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Investigations on Pollutants of Biodiesel Run Insulated Diesel Engine with Exhaust Gas Recirculation

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ABSTRACT

In the context of fast depletion of fossil fuels, ever increase of pollution levels with fossil fuels and increase of economic burden on Government of India due to import of crude petroleum, the search for alternative fuels has become pertinent. Alcohols and vegetable oils are important substitutes of diesel fuel. However, alcohols have low cetane number, while vegetable oils have high viscosity and low volatility to use them in diesel engines. Hence biodiesel which has oxygen in its molecular composition and high cetane number is good substitute for diesel fuels. Biodiesel is prepared form vegetable oils by the process known as esterification. The concept of the insulated engine or low heat rejection (LHR) engine is to minimize the heat loss to the coolant by providing thermal insulation in the path of heat flow to the coolant, thereby increase heat flow rate and provide faster rate of combustion and hence these engine are suitable for burning low calorific value fuels. Exhaust emissions from diesel engine are particulate matter (PM) and nitrogen oxide (NO_x) levels and breathing of which cause many health hazards and also cause environmental disorders like acid rain and Greenhouse effect. Hence control of these emissions is an immediate step. Investigations on carried out on LHR four-stroke, single-cylinder, 3.68 kW at the rated speed of 1500 rpm, water cooled diesel engine with air gap insulated piston and air gap insulated liner with tamarind biodiesel with exhaust gas recirculation (EGR). Exhaust emissions of PM and NO_x levels were reduced by 50% when compared without EGR.

Key words : Biodiesel, *Exhaust Gas Recirculation, Air pollution*

Introduction

Investigations on conventional engine with biodiesel

Several researchers conducted experiments with biodiesel with four–stroke, medium speed conventional diesel engine. They 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 (Murali Krishna *et al.*, 2014; Murali Krishna *et al.*, 2015) when compared with neat diesel operation. Comparative studies were made between waste cooking oil operation and its biodiesel with engine of the same configuration as mentioned in reference (Srikanth *et al.*, 2013) with varied injection timing and injector opening pressure. The optimum injection timing was found out to be 31°bTDC with biodiesel, while it was 32°bTDC with crude vegetable oil. They 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 tamarind oil, when compared with neat diesel operation at manufacturer's recommended injection timing of 27°b TDC.

Investigations on air gap insulated piston and insulated liner with biodiesel

Investigations were carried out on single–cylinder, four–stroke, water cooled compression ignition engine with brake power of 3.68 kW at a speed of 1500 rpm with air gap insulated piston with superni crown, air gap insulated liner with superni insert and ceramic coated cylinder head with vegetable oils and biodiesels at different operating conditions with varied injection timing and injector opening pressure. (Wallace *et al.,* 1983; Karthikeyan *et al,* 1985; Alkidas,1986; Murali Krishna, 2004; Ratna Reddy *et al.,* 2013; Janardhan *et al.,* 2012; Janardhan *et al*., 2013; Murali Krishna, 2014.a; Murali Krishna *et al.*, 2014.b; Murali Krishna *et al.*, 2014.c.). They reported from their studies, that the optimum injection timing was observed to be 29°b TDC with vegetable oil operation on high grade LHR engine. They concluded from their studies that engine with high grade LHR combustion chamber with vegetable oil operation at its optimum injection timing improved brake thermal efficiency by 7–12%, decreased particulate matter by 10–15% and increased NO_x emissions by 40–45% when compared with conventional engine with neat diesel operation at 27° bTDC. Increased injector pressure of 80 bar had reduced particulate matter emissions and nitrogen oxide levels by 15–20% with high grade LHR engine with crude vegetable oil operation. They further reported that the optimum injection timing was observed to be 31°bTDC with conventional engine, while it was 28°bTDC with high grade LHR engine with biodiesel operation. They reported from their studies that high grade LHR engine with biodiesel operation at its optimum injection timing improved brake thermal efficiency by 10–15%, decreased particulate matter by 15–20% and increased NO_x emissions by 50–55% when compared with conventional engine with neat diesel operation at 27°bTDC. Increased injector pressure by 80 bar had reduced particulate matter emissions and nitrogen oxide levels by 20–25% with high grade LHR engine with biodiesel operation.

Effect of pollutants on human beings

CO and UBHC, major exhaust pollutants formed due to incomplete combustion of fuel and quenching of the fuel-air mixture in the crevices of piston. Inhaling of these pollutants causes asthma, bronchitis, emphysema, slowing down of reflexes, vomiting sensation, dizziness, drowsiness and severe headache. Such pollutants also cause detrimental effects on animal and plant life, besides environmental disorders (Fulekar, 2004). Driving methodology, road layout, traffic density, traffic condition, age and maintenance of the vehicle were some of the reasons for the formation of pollutants (Sharma, 2012) Investigations were carried out on conventional spark ignition engine to control CO and UBHC emissions with expensive catalysts like Tungsten, Molybdenum and Platinum. It was reported from their investigations that these catalysts reduced exhaust emissions by 30% (Khopkar, 2012).

Investigations on EGR with LHR engines

Investigations were carried out using CInvalophyl luminophyllum methyl ester as a fuel on a regular CI engine at different injection timings and EGR rates of 10% optimum greatly reduced NO_x emissions without any penalty on efficiency (Vamsi Krishna *et al.,* 2018). Also, with the advancement of injection timing (IT) the BTE, BSFC, EGT and all other emissions improved significantly except NO_x levels. The test case was semi adiabatic diesel engine (SADE) produced by thermal barrier 8 YSZ (Yttria Stabilized Zirconia) ceramic coated cylinder head and liner with bond coat NiCrAl as an intermediate layer and coupled with an EGR (exhaust gas recirculation) of 10% constant rate. The test fuels injected directly into the combustion chamber are diesel and blend A15B85 by vol. (Additive Diethyl Ether 15% + Rubber seed based Biodiesel 85%). Throughout the experimentation, a constant compression ratio 18:1, fuel injection pressure190 bar and speed 1800 rpm. Load from 0% to 100% and start of injection (SOI) timing from 300 BTDC to 350 BTDC were varied to investigate performance, in-cylinder pressure and emission parameters of SADE and ordinary diesel engine (ODE) fuelled by test fuels. It was found that advancement of SOI timing improved all the investigated parameters except NO_x emissions. Compared to ODE with diesel at any specific SOI timing, the test case with blend found to be favorable. The optimum results of SADE were 7% enhancement of

BTE with the reduction in BSEC by 5.5%, particulates by 48.5%, NO_x by 19.5% and exhaust gas temperature by 18.5% found with the blend at 33°bTDC with higher load compared to ODE with neat diesel at 30°bTDC. The optimum configuration of ODE found to be diesel fuel at 34°bTDC with higher load

Research gaps

Little reports are available on reduction of pollution levels with EGR on LHR engine. Previous researchers employed superni-90 material as the material of crown which is very expensive and rarely available. However, the authors used stainless steel (304-Grade-A) as the material for the crown as well as the insert for the liner, which is less expensive and abundantly available. Hence the authors have made an attempt to reduce particulate matter and oxides of nitrogen from the exhaust of LHR engine consisting of air gap insulated piston and air gap insulated liner.

Materials and Methods

The flow chart of preparing biodiesel from vegetable oil is shown in Fig. 1

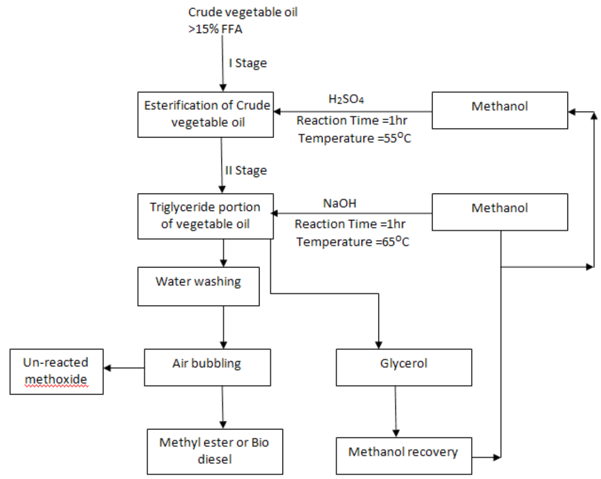
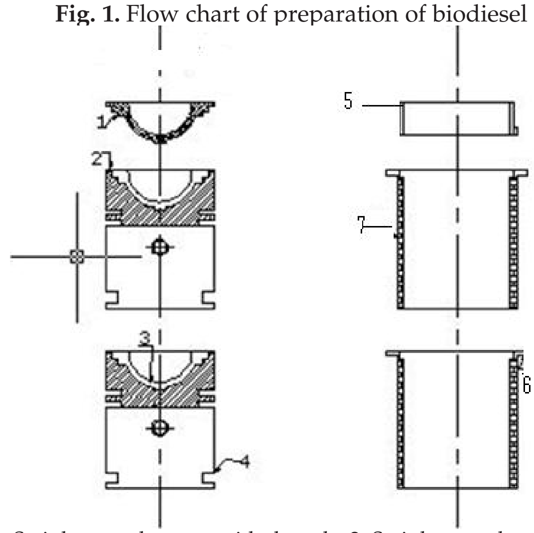


Fig. 1. Flow chart of preparation of biodiesel

Fabrication of engine with LHR combustion chamber

Fig. 2 shows assembly details of air gap insulated piston, air gap insulated liner and LHR combustion chamber. The top portion of the piston, crown made of low thermal conductivity material, stainless steel (304-Gr-A) was screwed to aluminum body of the piston, providing a 2.8 mm (which was found to be optimum by the same authors) aair gap in between

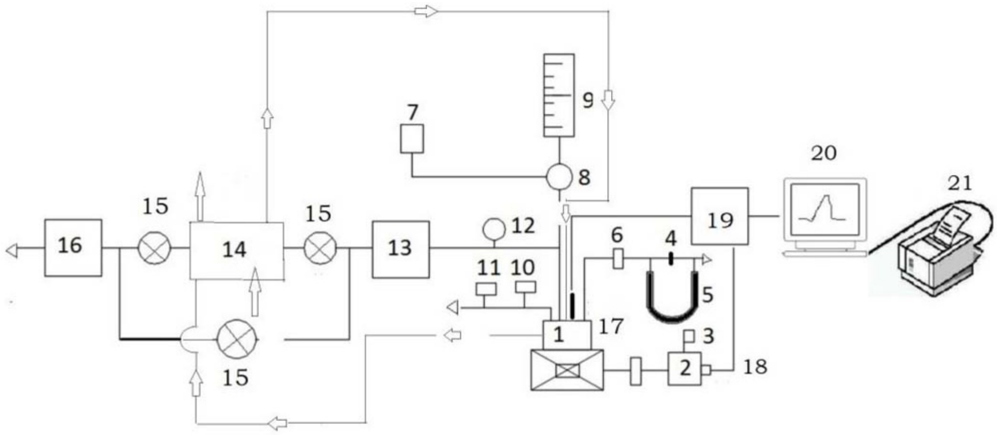


1. Stainless steel crown with threads, 2. Stainless steel gasket, 3. Air gap in piston, 4. Body of piston, 5.stainless steel insert with threads, 6. Air gap in liner, 7. Liner

Fig. 2. Assembly details of air gap insulated piston and air gap insulated liner

Properties of biodiesel are given in Table 1

Property	Unit	ASTM Standard	Diesel(DF)	Biodiesel(BD)
Carbon chain	—	——	C_8-C_{28}	C_{16}-C_{24}
Cetane Number		ASTM D 613	55	55
Density @ 25 °C	gm/cc	ASTM D 4809	0.84	0.87
Bulk modulus @ 20Mpa	Mpa	ASTM D 6793	1475	1800
Kinematic viscosity @ 40 °C	cSt	ASTM D 445	2.25	4.2
Sulfur	%	—-	0.25	0.0
Oxygen	%	——	0.3	11
Air fuel ratio (stochiometric)	—	—-	14.86	13.8
Lower calorific value	kJ/kg	ASTM D 7314	42 000	37000
Flash point (Open cup)	°C	ASTM D93	66	174
Molecular weight	–		226	261
Preheated temperature (PT)	°C	—	—	60
Colour	–	—	Light yellow	Yellowish orange



1. Engine, 2. Electical Dynamometer, 3. Load Box, 4. Orifice meter, 5. U–tube water manometer, 6. Air–box, 7. Fuel tank, 8. Pre–heater, 9.Burette, 10. Outlet jacket water temperature indicator, 11. Outlet jacket water flow meter, 12. Exhaust gas temperature indicator, 13. AVL Smoke meter 14. Heat exchanger (HE), 15. Control valve 16. Netel Chromatograph NO_x analyzer 17. Piezo electric pressure transducer, 18. TDC encoder, 19. Console, 20. Personal computer and 21. Printer.

Fig. 3. Schematic diagram of experimental set up

the crown and the body of the piston. A stainless steel insert was screwed to the top portion of the liner in such a manner that an air gap of 2.8 was maintained between the insert and the liner body. The combination of low thermal conductivity materials of air and stainless steel provide sufficient insulation for heat flow to the coolant thus resulted in LHR combustion chamber.

Experimental set–up

The schematic diagram of the experimental setup used for the investigations on the engine with LHR combustion chamber with tamarind biodiesel form is shown in Fig.3. Accuracy of the instruments is shown in Table 2. Specifications of the test engine are given in Table 3. The engine tests are carried out with a single–cylinder, four–stroke, naturally aspirated, water cooled, direct–injection compression ignition engine of brake power 3.68 kW operated at a constant speed of 1500 rev/min. The compression ratio of the engine is 16:1. The engine is connected to an electric dynamometer for measuring its brake power. Dynamometer is loaded by a loading rheostat. The accuracy of engine load is ±0.2kW. The speed of the engine is measured with digital tachometer with accuracy ±1%. The fuel consumption is registered with an aid of fuel measuring device (Burette and stop watch). The accuracy of brake thermal efficiency obtained is ±2%. Diesel/ biodiesel isinjected into the engine through conventional injection system. Provision is made for preheating of biodiesel (90 ^{0}C)to the required levels and so that its viscosity is matched to that of diesel fuel at room temperature. Airconsumption of the engine is obtained with an aid of air box, orifice flow meter and U–tube water manometer assembly. Air box with

Table 2. Accuracy of the Instruments

Instrument	Purpose	Accuracy
EGT indicator	For measuring EGT	±5^{o}C
Tachometer	For measuring speed of the engine	±5 rpm
Burette	For measuring flow rate of fuel to the engine	0.5 cc/s
Stop watch	For noting down time taken for 10 cc of fuel	0.5 Sec
Hydrometer	For measuring density of fuel	0.1 gm/cc
Dynamometer	For measuring brake power of the engine	1 watt
Water flow meter	For measuring water flow rate to the engine	5 gm/s
Particulate Analyzer	For measuring particulate emissions	1 HSU
NOx Analyzer	For measuring nitrogen oxide levels	5 ppm

diaphragm is used to damp out the pulsations produced by the engine, for ensuring a steady flow of air through the intake manifold.

Accuracies of the instruments are shown in Table 2.

Sensor method is provided in between the pump body and the engine frame, to vary the injection timing and its effect on the performance of the engine is studied, along with the change of injector opening pressure from 190 bar to 270 bar (in steps of 40 bar) using nozzle testing device. The maximum injector opening pressure is restricted to 270 bar due to practical difficulties involved. Coolant water jacket inlet temperature, outlet jacket temperature and exhaust gas temperature are measured by employing iron and iron-constantan thermocouples connected to analogue temperature indicators

The accuracies of analogue temperature indicators were ±5^o C. The naturally aspirated engine was provided with water–cooling system in which outlet temperature of water is maintained at 80 ^{o}C by adjusting thewater flow rate. The water flow rate is measured by means of analogue water flow meter, with accuracy of measurement of ±1%. Engine oil is provided with a pressure feed system. No temperature control was incorporated, for measuring the lube oil temperature. EGR system is designed based upon mass flow rate of hot fluid, cold fluid and their temperatures so as to find out the length of heat exchanger.

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. 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.

Exhaust emissions of particulate matter and nitrogen oxide (NO_x) levels were recorded by AVL (A company trade name) Particulate matter analyzer and Netelchromatograph (A company trade name) NO_x analyzer at full load operation of the engine. The accuracy of measurement of particulate emissions is ±1 HSU (Hartridge Smoke Unit), while it is ±5 ppm with NO_x analyzer. The specifications and operating principle of the analyzers are given in Table 4.

Results and Discussion

Performance Parameters With Normal Biodiesel

Fig. 4. shows the variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in the conventional engine (CE) with tamarind biodiesel, at various injection timings at an injector opening pressure of 190 bar. Curves of Fig. 4 indicate that conventional engine with biodiesel operation showed comparable performance at all loads

Table 3. 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^{o}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-BOSCHNo- 0431-202-120/HB
Fuel injection pump	Make: BOSCH: NO- 8085587/1

Table 4. Specifications of gas analyzers

Name of the analyzer	Measuring Range	Precision	Resolution	Accuracy of Measurement
AVL Particulate Matter Analyzer	0-100 HSU	1 HSU	1 HSU	±1 HSU
Netel Chromatograph NO_x analyzer	0-5000 ppm	5 ppm	5 ppm	±5 ppm

when compared with the neat diesel operation on conventional engine at 27°bTDC. This was due to difference between calorific value and viscosity between diesel and biodiesel. However, high density compensates the lower value of the heat of combustion of the biodiesel. Higher value of viscosity of biodiesel reduces leakage in plunger and barrel of the fuel pump. Minimum viscosity limits are imposed (preheated condition) to prevent the fuel from causing the wear in the fuel injection pump. As the injection timing was advanced with CE with biodiesel, brake thermal efficiency increased at all loads. This was due to initiation of combustion at earlier period and efficient combustion with increase of air entrainment in fuel spray giving higher brake thermal efficiency. Brake thermal efficiency increased at all loads when the injection timing was advanced to 31°bTDC in the conventional engine at the normal temperature of biodiesel. The increase of brake thermal efficiency at optimum injection timing over the recommended injection timing with conventional engine fuelled with biodiesel was attributed to its longer ignition delay and combustion duration.

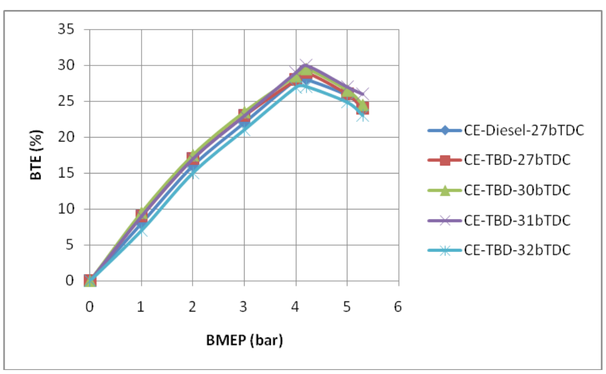


Fig. 4. Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) at various injection timings with tamarind biodiesel (TBD) in conventional engine.

Fig. 5 shows the variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in the LHR engine with tamarind biodiesel, at various injection timings at an injector opening pressure of 190 bar. From Fig. 5, it could be noticed that, LHR engine showed the improvement in the performance for entire load range compared with CE with neat diesel operation. High cylinder temperatures helped in better evaporation and faster combustion of the fuel injected into the combustion chamber. Reduction of ignition delay of the vegetable oil in the hot environment of the LHR engine was the reason for improved performance of the engine. The optimum injection timing was observed to be 28.5°b TDC with LHR engine with biodiesel operation, where it gave higher BTE at all loads when compared to CE with neat diesel operation.

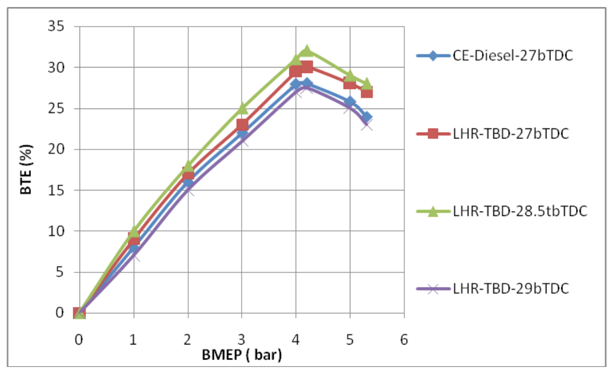


Fig. 5. Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) at various injection timings with tamarind biodiesel (TBD) in LHR engine

Fig. 6. shows the variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in the both versions of the engine with tamarind biodiesel, at various injection timings at an injector opening pressure of 190 bar.

LHR engine exhibited higher peak BTE when compared to CE at recommended injection timing and optimum injection timing. This showed that LHR engine was more suitable for biodiesel. Higher heat release rate and faster rate of combustion of fuel might have improved thermal efficiency with LHR engine in comparison with CE with biodiesel operation.

Fig. 7 shows variation of particulate matter (PM) with and without EGR with different versions of the

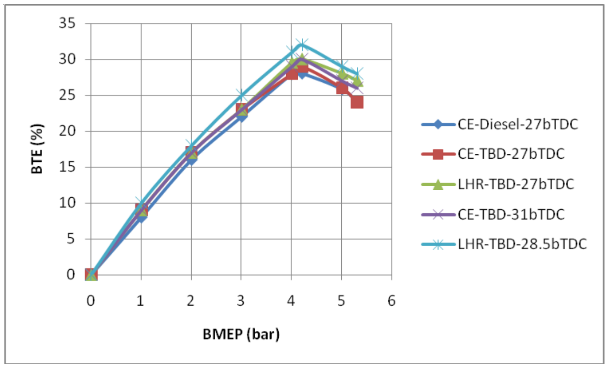


Fig. 6. Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) at recommended injection timing and optimum injection timing with tamarind biodiesel (TBD) in both versions of the engine.

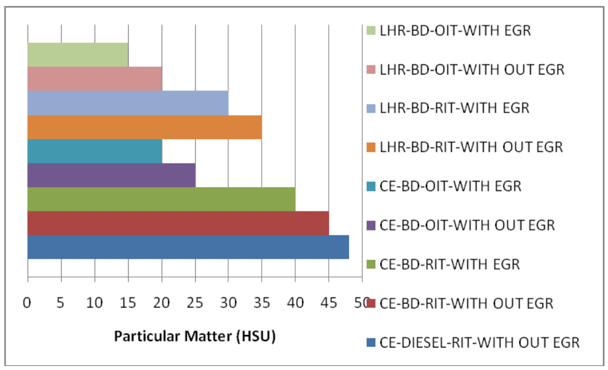


Fig. 7. Variation of particulate matter with and without EGR with different versions of the engine

engine at recommended injection timing and optimum injection timings.

Parrticulate matter (PM) at full load decreased marginally with provision of EGR with both versions of the engine at their different operating conditions due to faster rate of combustion of the fuel which improved combustion with lower combustion temperatures. PM depends on size of the fuel particle or SMD of fuel particle, injection pressure, depth of penetration of fuel particle in air or oxygen zone, properties of fuel particle such as density, viscosity, duration of combustion, atomization, spray characteristics of the fuel, oxygen-fuel ratio, availability of oxygen in the combustion chamber and combustion temperatures. Hence fuel cracking reactions were eliminated with low combustion temperatures with EGR due to non-availability or partial availability of oxygen causing reduction of PM. Depth of fuel particle into air or oxygen zone was improved with faster rate of combustion with EGR. Duration of combustion, which was proportional to viscosity of injected fuel was reduced with EGR due to hot exhaust gas which was re recirculated. Spray characteristics of fuel particle improved with EGR., which reduced PM.

Fig.8 shows variation of nitrogen oxide levels with and without EGR with different versions of the engine at recommended injection timing and optimum injection timings. As mentioned earlier, nitrogen oxide levels depend on availability of oxygen and combustion temperatures. Nitrogen oxide levels at full load decreased drastically with the provision of EGR with both versions of the engine at their different operating conditions due to reduction of combustion temperatures, as there was no supply of oxygen in the exhaust gases. There was a reduction of 60% of nitrogen oxide levels with provision of EGR when compared without EGR. Oxygen supply was reduced, hence combustion temperatures reduced leading to reduce NO_x levels. The principle of EGR is to reduce NO_x levels for both versions of the engine which includes LHR engine. As mentioned earlier, LHR engine gave higher NOx levels, which is reported by earlier researchers. So in order to improve the performance of the engine with simultaneous reduction of NO_x levels and PM, the principle of EGR was employed in the investigations carried out by the author.

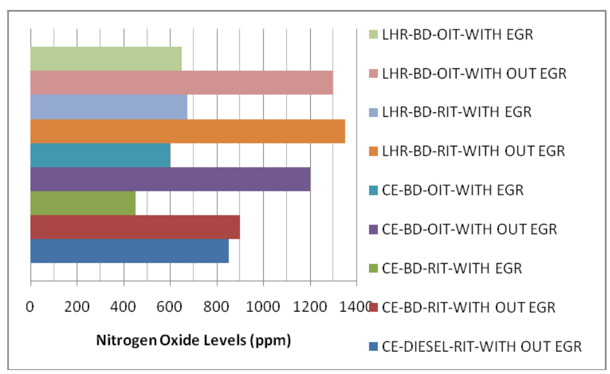


Fig. 8. Variation of nitrogen oxide levels with and without EGR with different versions of the engine.

Conclusion

1. The optimum injection timing was found to be 31°bTDC with biodiesel with conventional engine while it was 28.5°bTDC with LHR engine with biodiesel operation.

2. Particulate matter was reduced by 30% with EGR in comparison without EGR with both versions of the engine.
3. Nitrogen oxide levels were decreased by 50% with EGR in comparison without EGR with both versions of the engine.

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