 Oct 2014, Available online 10 Oct 2014, **Vol.4, No.5 (Oct 2014)**

***Abstract***

*Investigations were carried out to study exhaust emissions of a medium grade low heat rejection (LHR) diesel engine with an air gap insulated piston and air gap insulated liner with different operating conditions [normal temperature and pre-heated temperature] of cotton seed biodiesel with varied injector opening pressure and injection timing. Exhaust emissions of particulate emissions and nitrogen oxide ($NO_x$) levels were evaluated at different values of brake mean effective pressure (BMEP) of the engine. Comparative studies were made with conventional engine (CE) with biodiesel and also with mineral diesel operation with similar working condition. Particulate emissions decreased while $NO_x$ levels increased with engine with LHR combustion chamber with biodiesel in comparison with CE.*

***Keywords:*** *Crude vegetable oil, biodiesel, LHR combustion chamber, exhaust emissions.*

## 1. Introduction

In view of heavy consumption of diesel fuel involved in not only transport sector but also in agricultural sector and also fast depletion of fossil fuels, the search for alternate fuels has become pertinent apart from effective fuel utilization which has been the concern of the engine manufacturers, users and researchers involved in combustion & alternate fuel research. The idea of using vegetable oil as fuel has been around from the birth of diesel engine. Rudolph diesel, the inventor of the engine that bears his name, experimented with fuels ranging from powdered coal to peanut oil and hinted that vegetable oil would be the future fuel (Misra, R.D. *et al*, 2010). 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, low volatility and their polyunsaturated character. (Misra, R.D. *et al*, 2010; Avinash Kumar Agarwal. *et al*,2013,).These problems can be solved to some extent, if neat vegetable oils are chemically modified (esterified) to bio-diesel.
Experiments were conducted on conventional diesel engine with biodiesel operation and it was reported that biodiesel increased efficiency marginally, decreased particulate emissions and increased oxides of nitrogen.(McCarthy .*et al*, 2011; Krishna Maddali. *et al*, 2014). The drawbacks (high viscosity and low volatility) of biodiesel call for LHR engine which provide hot combustion chamber for burning these fuels which got high duration of combustion.

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The concept of engine with LHR combustion chamber is to minimize heat loss to the coolant by providing thermal insulation in the path of the coolant thereby increases the thermal efficiency of the engine. Several methods adopted for achieving LHR to the coolant are i) using ceramic coatings on piston, liner and cylinder head (low grade LHR combustion chamber) ii) creating air gap in the piston and other components with low-thermal conductivity materials like superni (an alloy of nickel), cast iron and mild steel etc. (medium grade LHR combustion chamber) and iii) combination of low grade and medium grade LHR combustion chamber resulted in high grade LHR combustion chamber.

Creating an air gap in the piston involved the complications of joining two different metals. Though Parker et al. observed an effective insulation provided by an air gap, the welded design employed by them could not provide complete sealing of air in the air gap. (Parker, D.A. *et al*, 1987). Ramamohan et al carried out experiments with pure diesel operation with engine with LHR combustion chamber contained a two–part piston, the top crown made of low thermal conductivity material, superni (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 keeping a superni gasket of 3 mm thickness with varied injection timing. (Rama Mohan, K. *et al* , 1999). BSFC was reduced by 12% at part load and 4% at full load at an injection timing of 29.5° bTDC with the optimized insulated piston engine with a Nimonic crown and a 3 mm air gap in comparison with a conventional engine operating at an injection timing of 27° bTDC.(Rama Mohan, K. *et al* ,1999). Murali

**Table.1** Properties Test Fuels

| Test Fuel | Viscosity at 25°C (Centi-Stroke) | Specific gravity at 25°C | Cetane number | Calorific value (kJ/kg) |
|---|---|---|---|---|
| Diesel | 2.5 | 0.82 | 51 | 42000 |
| Biodiesel (BD) | 5.4 | 0.87 | 56 | 39900 |

**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 |
| Engine Displacement | 553 cc |
| 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 at full load | 5.31 bar |
| Manufacturer’s recommended injection timing and injector opening 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 |

Krishna conducted experiments with engine with an air gap insulated piston with a low thermal conductivity material superni (an alloy of nickel) crown and an air gap insulated liner with superni insert with neat diesel and reported that engine with LHR combustion chamber improved its performance and pollution levels at 80% of the full load operation and deteriorated its performance at full load operation at 27°bTDC.(Murali Krishna, M.V.S. *et al* , 2004).

Investigations were carried out on engine with medium grade LHR combustion chamber with biodiesel and it was reported that air gap insulation provided adequate insulation and improved thermal efficiency, reduced particulate emissions and increased nitrogen oxide levels, when compared with mineral diesel operation on CE. (Ratna Reddy,T. *et al*,2012, Murali Krishna, M.V.S.*et al*,2014). However, comparative studies were not made with mineral diesel operation working on similar conditions.

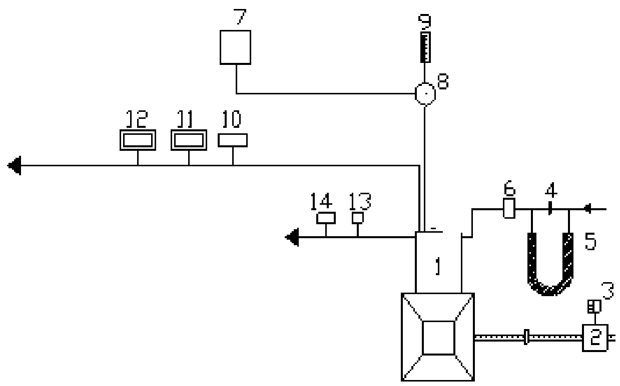
The present paper attempted to study exhaust emissions of engine with LHR combustion chamber which contained an air gap insulated piston and air gap insulated liner fuelled with different operating conditions of cotton seed biodiesel with varied injector opening pressure and injection timing and compared with CE with biodiesel operation and also with mineral diesel operation working on similar working conditions.

## 2. Materials and Methods

*2.1 Preparation of biodiesel:* The chemical conversion of esterification reduced viscosity four fold. Crude cotton seed oil contains up to 70 % (wt.) free fatty acids. The methyl ester was produced by chemically reacting crude cotton seed oil with methanol in the presence of a catalyst (KOH). A two–stage process was used for the esterification of the crude cotton seed oil (Anirudh Gautam. *et al*,2013). The first stage (acid-catalyzed) of the process is to reduce the free fatty acids (FFA) content in cotton seed oil by esterification with methanol (99% pure) and acid catalyst (sulfuric acid-98% pure) in one hour time of reaction at 55°C. Molar ratio of cotton seed oil to methanol was 9:1 and 0.75% catalyst (w/w). In the second stage (alkali-catalyzed), the triglyceride portion of the cotton 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 (biodiesel) 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 properties of the Test Fuels used in the experiment were presented in Table-1.

*2.2. Fabrication of engine with medium grade LHR combustion chamber:* The low heat rejection diesel engine contains a two–part piston– the top crown made of low thermal conductivity material, superni was screwed to aluminum body of the piston, providing a 3mm air gap in between the crown and the body of the piston by placing superni gasket in between piston crown and body of the piston. A superni insert was screwed to the top portion of the liner in such a manner that an air gap of 3mm is maintained between the insert and the liner body.

*2.3 Experimental Set-up:* Experimental setup used for study of exhaust emissions on medium grade LHR diesel engine with cotton seed biodiesel in Fig.1 The specification of the experimental engine is shown in Table.2 The engine was connected to an electric dynamometer (Kirloskar make) for measuring its brake power. Dynamometer was loaded by loading rheostat. The combustion chamber consisted of a direct injection type with no special arrangement for swirling motion of air. Burette method was used for finding fuel consumption of the engine. Air-consumption of the engine was measured by air-box method. The naturally aspirated engine was provided with water-cooling system in which 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.




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,

**Fig.1** Experimental Set-up

Injector opening pressure was changed from 190 bar to 270 bar using nozzle testing device. The maximum injector opening pressure was restricted to 270 bar due to practical difficulties involved. Injection timing was changed by inserting copper shims between pump body and engine frame. Exhaust gas temperature (EGT) was measured with thermocouples made of iron and iron-Constantan. Exhaust emissions of particulate matter and nitrogen oxides ($NO_x$) were recorded by smoke opacity meter (AVL India, 437) and $NO_x$ Analyzer (Netel India; 4000 VM) at various values of BMEP of the engine.

*2.4 Operating Conditions:* The different configurations used in the experimentation were conventional engine and engine with LHR combustion chamber. The various operating conditions of the vegetable oil used in the experimentation were normal temperature (NT) and preheated temperature (PT–It is the temperature at which viscosity of the vegetable oil is matched to that of diesel fuel, 90°C). The injection pressures were varied from 190 bar to 270 bar. Various test fuels used in the experiment were biodiesel and diesel.

## 3. Results and Discussion

*3.1. Performance Parameters:* The optimum injection timing was 31° bTDC with CE, while it was 29° bTDC for engine with low grade LHR combustion chamber with mineral diesel operation (Murali Krishna, M.V.S. *et al*, 2004).Curves in Fig.2 indicate that CE with biodiesel at 27° bTDC showed comparable performance at all loads due to improved combustion with the presence of oxygen, when compared with mineral diesel operation on CE at 27° bTDC. CE with biodiesel operation at 27° bTDC decreased peak BTE by 3%, when compared with diesel operation on CE. This was due to low calorific value and high viscosity of biodiesel. CE with biodiesel operation increased BTE at all loads with advanced injection timing, when compared with CE with biodiesel operation at 27° bTDC. This was due to initiation of combustion at early period and increase of resident time of fuel with air leading to increase of peak pressures. CE with biodiesel operation increased peak BTE by 3% at an optimum injection timing of 31° bTDC, when compared with diesel operation at 27° bTDC.

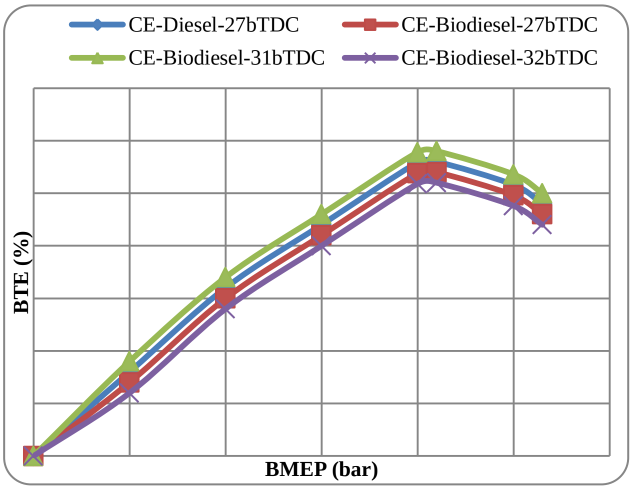



**Fig. 2** Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in conventional engine (CE) with biodiesel at various injection timings at an injector opening pressure of 190 bar

From Fig.3, it is observed that at 27° bTDC, engine with LHR combustion chamber with biodiesel showed the improved performance at all loads when compared with diesel operation on CE.

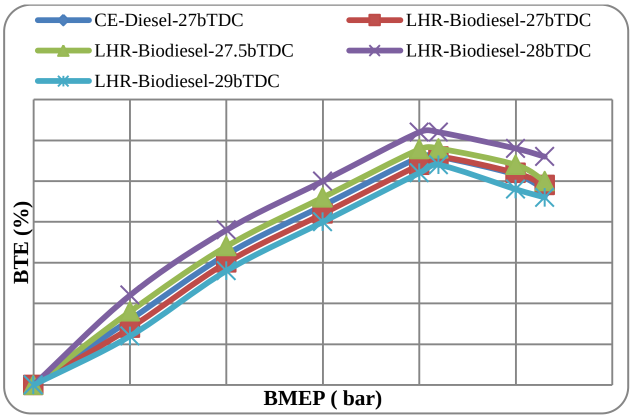



**Fig. 3** Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in engine with LHR combustion chamber with biodiesel at various injection timings at an injector opening pressure of 190 bar

High cylinder temperatures helped in improved evaporation and faster combustion of the fuel injected into the combustion chamber. Reduction of ignition delay of the biodiesel in the hot environment of the engine with LHR combustion chamber improved heat release rates. Engine with LHR combustion chamber with biodiesel operation increased peak BTE by 14% at an optimum injection timing of 28° bTDC in comparison with mineral diesel operation on CE at 27° bTDC. Hot combustion chamber of LHR engine reduced ignition delay and combustion duration and hence the optimum injection timing ($29^o$ bTDC) was obtained earlier with engine with LHR combustion chamber when compared with CE ($31^o$ bTDC) with biodiesel operation.

*3.2 Exhaust Emissions:* From Fig.4, it is noticed that during the first part, particulate emissions were more or less constant, as there was always excess air present. However, at the higher load range there was an abrupt rise in particulate emissions due to less available oxygen, causing the decrease of air–fuel ratio, leading to incomplete combustion, producing more smoke levels.

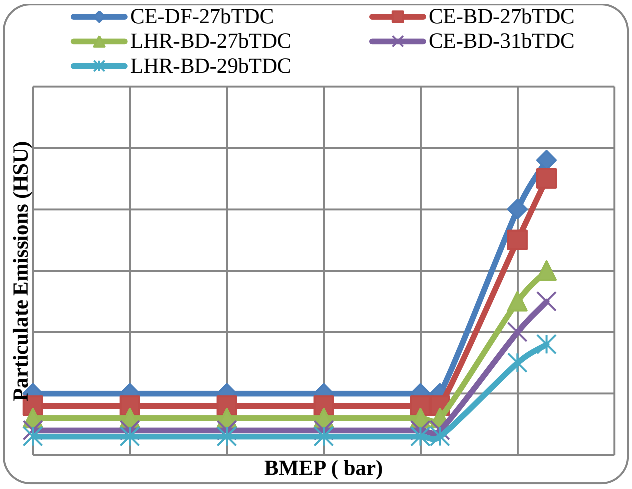



**Fig.4** Variation of particulate emissions in Hartridge smoke unit (HSU) with brake mean effective pressure (BMEP) in conventional engine (CE) and engine with LHR combustion chamber at recommended injection timing and optimum injection timing and at an injector opening pressure of 190 bar with biodiesel (BD)

Particulate emissions reduced marginally with CE with biodiesel operation in comparison with mineral diesel operation on CE. This was due to improved combustion with improved cetane number and also with presence of oxygen in composition of fuel. Particulate emissions further reduced with engine with LHR combustion chamber when compared with CE. This was due to improved combustion with improved heat release rate. Particulate emissions reduced with advanced injection timing with both versions of the combustion chamber. This was due to increase of resident time and more contact of fuel with air leading to increase atomization.

Availability of oxygen and high temperatures are favorable conditions to form $NO_x$ levels. Fig.5 indicates for both versions of the engine, NOx concentrations raised steadily with increasing BMEP at constant injection timing. At part load, $NO_x$ concentrations were less in both versions of the engine. This was due to the availability of excess oxygen. At remaining loads, $NO_x$ concentrations steadily increased with the load in both versions of the engine. This was because, local $NO_x$ concentrations raised from the residual gas value following the start of combustion, to a peak at the point where the local burned gas equivalence ratio changed from lean to rich. At full load, with higher peak pressures, and hence temperatures, and larger regions of close-to-stoichiometric burned gas, $NO_x$ levels increased in both versions of the engine. It is noticed that $NO_x$ levels were marginally higher in CE, while they were drastically higher in engine with LHR combustion chamber at different operating conditions of the biodiesel at the full load when compared with diesel operation on CE. This was also due to 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. Increase of combustion temperatures with the faster combustion and improved heat release rates associated with the availability of oxygen in LHR engine caused drastically higher $NO_x$ levels in engine with LHR combustion chamber.

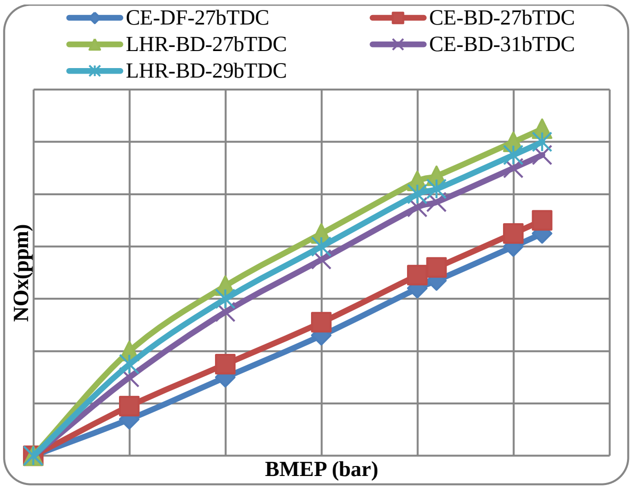



**Fig.5** Variation of nitrogen oxide levels with brake mean effective pressure (BMEP) in conventional engine (CE) and engine with LHR combustion chamber at recommended injection timing and optimum injection timing and at an injector opening pressure of 190 bar with biodiesel (BD)

From Table.3, it is understood that particulate emissions decreased with preheating with both versions of the combustion chamber. This was because of reduction of density, viscosity of fuel and improved spray characteristics of fuel. From same Table, it is noticed that, particulate emissions decreased with increase of injector opening pressure in both versions of the engine with test fuels. This was due to improved air fuel ratios with improved spray characteristics of the test fuels.

Data in Table.3 shows that, $NO_x$ levels decreased with preheating of biodiesel. As fuel temperature increased, there was an improvement in the ignition quality, which caused shortening of ignition delay. A short ignition delay period lowered the peak combustion temperature which suppressed $NO_x$ formation. $NO_x$ levels increased with an increase of injector opening pressure with different operating conditions of biodiesel with CE. Fuel droplets penetrate and find oxygen counterpart easily with the increase of injector opening pressure. Turbulence of the fuel spray increased the spread of the droplets which

**Table.3** Data of Exhaust Emissions with biodiesel operation

| Injection timing (deg. bTDC) | Combustion chamber version | Test Fuel | Exhaust Emissions at full load operation | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Particulate Emissions (HSU) | | | | $NO_x$ Levels (ppm) | | | |
| | | | Injector Opening Pressure (bar) | | | | Injector Opening Pressure (bar) | | | |
| | | | 190 | | 270 | | 190 | | 270 | |
| | | | NT | PT | NT | PT | NT | PT | NT | PT |
| 27 | CE | Diesel | 48 | -- | 34 | -- | 850 | -- | 950 | -- |
| | CE | BD | 45 | 40 | 35 | 30 | 900 | 850 | 1000 | 950 |
| | LHR | Diesel | 55 | -- | 45 | -- | 1100 | -- | 900 | -- |
| | LHR | BD | 30 | 25 | 20 | 15 | 1250 | 1150 | 1050 | 950 |
| 29 | LHR | Diesel | 40 | -- | 30 | -- | 1050 | -- | 950 | -- |
| | LHR | BD | 18 | 15 | 12 | 10 | 1200 | 1100 | 1000 | 900 |
| 31 | CE | Diesel | 30 | -- | 35 | -- | 1100 | --- | 1200 | -- |
| | CE | BD | 25 | 20 | 35 | 30 | 1150 | 1200 | 1250 | 1200 |

caused increase of gas temperatures marginally thus leading to increase in $NO_x$ levels with CE. Marginal decrease of $NO_x$ levels was observed in engine with LHR combustion chamber, due to decrease of combustion temperatures with improved air fuel ratios.

## 4. Summary

Advanced injection timing and increase of injector opening pressure improved exhaust emissions with biodiesel operation on engine with LHR combustion chamber. Preheated biodiesel reduced particulate emissions and $NO_x$ levels in both versions of the combustion chamber.

*Comparison with CE with biodiesel:* Engine with LHR combustion chamber with biodiesel increased peak brake thermal efficiency by 4% at 27$^o$ bTDC and 7% at 29$^o$ bTDC, in comparison with CE 27$^o$ bTDC and at 31$^o$ bTDC. It decreased particulate emissions at full load operation by 33% at 27$^o$ bTDC and 28% at 29$^o$ bTDC in comparison with CE at 27$^o$ bTDC and 31$^o$ bTDC. It increased nitrogen oxide levels by 39% at 27$^o$ bTDC and 4% at 29$^o$ bTDC in comparison with CE at 27$^o$ bTDC and 31$^o$ bTDC.

*Comparison with mineral diesel operation:* Conventional engine and engine with medium grade LHR combustion chamber with biodiesel operation showed comparable peak brake thermal efficiency in comparison with mineral diesel operation at recommended injection timing and optimum injection timing. Engine with LHR combustion chamber with biodiesel operation decreased particulate emissions at full load operation by 6% at 27$^o$ bTDC and 17% at 31$^o$ bTDC in comparison with CE at 27$^o$ bTDC and 31$^o$ bTDC with mineral diesel operation. Engine with LHR combustion chamber with biodiesel decreased particulate emissions at full load operation by 45% at 27$^o$ bTDC and 40% at 29$^o$ bTDC in comparison with same configuration of the combustion chamber with diesel operation at 27$^o$ bTDC and 29$^o$ bTDC.

Conventional engine with biodiesel operation increased nitrogen oxide levels at full load operation by 6% at 27$^o$ bTDC and 5% at 31$^o$ bTDC in comparison with CE at 27$^o$ bTDC and 31$^o$ bTDC with mineral diesel operation. Engine with LHR combustion chamber with biodiesel increased nitrogen oxide levels at full load operation by 14% at 27$^o$ bTDC and 14% at 29$^o$ bTDC in comparison with same configuration of the combustion chamber with diesel operation at 27$^o$ bTDC and 29$^o$ bTDC.

*4.1. Research Findings:* Exhaust emissions from engine with air gap insulation were studied with varied injector opening pressure and injection timing at different operating conditions of cotton seed biodiesel.

*4.2Recommendations:* Engine with low grade LHR combustion chamber gave higher levels of $NO_x$ at full load operation, These emissions can be controlled by selective catalytic reduction technique.

*4.3 Scientific Significance:* Change of injection timing and injection pressure were attempted to reduce pollutants from the engine along with change of configuration of combustion chamber with different operating conditions of the biodiesel.

*4.4 Social Significance:* Use of renewable fuels will strengthen agricultural economy, which curbs crude petroleum imports, saves foreign exchange and provides energy security besides addressing the environmental concerns and socio-economic issues.

*4.5 Novelty:* Change of injection timing of the engine was accomplished by inserting copper shims between pump body and engine frame

## Acknowledgments

Authors thank authorities of Chaitanya Bharathi Institute of Technology, Hyderabad for providing facilities for carrying out research work. Financial assistance provided by All India Council for Technical Education (AICTE), New Delhi is greatly acknowledged.

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