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# Control exhaust emissions of insulated diesel engine fuelled with biogas and cottonseed biodiesel

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## ABSTRACT

Gaseous fuels have many advantages than liquid fuels, as their calorific values of fuels are high, pollutants emitted by gaseous fuels are low and less dangerous when compared with liquid fuels. The drawbacks associated with use of vegetable oils in diesel engines such as high viscosity and low volatility can be reduced to some extent by converting them into biodiesel. However, they (biodiesel) cause combustion problems in diesel engine, due to their moderate viscosity, and hence call for low heat rejection (LHR) engine, which can burn low calorific value fuel, give high heat release rate and faster rate of combustion. The concept of LHR engine is to minimize heat loss to the coolant, thereby increasing thermal efficiency. LHR engine in this investigation consisted of ceramic coated diesel engine. They are many methods to induct gaseous fuels such as port injection, carburetion technique, injection of gaseous fuel at the near end of compression stroke etc,. Investigations were carried out with biogas gas as primary fuel inducted by port injection and cottonseed biodiesel was injected into the engine in conventional manner, as India is second large producer of cottonseed oil in the world. Particulate matter (PM), oxides of nitrogen ($NO_x$), carbon mono oxide (CO) levels and un-burnt hydro carbons (UBHC) are the exhaust emissions from a diesel engine. They cause health hazards, once they are inhaled in. They also cause environmental effects like Green-house effect and Global Warming. Hence control of these emissions is an immediate effect and an urgent step. The pollutants of PM, $NO_x$,CO and UBHC were determined at full load operation of the engine with varied injection timing such as recommended injection timing and optimum injection timing. $NO_x$ levels were reduced with provision of exhaust gas recirculation (EGR) at optimum flow rate of 10%. The maximum induction of biogas with conventional engine (CE) was 35% of total mass of biodiesel as full load operation, while it was 45% with LHR engine. Particulate emissions were determined by AVL Smoke meter, while other emissions were measured by Netel Chromatograph multi-gas analyzer at full load operation. These pollutants were drastically reduced with induction of biogas and further reduced with advanced injection timing. $NO_x$ levels drastically reduced with EGR.

***Key words*** *: Health hazards, Environmental disorder, Diesel, biodiesel, CE, LHR engine, Exhaust emissions.*

## Introduction

The exhaust emissions of diesel engine cause severe health hazards, once they are inhaled in, like respiratory diseases like tuberculosis, dizziness, vomiting sensation, severe headache, carcinogenic in nature (

Fulekar, 2004; Sharma, 2012; Khopkar, 2012). They also cause environmental disorders like Global warming, Green-House effect, acid rain etc,. (Khopkar, 2012). Hence they are to be controlled at any cost. Government of India is imposing Bharath Stage VIII pollution norms to control the pollutants.

The civilization of a particular country has come to be measured on the basis of the number of automotive vehicles being used by the public of the country. The tremendous rate at which population explosion is taking place imposes expansion of the cities to larger areas and common man is forced, these days to travel long distances even for their routine works. This in turn is causing an increase in vehicle population at an alarm rate thus bringing in pressure in Government to spend huge foreign currency for importing crude petroleum to meet the fuel needs of the automotive vehicles. The large amount of pollutants emitting out from the exhaust of the automotive vehicles run on fossil fuels is also increasing as this is proportional to number of vehicles. 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.

Rudolph diesel, the inventor of the engine that bears his name, experimented with fuels ranging from powdered coal to peanut oil (Cummins, 1993). The biodiesel is manufactured by the process of esterification from vegetable oils. Biodiesel has oxygen in its molecular composition. It has high cetane number. Several researchers conducted investigations on biodiesel with conventional engine (CE) and reported that the performance marginally improved, along with reduction of particulate emissions (Agarwal, 2006; Rasim, 2011; Jaichandar *et al.*, 2011; Ridvan Arslan, 2011; Xue *et al.,* 2011; McCarthy *et al.,* 2011) However, they further reported that $NO_x$ emissions were marginally higher with biodiesel operation in comparison with neat diesel operation on CE.

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 or LHR-1, medium grade or LHR-2 and high grade insulated engines or LHR-3 engine. Several methods adopted for achieving low grade LHR engines are using ceramic coatings on piston, liner and cylinder head, while medium grade LHR engines provide air gap in the piston and other components with low-thermal conductivity materials like superni, cast iron and mild steel etc and high grade LHR-3 engine is the combination of low grade and medium grade engines.

Experiments were conducted on low grade LHR engines with diesel and reported that diesel operation with LHR-1 engine improved performance and reduced particulate levels (Parlak *et al.*, 2005; Ekrem *et al.,* 2006; Ciniviz *et al.,* 2008). However, they increased nitrogen oxide levels ($NO_x$) levels.

Investigations were carried out with low grade LHR engines with biodiesel and reported that biodiesel operation with LHR-1 engine improved performance and reduced particulate emissions. (Hanbey Hazar, 2009; Modi *et al.,* 2010; Rajendra Prasath *et al.,* 2010; Mohamed Musthafa *et al.*, 2011) However, they increased $NO_x$ levels.

Biogas is produced by extracting chemical energy from organic materials in a sealed container called a digester. (Abdelaal *et al.,* 2013) The generation of biogas is the concept of anaerobic digestion, also called biological gasification. It is a naturally occurring, microbial process that converts organic matter to methane and carbon dioxide. The chemical reaction takes place in the presence of methanogenic bacteria with water an essential medium. The anaerobic digestion process, as the name states, is one that functions without molecular oxygen. Ideally, in a biogas plant there should be no oxygen within the digester. Oxygen removal from the digester is important for two main reasons. First, the presence of oxygen leads to the creation of water, not methane. Second, oxygen is a contaminant in biogas and also a potential safety hazard. Due to presence of oxygen, calorific value of biogas becomes low. Table 1 shows composition of biogas.

**Table 1.** Composition of biogas

| Components | Amount (%) |
|---|---|
| Methane (CH4 ) | 50 – 70 |
| Carbon Dioxide (CO2) | 30 – 40 |
| Hydrogen (H2 ) | 5 – 10 |
| Nitrogen (N2 ) | 1 – 2 |
| Water Vapour (H2O ) | 0.3 |
| Hydrogen Sulphide (H2S) | Hydrogen Sulphide (H2S) |

CO is high corrosive when wet and it has no combustion value so its removal is must to improve the biogas quality. The processes to remove CO are as follows

a) Caustic solution, NAOH- 40% NAOH + CO = NAHCO
b) Refined process, KCO - 30 % KCO + CO = 2KCO

Investigations were carried out with biogas in conventional engine. The dual fuel mode exhibited lower peak values of heat release rate and also they reported the application of exhaust gas recirculation (EGR) to dual-fuel mode additionally decreased the in-cylinder pressure and increased the ignition delay (Ray *et al.*, 2013). Dual fuel mode displayed lower emissions of $NO_x$ and smoke opacity while HC and CO concentrations were considerably higher as compared to other fuels. In dual fuel mode peak pressure and heat release rate were slightly higher compared to diesel and biodiesel mode of operation for all engine loads. (Ramesha *et al.*, 2015). Investigations were carried out with biogas, diesel-methane, and neat diesel operation in conventional engine (Ramesha *et al.*, 2015). They observed higher brake thermal efficiencies compared to diesel mode at high loads. Though volumetric efficiency was almost identical in diesel and diesel-CH4 dual modes, exhaust gas temperatures were higher in diesel-biogas mode, followed by diesel-methane and diesel modes (Ramesha *et al.*, 2015). $NO_x$ is a strong function of local temperatures. They reported that in compression ignition engine at constant speed of 1500 r/min at full load both $NO_x$ and soot missions were dropped, energy content rates in gas–fuel mixture compared to only diesel fuel (Feros Khan *et al.*, 2016; Yasin *et al.*, 2016).

However, little reports were available with the use of biogas and biodiesel. Hence authors have made work in this direction. It is attempted to determine the pollution levels of conventional engine with biogas and cottonseed biodiesel with varied injection pressure and compared the data with diesel operation on CE.

## Materials and Methods

### Insulated or LHR engine

Partially stabilized zirconium (PSZ) of thickness of 300 µm was applied at the inner side of head of cylinder by applying with spray coating. The bonding materials Al Si and $Al_2O_3$ were provided each 100 µm resulting insulated engine.

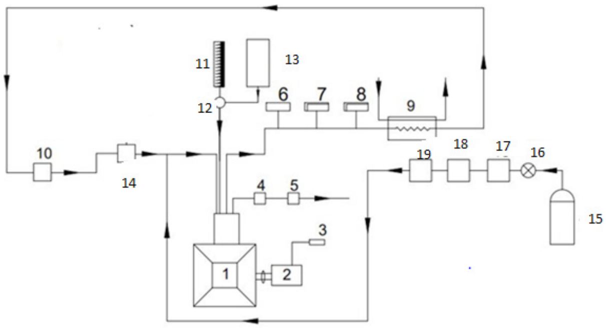
**The properties of Test Fuels:** The Properties of biodiesel along with DEE were taken from the Reference (Anirudh Gautam *et al.*, 2013), while the properties of biogas were taken from Reference (Ray *et al.*, 2013).

### Experimental Set-up

Table 1 gives the details of the engine. Fig.1 shows that the test engine (1) and the details of the CRDi engine are given in Table 1. It was located at Applied Thermo Dynamics Laboratory of MED, CBIT, Hyderabad. The engine was connected to power measuring device (2). The engine had computerized test bed. There was facility of loading the engine by means of variable rheostat. (3). Outlet jacket water temperature was indicated with temperature sensor (4). The flow of the coolant was measured with flow meter (5). The temperature of the exhaust gas was indicated with exhaust gas temperature sensor (6). The particulate levels were determined with AVL Smoke meter (7) at full load operation. The pollutants of CO and UBHC were determined by Netel Chromatograph multi gas analyzer (8) at full load operation. The range and accuracy of the analyzers in multi gas analyzer are shown in Table 2. EGR (9) system was employed in the system to reduce $NO_x$ emissions.

**Table 1.** Details of the Engine

| Description | Specification |
|---|---|
| Make | Mahindra & Mahindra |
| Number of cylinders | 01 |
| Number of Strokes | 04 |
| Ratio of bore to stroke | 93 mm/92 mm |
| Power | 6.6 kW (9 HP) at the rated speed of 3000rpm |
| Compression Ratio | 18:1 |
| Type of cooling Arrangement | Water cooling |
| Recommended Injection Pressure | 190 bar |
| Recommended Injection Timing | 27 degrees before top dead centre |
| Maximum Torque | 30 Nm at 1800 rpm. |




1. Engine, 2. Power measuring device, 3.Variable rheostat 4. Outlet jacket water temperature sensor, 5.Water flow meter, 6.Exhaust gas temperature sensor 7. AVL Smoke meter, 8.Netel Chromatograph multi-gas analyzer 9. . EGR Heat exchanger, 10. Air flow rate sensor, 11. Fuel flow rate device, 12. Three-way butterfly valve, 13. CSO +DEE tank 14. Air Accumulator 15. Gas cylinder, 16. Pressure regulator, 17. Gas pressure sensor, 18. Flow rate measuring device and 19. Flame prohibitor.

**Fig. 1.** Schematic diagram of experimental set up

Air flow was measured with air flow sensor (10). Biodiesel tank (11), burette (12) and three way valve (13) were used to induct biodiesel into the engine in conventional injection system. Bypass system was provided for EGR system. Air accumulator was provided to mix biogas and air. Biogas clean from CO2 was stored in a gas cylinder (15). Pressure regulator (16) was incorporated in the system. The pressure of the gas was noted in gas pressure sensor (17). The mass flow rate of the gas was noted by means of a rotometer (18). The flame arrestor (19) was employed in the gas circuit to ensure safety. Cam position senor was used to measure injection timing. Crank position sensor was used to determine the speed of the engine. Fuel temperature was determined with fuel temperature sensor. Gas was injected through gas injector.

The engine was provided with gravity lubrication system. Biogas was inducted through port injectionat the near end of compression stroke of the engine. There was facility to increase injection pressure by means of sensor.

The test fuels of the investigations were i) neat diesel and ii) biogas, and biodiesel blended with optimum quantity (20% by volume) of diethyl ether (DEE). The configurations or the versions of the engine were normal or base engine and insulated engine. Pollutants of PM, $NO_x$, CO and UBHC were determined at full load of the engine, at recommended injection timing and optimum injection timing with test fuels.

## Results and Discussion

### Performance Parameters

Fig. 2 shows the variation of brake thermal efficiency (BTE) with brake power (BP) of LHR engine with various percentages of biogas induction along with biodiesel operation. BTE increased with an increase of BP up to 80% of the full load and beyond that load, it decreased with different percentages of induction of biogas. This is due to increase of fuel conversion efficiency and mechanical efficiency up to 80% of the full load causing increase of BTE. However, beyond 80% of the full load, decrease of fuel conversion efficiency and oxygen-fuel ratio made reduction of BTE. At all loads, BTE increased with increase of induction of biogas up to 45%. This is due to improved oxidation reaction of CH4 in

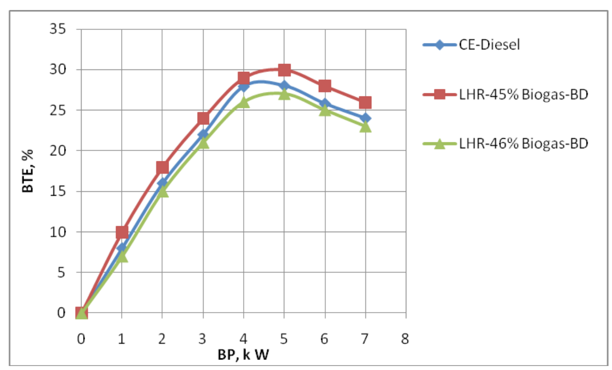



**Fig. 2.** Variation of BTE with BP in LHR engine with biogas and biodiesel

**Table 2.** Range and accuracy of Analyzers

| S.No | Name of the Analyzer | Principle adopted | Range | Accuracy |
|---|---|---|---|---|
| 1 | AVL Smoke Analyzer | Opacity | 0-100 HSU (Hartridge Smoke Unit) | ±1 HSU |
| 2 | Netel Chromatograph CO analyzer | Infrared absorption spectrograph | 0-10% | ± 0.1% |
| 3 | Netel Chromatograph UBHC analyzer | NDIR | 0-1000 ppm | ±5 ppm |
| 4 | Netel Chromatograph $NO_x$ analyzer | Chemiluminiscence | 0-5000 pm | ±5 ppm |

biogas and O2 in the hot combustion chamber provided by LHR engine. However, beyond 45% induction of biogas, BTE decreased at all load when compared with neat diesel operation on CE. This is due to reduction of ignition delay with biogas causing to produce peak pressure at an early stage. Hence the optimum induction of biogas was limited up to 45% of total consumption of biodiesel by mass basis along with diesel operation.

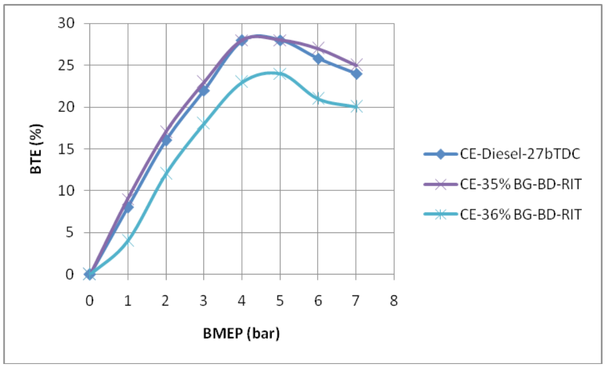



**Fig. 3.** Variation of brake thermal efficiency (BTE0 with brake power (BP) in conventional engine (CE), with various induction of biogas (BG).

Fig. 3 Shows variation of BTE with BP in conventional engine (CE) with various induction of biogas.

The maximum induction of biogas with CE was 35% which was less than LHR engine. This is due to Biogas absorbed by LHR engine with its hot insulated components.

Fig. 4 shows variation of brake thermal efficiency with Brake power in CE at different injection timings in CE.

The optimum injection timing at its maximum induction of biogas with CE was 31°bTDC.

Fig. 5 shows variation of BTE with BP for LHR

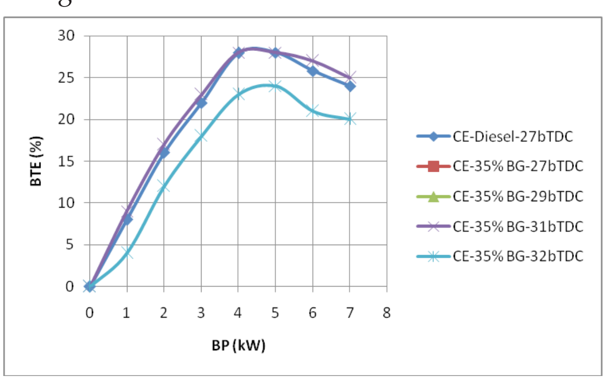



**Fig. 4.** Variation of BTE with BP in LHR engine with biogas and biodiesel

engine with maximum induction of biogas (45%) for various injection timings. The optimum injection timing was observed to be 29 o b TDC, which was less than with CE as combustion chamber was hot with LHR engine.

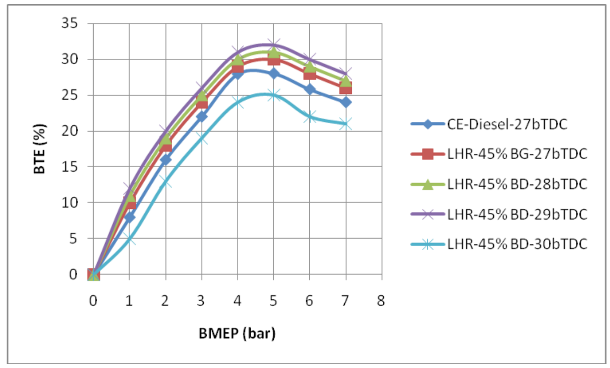



**Fig. 5.** Variation of BTE with BP for various injection timings with LHR engine

**Exhaust Emissions.**

Fig.6 presents the bar chart showing the variation of particulate emissions in Hartridge Smoke Unit (HSU) at full load with both versions of the engine at recommended injection timing (RIT) and optimum injection timing ( OIT) at maximum induction of biogas at injection pressure of 190 bar.

Particulate emissions at full load decreased with advanced injection timing with both versions of the engine due to improved atomization characteristics of the fuel. Particulate emissions at full load decreased with increase of induction of biogas at different injection timings. Improved oxidation reaction of CH4 present in the biogas and oxygen present in the biodiesel with faster rate of combustion had caused reduction of particulate emissions at full load. CE with biodiesel produced comparable

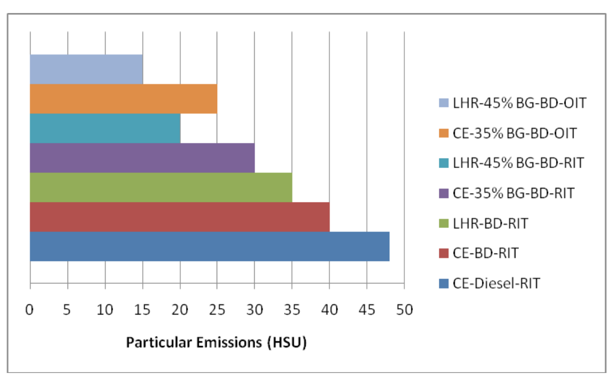



**Fig. 6.** Variation of particulate emissions at full load with injection pressure.

PM when compared to diesel operation. This is due to presence of oxygen and improved cetane number of biodiesel. LHR engine produced lower PM than CE due to improved combustion with high heat release rate.

Fig.7 presents the bar chart showing the variation of $NO_x$ levels at full load with LHR engine at maximum induction of biogas with varied injection timings with and without EGR at an injection pressure of 190 bar. The optimum EGR was found to be 10% flow rate. $NO_x$ levels increased with CE, while they decreased with LHR engine with advanced injection timing. This is due to increase of gas temperature and resident timing with CE, and reduction of gas temperature with LHR engine. $NO_x$ levels decreased with induction of biogas. This is due to presence of oxygen in biodiesel improved combustion, due to enrichment of oxygen with oxidation reaction of CH4 present in biogas with oxygen present with biodiesel.

$NO_x$ emissions were observed to be higher with biodiesel operation than diesel operation without EGR. This is due to presence of oxygen in biodiesel causing higher temperature leading to increase of $NO_x$ emissions. However, EGR drastically reduced NOx emissions at its optimum flow rate. This is due to cut off fresh oxygen with its residue gases. LHR engine without EGR increased NOx emissions than CE. This is due to improved heat release rate and faster rate of combustion of fuel.

Fig. 8 presents the bar chart showing the variation of carbon monoxide (CO) emissions at full load with CE at maximum induction of biogas with varied injection timings at an injection pressure of 190 bar. CO is formed due to incomplete combustion of fuel. CO emissions decreased with advanced injection timing with both versions of the engine. This is due to improved atomization characteristics of the fuel. CO emissions reduced with biogas induction. This is due to improved oxidation reaction of CH4 with oxygen available with biodiesel. Improved cetane (a measure of ignition quality of the fuel in diesel engine) number of biodiesel also improved combustion and thus reduced CO emissions. CO emissions reduced with LHR engine than CE. Combustion improved with LHR engine due to improved heat release rate had caused reduction of CO emissions.

Fig. 9 presents the bar chart showing the variation of un-burnt hydro carbon (UBHC) emissions at full load with CE at maximum induction of biogas with varied injection pressure. The UBHC emissions at full load followed similar trends with CO emissions. CO is formed due to incomplete combustion of the fuel, while UBHC emissions are formed due to accumulation of the fuel in the crevice volume. UBHC emissions decreased with advanced injection timing due to improved atomization characteristics of the fuel. BHC emission decreased with biodiesel operation. Presence of oxygen in its molecular composition and high cetane number of biodiesel improved combustion and hence reduced the un-burnt fuel in the crevice volume, thus reducing UBHC emissions. UBHC emissions at full load decreased with induction of biogas. LHR engine reduced UBHC emissions drastically than CE with improved combustion due to improved heat release rate.

High cetane number and presence of oxygen in the molecular structure of biodiesel caused improved oxidation reaction of CH4 present in biogas and thus reduced accumulation of the fuel in the crevice volume leading to reduce UBHC emissions at full load with induction of biogas.

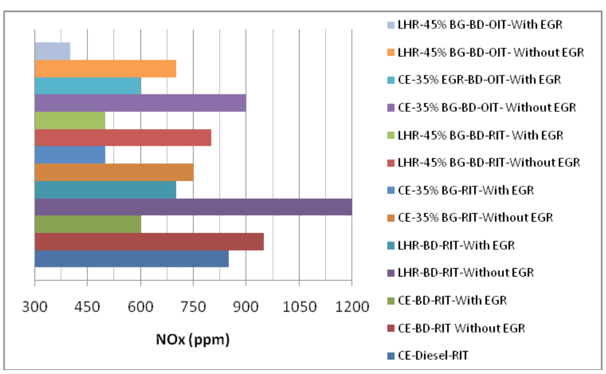



**Fig. 7.** Variation of Nitrogen Oxide emissions at full load with and with out EGR at an injection pressure of 190 bar.

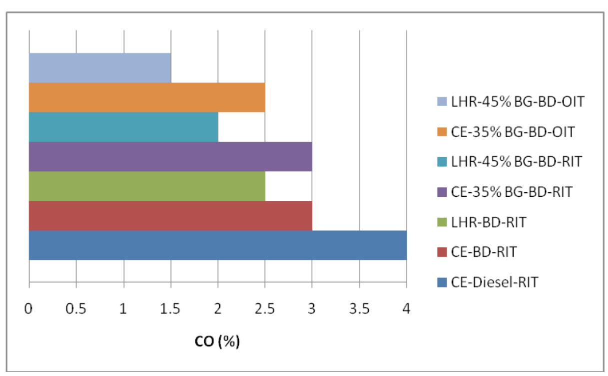



**Fig. 8.** Variation of CO emissions at full load with injection pressure.

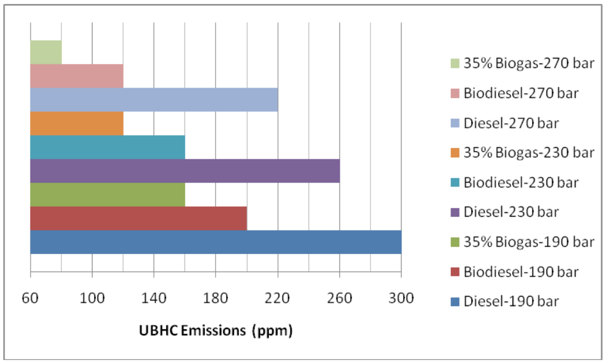



**Fig. 9.** Variation of UBHC emissions at full load with injection pressure.

## Conclusion

The maximum induction of biogas in LHR engine was 45% , while it was 35% with CE of total mass of biodiesel at full load operation. The optimum injection timing with CE was 31°bTDC, while it was 29°bTDC at maximum induction of biogas. Particulate emissions, nitrogen oxide levels, carbon monoxide levels and un-burnt hydro carbons drastically decreased drastically with dual fuel operation in comparison with neat diesel operation on conventional engine. LHR engine drastically reduced pollutants in comparison with CE. Increased injection pressure from 190 bar to 270 bar marginally decreased pollutants with test fuels. EGR drastically reduced $NO_x$ emissions.

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