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Impact of Turbocharger and Exhaust Gas re-circulation on performance, Combustion and Emission Characteristics on Diesel Engine with Zirconia Coated Piston Fueled with Rape Seed oil Methyl Ester

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ABSTRACT

This paper presents the rape seed oil methyl ester fueled combustion study undertaken on a supercharged, ceramic coated piston DI diesel engine investigating the combustion, performance and emissions production at a range of engine loads, EGR levels and intake air boosting conditions. The utilization of EGR and intake air boost with biodiesel fuel combustion allows simultaneous NO_x and particulate emissions reduction at conditions closer to on-road driving conditions. The results showed that while biodiesel can be favorable in reducing CO_2 and particulate emissions, it causes an increase in NO_x emissions when the intake energy contribution is increased. A reduction in the number of fine and ultrafine particles (diameter 0.05–0.2 μm) was observed when EGR was added to the engine, especially at the low and intermediate intake air boost levels. At high EGR levels (equivalent to 20% intake O_2 concentration reduction) significant reductions in exhaust particulate mass of up to 75% were observed at 15% energy levels. An attempt was made to identify the optimum EGR operating window at the different engine loads, intake air boost levels. It was observed that the RME, ceramic coated piston with 15% EGR along with turbocharger reduces NOx emission to a significant value without rise in BSFC.

KEYWORDS: Rape see oil methyl ester; EGR; Ceramic coated piston; Turbocharger; Performance and emission study..

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INTRODUCTION

Biodiesel is an alternative fuel for diesel engines that is produced by chemically reacting a vegetable oil or animal fat with an alcohol such as methanol. The reaction requires a catalyst, usually a strong acid or base such as sulphuric acid sodium or potassium hydroxide, and produces new chemical compounds called methyl esters. It is these esters that have come to be known as biodiesel. A possible association has been shown between the intake of trans fatty acids and the risk of coronary heart disease. They are proven to produce adverse effects on blood lipids, including increasing LDL-cholestrol concentration and decreasing HDL-cho-lestrol concentration. Dietary trans fats not only include mono- and poly unsaturated fatty acids, but also conjugated linoleic acids [1,2]. Biodiesel, produced from different vegetable oils (soybean, rapeseed and sunflower, for example), seems very interesting for several reasons: it can replace diesel oil in boilers and internal combustion engines without major adjustments; only a small decrease in performances is reported; almost zero emissions of sulfates; a small net contribution of carbon dioxide (CO_2) when the whole life-cycle is considered (including cultivation, production of oil and conversion to biodiesel); emission of pollutants comparable with that of diesel oil. Criteria pollutants are reduced with biodiesel use. Tests show the use of biodiesel in diesel engines results in substantial reductions of unburned hydrocarbons, carbon monoxide, and particulate matter. The exhaust emissions of total hydrocarbons (a contributing factor in the localized formation of smog and ozone) are on average 67 percent lower for biodiesel than diesel fuel. Biodiesel reduces the health risks associated with petroleum diesel. Biodiesel emissions show decreased levels of polycyclic aromatic hydrocarbons (PAH) and nitrated polycyclic aromatic hydrocarbons, which have been identified as potential cancer causing compounds. Biodiesel is the first and only alternative fuel to have a complete evaluation of emission results and potential health effects submitted to the U.S. Environmental Protection Agency. For these reasons, several campaigns have been planned in many countries to introduce and promote the use of biodiesel [3-6].

However production cost of the biodiesel is not economically, competitive with petroleum based fuel according to relatively high cost of the lipid feed stocks, which are usually edible-grade refined oils. The process of removal of all glycerol and the fatty acids from the vegetable oil in the presence of a catalyst is called transesterification. With low-cost lipid feed stocks containing high amount of free fatty acids (FFA), conventional biodiesel production by transesterification with alcohol using base catalyst is not appropriated. A two-step process is then proposed [7-9]. The first step of the process is to reduce FFA content in vegetable oil by esterification with methanol and acid catalyst. The second step is transesterification process, in which triglyceride (TG) portion of the oil reacts with methanol and base catalyst to form ester and glycerol. The acid catalyst is generally sulfuric acid [10,11], while the base catalyst is usually sodium or potassium hydroxide. Product from the reaction is separated into two phases by gravity [12,13]. One of the considerable alternative renewable fuel sources is vegetable oils which have similar combustion characteristics and psychochemical properties to the petroleum diesel. The researchers krupakaran et al (2018) conducted an experimental investigation on various blends of Mimusops Elangi biodiesel on four stroke single cylinder diesel engine at a constant speed. They revealed that B20 has superior performance and decrease the emission levels and marginally increased the NOx emissions[14]. The researchers krupakaran et al (2018) conducted an experimental investigation on various injection timing like 19 ^{0} bTDC, 21^0 bTDC, 23^0 bTDC , 25^0 bTDC and 27 ^{0} bTDC on four stroke single cylinder diesel engine at constant speed for B20+25ppm of TiO_2 nanoparticle[15]. They revealed that 250 bTDC has optimum injection timing for the engine behavior. R. L. Krupakaran et al. (2016) investigated the palm oil methyl ester (PME) with various dosages of Al_2O_3 nanopartical as a result of this study, improved the engine performance and reduced the engine exhaust emissions[16].

2. MATERIALS AND METHODS

2.1. Production of Biodiesel

The process of preparation of biodiesel from vegetable oil is called transesterification. The method of preparation of biodiesel from vegetable oil varies based on the content of Free Fatty Acid present in the vegetable oil. The Rape seed oil was used for making Rape seed oil methyl ester in this study. The Rape seed oil contains high free fatty acid of 4.9%. It is difficult to transesterify the high FFA vegetable oils using the commercially available alkaline catalyst process. Hence a two stage process namely acid esterification and alkaline esterification has to be followed to esterify the vegetable oil containing high FFA.

2.2. Acid Esterification

The one liter of rape seed oil is poured into the flask and heated to about 50ºC. Then 250ml of methanol is added with the preheated rape seed oil and stirred for a few minutes. Then 0.5% of sulphuric acid is added with the mixture. Heating and stirring is continued for 20-30 minutes at atmospheric pressure. On completion of this reaction the product is poured into a separating funnel for separating the excess alcohol. The excess alcohol with sulphuric acid and impurities moves to the top surface and is removed. The lower layer is separated for further processing. The first step reduces the FFA value of raw rape seed oil to about 2% using acid catalyst.

2.3. Alkaline Esterification

The product of acid catalyzed esterification are preheated to the required reaction temperature of 45 ± 5ºC in the flask. Meanwhile 5 gm of KOH is dissolved in 300ml of methanol and is poured into the flask. The mixture is heated and stirred for 30 minutes and the reaction is stopped and the products are allowed to separate into two layers. The two layers which contained impurities and glycerol is drawn off. The ester remains in the upper layer. Methyl esters are washed to remove the entrained impurities and glycerol. Hot distilled water is sprayed over the surface of the ester and stirred gently. Lower layer is discarded and the upper layer is separated.

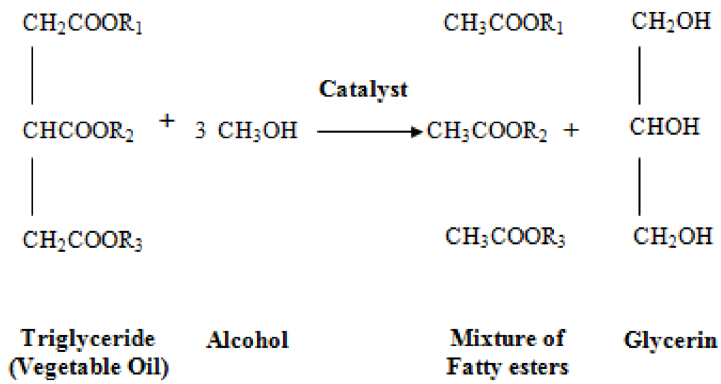

Fig.1. Transesterification process

Table 1: Comparison of properties of diesel and RME

Properties	Diesel	RME
Heatingvalue(kJ/kg)	43,000	39,500
Fire point° C	65	72
Viscosity Cst	2.7	4.7
Specific gravity	0.85	0.872
Flash point °C	52	80
Density(kg/m^3)	850	860

3. EXPERIMENTAL APPARATUS AND PROCEDURE

The Experimental work involves observing and taking safety precautions, observations and noting down the engine performance, emissions and combustion parameters using appropriate Instruments. It includes intake air measurement, fuel measurement, power measurement, cylinder pressure measurement and emission measurements. The schematic and photographic view of the experimental set up is shown in Figure 1(a) and Figure 1(b). Two separate fuel-measuring systems were provided to measure both conventional fuel and rape seed oil methyl ester. If the present quantity was not enough to maintain the rated speed then the period was adjusted to maintain the speed and the corresponding fuel consumption was calculated from Figure 1(a) and Figure 1(b). The electrical dynamometer was used for measuring power output of the engine. The detailed specification of the engine shown in Table 4. The electrical power created by the dynamometer is usually released as heat through set of electrical resistances. The load and speed of the engine can be enhanced or decreased on the dynamometer and thereby on the engine, by switching on or off the load resistances and by varying the field strength.

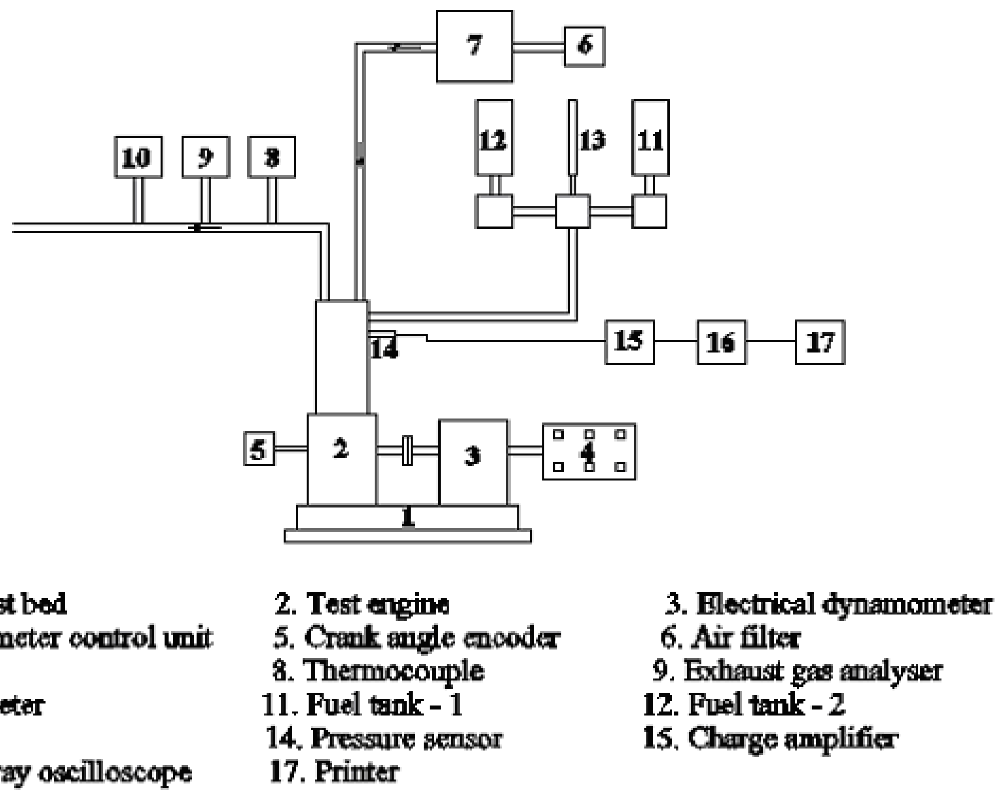

Fig.2. Experimental setup

Exhaust emission from the engine was measured with the help of AVL DI Gas 444 analyzer and smoke intensity was measured with the help of Bosch AVL 437 smoke meter. Two separate sampling probes were used to receive sample exhaust gases from the engine for measuring emission and smoke intensity, respectively. An AVL smoke meter was used to measure smoke samples from the engine. A K-type thermocouple and a temperature indicator were used to measure the exhaust gas temperature. A Kistler (601A) water cooled pressure transducer was used to measure cylinder. A Kistler crank angle encoder on the crankshaft (7200 points per cycle) was used to measure pressure data acquisition. For each measured point, the pressure data of 100 cycles were recorded. The analysis software AVL indicom to determine the Heat release rate, cumulative heat release rate, etc. At the beginning engine was started at no load for engine to warm up and the engine was gradually loaded from zero load to full load and all the necessary reading are taken.

Table 2: Specification of the test engine

Make & Model	Kirloskar & TV1
Rated Power	5.2 kW @ 1500 rpm
Number of Cylinders	Single
Combustion chamber	Hemispherical
Piston bowl	Shllow bowl
Compression ratio	17:5:1
Rated Speed	1500 rpm
Bore Diameter	87.5 mm
Stroke Length	110 mm
Injection Pressure	220 bar
Injection Timing	23 deg CA BTDC
Fuel Injection type	Direct
Number of holes in nozzle	3
Spray hole diameter	0.25mm
Spray cone angle	110
Cubic Capacity	661.45 cc
Type of loading	Electrical Load
Type of cooling	Water cooling
Type of ignition	Compression Ignition

A schematic diagram of the EGR arrangement and Turbocharger is shown in Figure 3. Metal pipes were installed between the exhaust pipe and the intake pipe, to route the exhaust gases back to the engine inlet system, where the hot gases were inducted into the succeeding cycles. Two gate valves were provided, one in the exhaust pipe and other in the intake pipe to divert a fixed quantity of the exhaust gases into the intake manifold so as to mix with the incoming air before being inducted into the combustion chamber. The photographic view of the experiment is shown in Figure 3.

The EGR ratio was obtained from the measured mass flow rate of air with and without EGR and the EGR percentage was calculated using the formula given by Deepak Agarwal et al (2006), Yasufumi Yoshimoto et al (2001):

$$EGR\% = \frac{[M_a] \text{ without EGR} - [M_a] \text{ with EGR}}{[M_a] \text{ without EGR}}$$

where, = $[M_a]$ Mass flow rate of air, kg/s

With the knowledge of the intake air flow without EGR, the mass flow rates and the manometer heads for the required quantities of EGR are predetermined and the EGR control valve is opened until the required head is achieved. For the EGR, uncooled recirculated exhaust gas was directly inducted into the intake pipe and the gas flow was regulated with an EGR control valve and inlet/outlet gas temperatures were measured with a digital thermocouples. During the experiment, the engine was operated at a constant speed of 1500 rpm.

Fig.3. Experimental setup with EGR and Turbocharger

Tests were carried out for constant speed with various loads from 0 to 100 % with varying EGR quantity admitted in to the cylinder. Inlet gas temperature which was recirculated can be kept close to exhaust temperature to reduce ignition delay which reduce the quantity of fuel burned in the premixed burning zone which reduce NOx emission. The temperature of the intake gas, exhaust gas and outlet cooling water were measured using thermocouples. The experiments were repeated from no load to full load while the EGR quantity varies in the values of 10%,15% and 20 %. Since 5% EGR does not show significant difference on the performance and emission characteristics. At these three different EGR flow rates the combustion, performance and emission characteristics were analysed for the 30% Water emulsified biodiesel fuel and compared with the 30% water-biodiesel emulsion without EGR.

3.1 Yitria stabilized Zorconia coating

A bond coat of 50 µm and a yttria stabilized zirconia (YSZ) coat of 250 µm were then applied onto the piston crown by plasma spraying using a robot arm. The application of a TBC is only restricted to the piston crowns in this context because the surface constitutes a major part of the combustion chamber surfaces exposed to high-temperature gases. The authors report that when thermal insulation is applied only to a certain part of the combustion chamber, it would surely increase the thermal loading of the others due to the increase in gas temperature. Extension of surface coating to other parts of the engine components is under exploration.

Fig. 4. Yitriya stabilized Zirconia coated piston

3.2 Estimation of uncertainty

Ambiguities and uncertainties are to be estimated while conducting an experimental analysis. These inaccuracies may arise due to environmental factors, errors in calibration of instruments, human errors while observation and reading. The uncertainty values of measured parameters were estimated from the range and accuracy of instruments and are shown in Table 4. In order to get more accurate uncertainty limits for computed parameters the principle of root sum square method was used and it is given by equation -1.

R= ∑ Xi2 -- (1)

Where R is the total percentage of uncertainty and Xi is the individual uncertainty of computed parameters. The total percentage uncertainty of computed parameters were calculated and given below

$R= X_1^2+X^2+X_3^2+X^2+X_5^2$

$R= (1)^2+(.4)^2+(1)^2+(.1)^2+(.2)^2$

$R= \pm 1.48\%$

4. RESULTS AND DISCUSSION

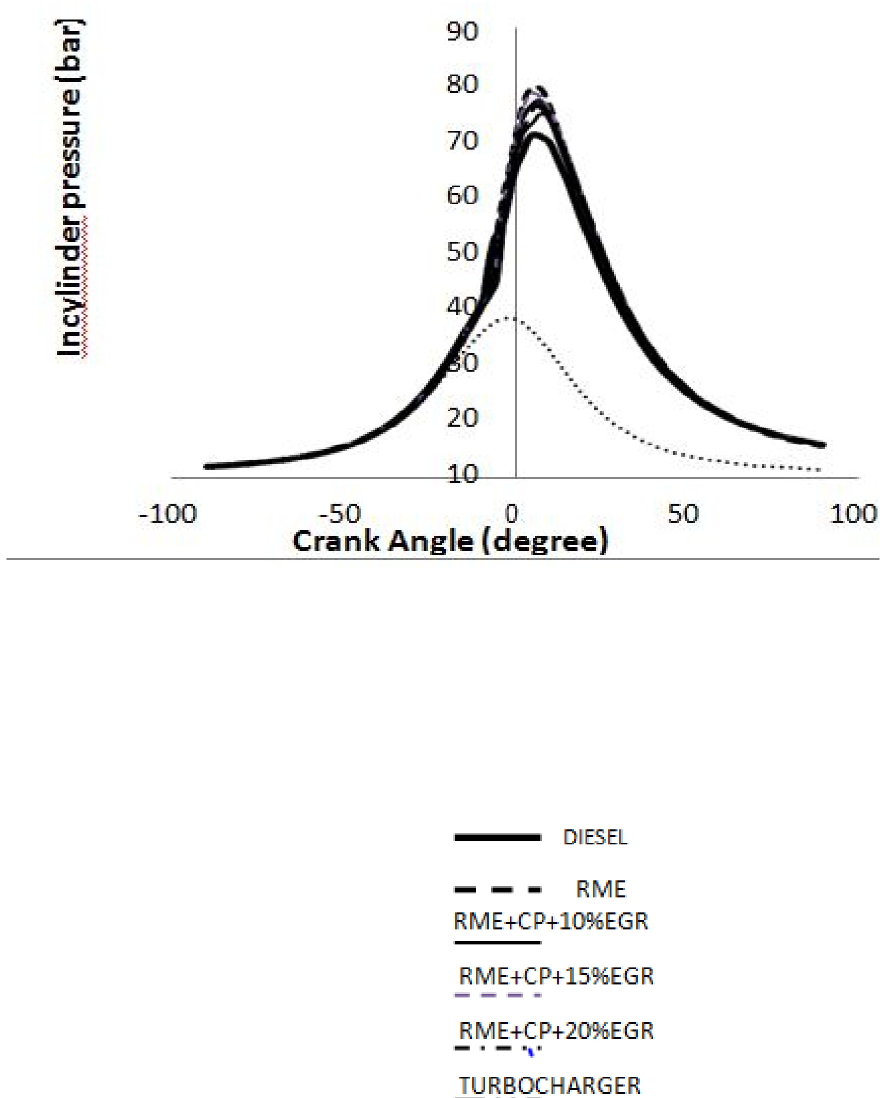

Fig.5 Variation of cylinder pressure with crank angle

Figure 5 shows the variation of cylinder pressure with crank angle for diesel, Rape seed oil methyl ester, rape seed oil methyl ester with various proportions of EGR in a ceramic coated piston engine with turbocharger. The combustion characteristics were analyzed based on the measured in-cylinder pressure. From the figures, it can be seen that the occurrence of peak pressure advances with respect to the top dead centre with an increase in load. Also, the occurrence of peak pressure retards with an increase in EGR levels. This leads to an increased rate of pressure rise and engine noise, whereas the cylinder pressure reduces for EGR and the occurrence of peak pressure is maximum in RME biodiesel. The ignition delay has been increased in increasing the EGR concentration in both diesel and biodiesel and the engine knock increases at higher load with these blends. The B100 also has variable increase in peak pressure compared to diesel. In general, peak pressure varies from about 69 to 70 bars for the entire load range considered. For diesel the cylinder peak pressure was 69 bar , for rape seed oil methyl ester the peak cylinder pressure was 73 bar, for ceramic coated piston with RME and with 10% EGR the peak cylinder pressure was 74.5 bar, for RME with ceramic coated piston with 15% EGR the peak cylinder pressure was 76 bar , for ceramic coated piston with RME and 20% EGR the cylinder peak pressure was 76.6 bar, for RME with ceramic coated piston with 20 % EGR and turbocharger the peak cylinder pressure was 77 bar. This increase in pressure with the increase in EGR quantity and turbocharger was to rise in delay period due to the presence of exhaust gas in to the cylinder.

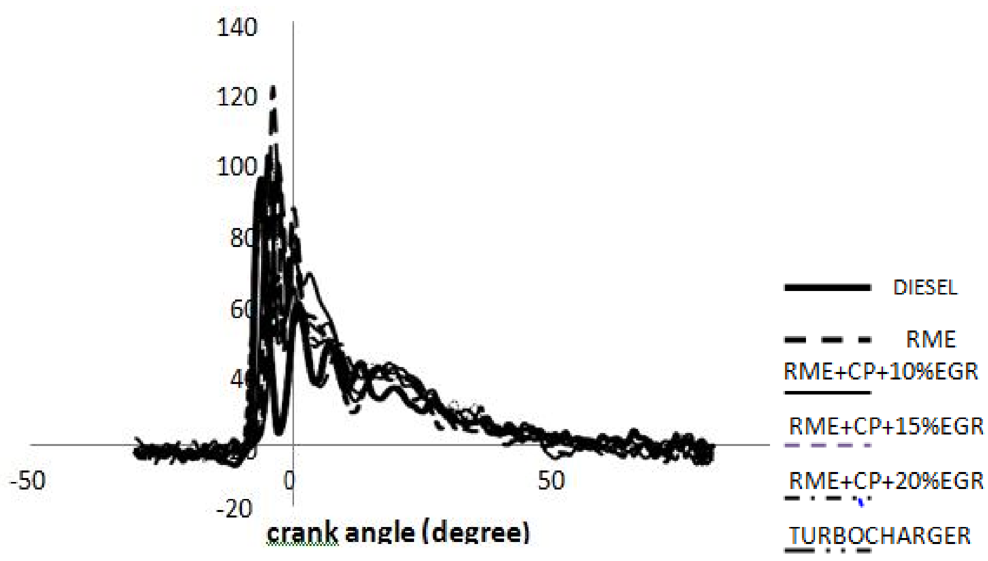

Fig. 6 Variation of heat release with crank angle

The Figure 6 shows the variation of net heat release rate with crank angle for diesel, RME, RME with ceramic coated piston and with different % of EGR. It is seen from the figure that the heat release was found to be high for RME and with the addition of EGR the heat release decreases. This may be due to the fact that with the addition of EGR the quantity of oxygen available for combustion reduces which makes incomplete combustion and also due to hot EGR the ignition lag reduces and the amount of fuel burned in the premixed combustion zone also reduces and hence the heat release decreases. For diesel the heat release rate was found to be 89 J/deg CA, for RME the heat release was found to be 85 J/deg CA, for RME with coated piston and 10% EGR the heat release rate was found to be 80J/deg CA, for RME with coated piston and 15% EGR the heat release rate was found to be 72 J/deg CA, for RME with coated piston and 20 % EGR the heat release rate was found to be 70 J/deg CA, for RME with coated piston and 20 % EGR with turbocharger the heat release rate was found to be 74.5 J/deg CA, The heat release rate decrease with the addition of EGR in to the cylinder because the amount of oxygen available for combustion got reduced and the cylinder temperature reduces which in turn reduces the combustion chamber temperature and the NOx formation. The HRR increases with turbocharger due to the supply of compressed air to the engine by the compressor.

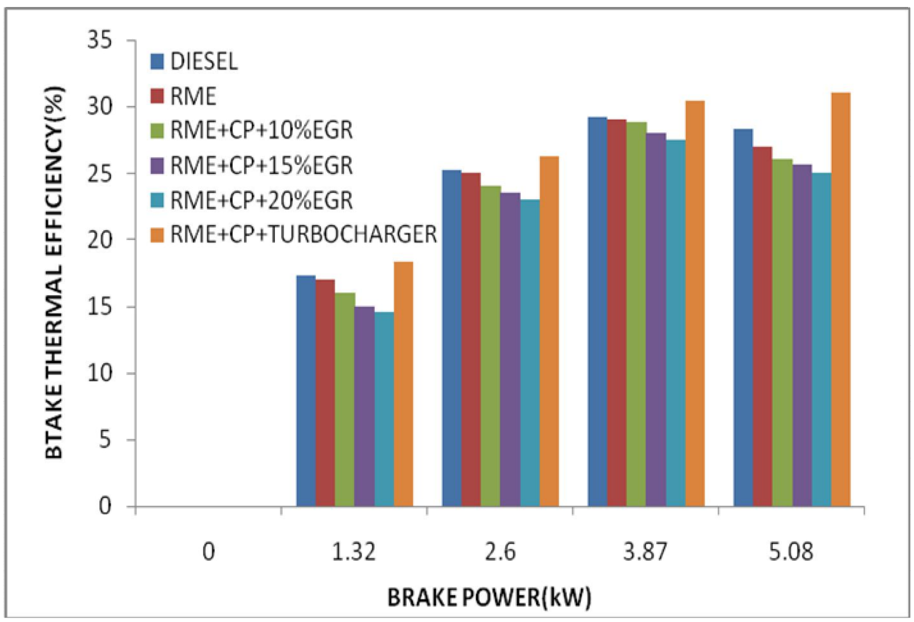

Fig. 7. Variation of BTE with BP

Figure 7 shows the variation of BTE with respect to BP for the engine running with Rape seed oil methyl ester at different operating conditions. It was found that the engine has lower brake power compared to conventional diesel when using RME as duel with and without EGR. Lower heating value and higher density as well as higher viscosity of Rape seed biodiesel were found to be the major factors for the results. EGR employment on diesel engine for the fuel tests also establishes profound results. Biodiesel with EGR has produced lower power compared to the condition without EGR with the reduction rate of nearly of 4.1% due to different combustion efficiency of the engine. This result shows that when diesel engine operating with EGR, engine power dropped rapidly due to lower oxygen burned in the chamber and leads to incomplete fuel burning as well as lower thermal efficiency. It is illustrated that the brake torque when the engine running with RME has decreased to average 2.8% respectively compared to conventional diesel. Again, biodiesel psychiochemical properties include density and viscosity has to be blamed for the existing results. In other section, RME with EGR had lower torque as compared to diesel with EGR over 76.3% respectively. Lack of oxygen during combustion leads to the combustion inefficiency and incomplete burning of the fuels for EGR. Incorporating Turbocharger at the exhaust of the diesel engine results in increased thermal efficiency when compared to raw diesel operation.

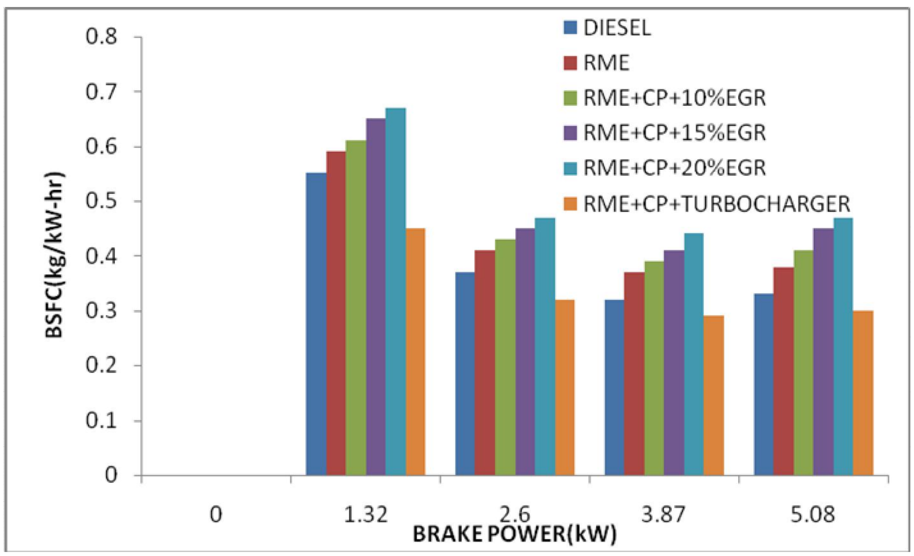

Fig. 8 Variation of BSFC with BP

Figure 8 shows the variation of brake specific energy consumption with respect to Brake power for Diesel, RME, RME with coated piston, various EGR rates and turbocharger. It can be seen from the figure that increase in EGR rate increases the specific energy consumption of the engine due to reduced intake oxygen concentration which resulted in reduced combustion gas temperature. It is also seen that for RME the BSFC was found to be 0.3 kg/kW-hr, for ceramic coated piston with RME with 10% EGR the BSFC was found to be 0.31 kg/ kW hr, for RME and ceramic coated piston with 15% EGR the BSFC was found to be 0.33 kg/kW hr, for RME and ceramic coated piston with 20% EGR the BSFC was found to be 0.36 kg/kW hr. This increase in specific energy consumption was due to insufficient quantity of oxygen available for combustion.

Results have demonstrated that diesel had the lowest bsfc overall with those two conditions throughout the study. Increase in BSFC was understandable as RME have approximately 2.1% less energy than conventional diesel (figure 2(c)). The higher the RME contents in the biodiesel, the lower its heating value.

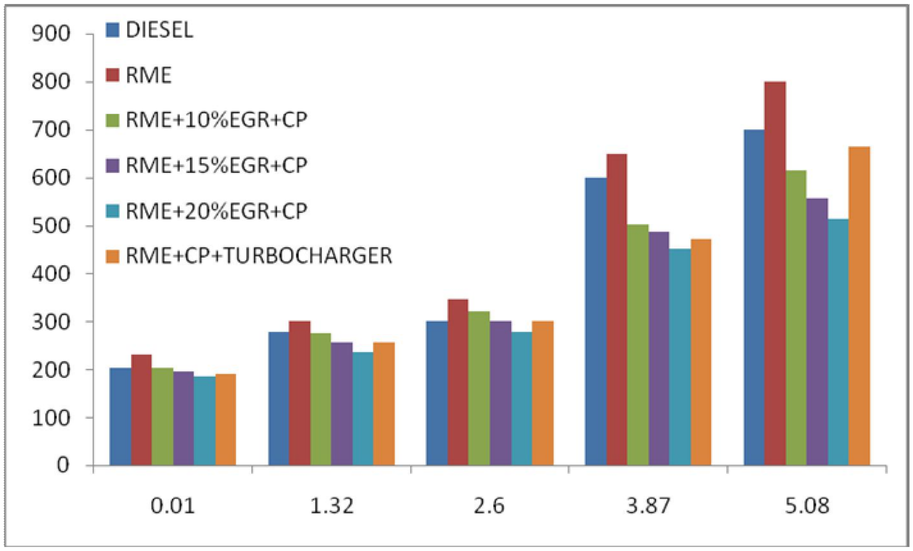

Fig.9 Variation of NOx emission with BP

Figure 9 shows the variation of NOx emission with brake power output for Diesel, RME, RME with coated piston and various EGR rates. It can be seen from the figure that increase in EGR rate reduces the NOx emission due to reduced intake oxygen concentration which resulted in reduced combustion gas temperature. It is also seen that for RME the NOx emission was found to be 2282 ppm , for ceramic coated piston with RME with 10% EGR the NOx emission was found to be 1562ppm, for RME and ceramic coated piston with 15% EGR the NOx emission was found to be 955 ppm, for RME and ceramic coated piston with 20% EGR the NOx emission was found to be 1280 ppm. This increase in NOx emission was due to insufficient quantity of oxygen available for combustion, reduced intake oxygen concentration which reduced flame temperature which reduces the formation of NOx.

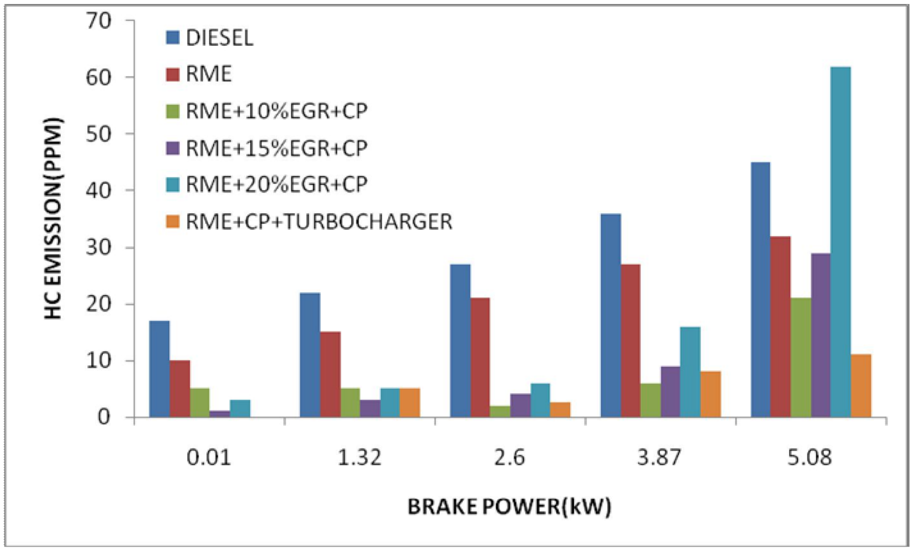

Fig.10 Variation of HC emission with BP

Figure10 shows the variation of HC emission with brake power output for Diesel, RME, RME with coated piston and various EGR rates and turbocharger. It can be seen from the figure that increase in EGR rate increase the HC emission due to reduced intake oxygen concentration which resulted in reduced combustion gas temperature. It is also seen that for RME the HC emission was found to be 17 ppm, for ceramic coated piston with RME with 10% EGR the HC emission was found to be 21ppm, for RME and ceramic coated piston with 15% EGR the HC emission was found to be 29 ppm, for RME and ceramic coated piston with 20% EGR the HC emission was found to be 62 ppm. This increase in HC emission was due to insufficient quantity of oxygen available for combustion, reduced intake oxygen concentration which reduced flame temperature which increase the formation of HC.

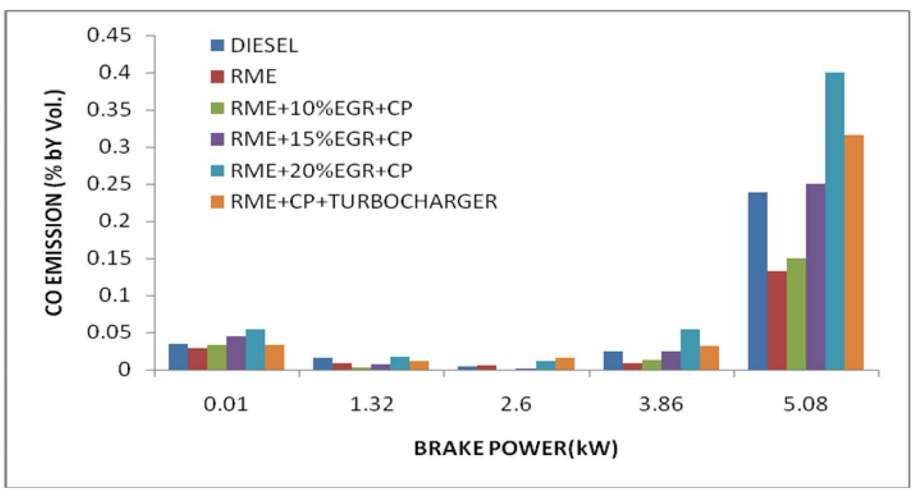

Fig. 11 Variation of CO with BP

Fig. 11 shows the variations of CO emission with respect to the load. The CO emission decreases with increase in load for all the fuel samples except at full load condition. It is observed that CO emissions increase with the addition of EGR. The EGR shortens the ignition delay period, reduces the air-fuel mixing and higher carbon combustion activation leads to complete combustion. Low flame temperature and too rich fuel air ratio are the major causes of CO emissions from diesel engine. CO emissions are due to incomplete combustion of fuel either due to inadequate oxygen or flame quenching. Higher CO emissions results in loss of power in engine. Different factors can be at the origin of its formation like insufficient residence time, too low or too high equivalence ratios are part of those reasons. CO emissions are the products of improper and incomplete combustion resulting from antioxidant addition. The oxidation of CO is directly related to the amount of OH radicals present in the reaction. It is also seen that for RME the CO emission was found to be 0.133 % by volume, for ceramic coated piston with RME with 10% EGR the CO emission was found to be 0.65 % by volume, for RME and ceramic coated piston with 15% EGR the CO emission was found to be 0.79 % by volume, for RME and ceramic coated piston with 20% EGR the CO emission was found to be 0.60 % by volume.

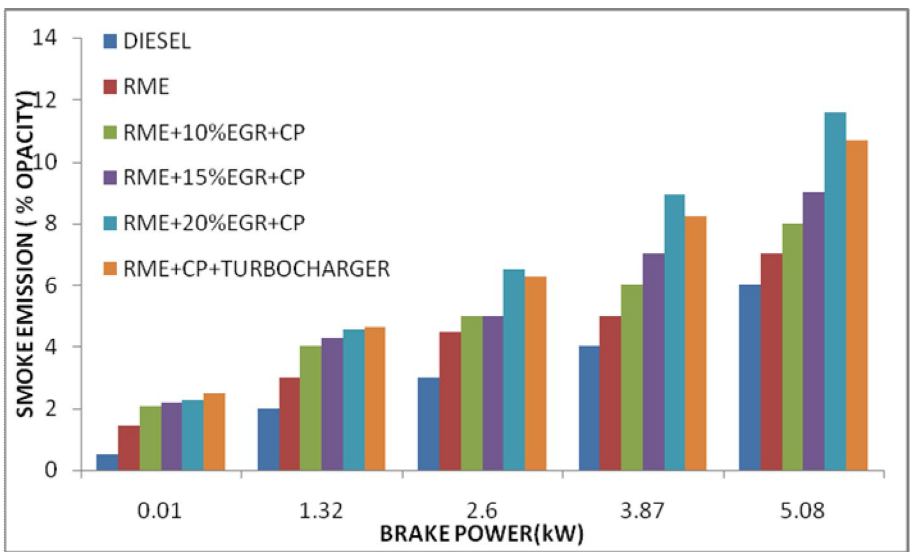

Fig. 12. Variation of smoke opacity with BP

The Fig 12 shows the variation of smoke emission with brake power for Diesel, RME, RME with coated piston and various EGR rates along with turbocharger. It is seen that the smoke emission was found to increase with the increase in EGR % and decrease with turbocharger. This may be attributed to the absence of lean mixture due to the addition of exhaust gas into the combustion chamber. The smoke emission increases partly because the diffusion combustion is extended by EGR due to slow down of the premixed combustion resulting in longer combustion duration. At high loads the flame engulfing the fuel spray propagates all over the combustion chamber producing a large amount of soot which in turn indicates the lack of oxygen at high loads causes a sharp rise in smoke emission. It is also seen that for diesel the smoke emission was found to be 61.8 opacity %, for RME the smoke emission was found to be 60.2 opacity %, for ceramic coated piston with RME with 10% EGR the smoke emission was found to be 63.5 opacity %, for RME and ceramic coated piston with 15% EGR the smoke emission was found to be 69 opacity %, for RME and ceramic coated piston with 20% EGR the smoke emission was found to be 75 opacity %. This increase in smoke emission was due to insufficient quantity of oxygen available for combustion, reduced intake oxygen concentration which reduced flame temperature which increase the formation of smoke.

5. CONCLUSIONS

Based on the experimental test results from the engine testing, it can be concluded as follows:

- Both EGR and biodiesel have increased the specific fuel consumption (SFC) and reduced the engine performance of the diesel engine include engine power and torque as well as brake thermal efficiency.
- Other emissions such as CO and HC also found to have decreased simultaneous with the use of biodiesel fuel.
- Biodiesel has higher oxygen-natured which leads to better combustion, produced higher NOx emission in exchange.
- This higher NOx emission can be effectively controlled by using EGR.
- EGR increases the CO and HC emissions due to incomplete combustion and reduced the exhaust temperature in advance.
- For turbo charger the brake thermal efficiency increased and decreased the brake specific fuel consumption.
- Both the heat release and pressure in the cylinder was increased by providing turbo charger.
- The emissions of HC,CO and smke was decreased by providing turbo charger.
- In summary, engine operation fueled with rape seem-biodiesel while employing EGR results in NOx emission reductions without neglecting engine performance as well as exhaust emissions.

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