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Experimental Investigation of Thermal Barrier (8YSZ-MGO-TIO$_2$) Coated Piston used in Diesel Engine

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ABSTRACT

A single cylinder diesel engine was tested under different loading conditions with its piston crown coated with the Thermal Barrier Coating (TBC). The main objective of this work is to investigate the effect of the TBC on performance and emission characteristics in the diesel engine. The top surface of the piston was coated with 100 µm thick NiCrAl as lining layer by plasma spray method. A mixture of 88% Yttria stabilized Zirconia, 4% MgO and 8% TiO_2 of 150 µm thick were coated over the lining layer. Exhaust emission (HC, NOx, CO and CO_2) parameters were investigated using AVL exhaust gas analyzer. The results showed that the brake thermal efficiency was increased by 10% and brake specific fuel consumption was decreased by 9.8% for coated piston in comparison with the uncoated piston engine. It was also observed that, smoke, CO and HC emissions were decreased in the TBC engine as compared with the baseline engine. In addition carbon di oxide (CO_2) and nitrogen oxide (NOx) emissions were partially increased.

Keywords*:* Yttria stabilized zirconia; Thermal barrier coating; Diesel engine; Piston crown; Plasma spray; Emission.

NOMENCLATURE

BP	Brake Power	CO_2	Carbon di-Oxide
BSFC	Brake Specific Fuel Consumption	HC	Hydro Carbon
BTE	Brake Thermal Efficiency	NO_x	Nitrogen Oxide
CO	Carbon Monoxide	TBC	Thermal Barrier Coating

1. INTRODUCTION

Diesel engines being an important part in today's agricultural and transport industries has limitations like rejection of about two third of the heat energy of the fuel energy to the coolant and exhaust. Only one third of the heat energy is used as power output. Low heat rejection (LHR) engine is the Diesel engine insulated by ceramics of combustion chamber parts like piston, connecting rod, cylinder head and manifold. LHR engines aims to do increase the thermal efficiency by reducing the heat lost to the coolant and exhaust. In order to maintain the engine temperature below the safe level, the cooling system absorbs the heat energy generated by combustion and friction by dissipating it to the surroundings.

Numerous analysts have utilized the thermal barrier coating technique dominatingly to build the heat resistance inside the ignition chamber to enhance the warm productivity of the current internal combustion engines. Ceramic coatings not just go about as heat opposing medium, yet in addition to keep the heat weariness and stuns in securing the substrates. The main purpose of ceramic coating is to reduce the emission of harmful gases like hydrocarbon and CO_2. The purpose of TBC supports the engine for better combustion in the combustion chamber by reducing the heat transfer through the cooling water.

Gehlot *et al*. (2016) predicted that the temperature of top surface of the piston (coated surface) is increasing by the increase in the radius of the holes. Sivakumar *et al*. (2014) indicated that the thin thermal barrier coated engine could reduce the heat loss to the cooling water and thermal efficiency improved at the level of 5% and also hydro carbon (HC) emission was reduced. Cerit *et al*. (2014) reported that the improvement in the performance of diesel engine by applying plasma splashed magnesia-stabilized zirconia coating on a piston crown. Jalaludin *et al*. (2013) exposed that the yttria-stabilized zirconia/NiCrAl coated piston crown encountered the minimum heat transitions than the uncoated piston surfaces and giving additional protection at the time of ignition operation. Azadi *et al*. (2013) demonstrated that the superior lifetime has to be achieved by maintaining the minimum thickness of coating layer. Das *et al*. (2014) Kirubadurai *et al.* (2016) in their research work, discussed about the result of thermal barrier coating thickness on the performance of a diesel engine. At first piston crowns were coated by Al_2O_3 (bond coat), then partially stabilized zirconia was coated on these piston crowns with different thickness. Finally, they predicted that the thermal efficiency were increased and the specific fuel consumption and smoke emissions were decreased with increasing the given load level. Sharma *et al*. (2015) by an experimental investigation, determined that the most suitable Y-PSZ thermal barrier coating thickness by conducting thermal torch and the thermal shock tests on aluminum alloy (AlSi) substrates coated by yttria stabilized zirconia. By experimental investigation, Karthickeyan and Balamurugan (2017) predicted that the effects of partially stabilized zirconia (PSZ) thermal barrier coating on engine piston crown, inlet and exhaust valve by using the blend of pumpkin seed oil methyl ester. Finally, they identified that at the condition of B25 and diesel mixture level, thermal efficiency was increased and fuel consumption was reduced both in coated and uncoated condition in engine. Based on experimental investigation, Karthickeyan (2017) has shown that Orange methyl ester with diesel was the best alternative to the conventional fuel. This has higher thermal efficiency, lower specific fuel consumption. Also CO, HC, NOx, and smoke were lowered in engine coated with partially stabilized zirconia. Banka *et al*. (2017) based on his thermal analysis with creating different sizes of hole on yttria-stabilized zirconia thermal coated piston surfaces, predicted that the highest temperature distribution occurred in the maximum size of hole present in the coated piston crown. Powell *et al*. (2017) investigated the effect of low temperature combustion engine performance and emission characteristics with coated yttria-stabilized zirconia piston. Thirunavukkarasu *et al*. (2016) reported that the effect of $MgO\text{-}ZrO_2$ and $Al_2O_3\text{-}13\%TiO_2$ thermal barrier coating on the piston crown with using methanol as a blend fuel in an engine. Finally, they concluded that the B20 methanol blend mixture with diesel is the best for both performance and emission characteristics in the diesel engine. Thirunavukkarasu *et al*. (2018) investigated the performance characteristics of thermal barrier coated piston crown in the variable compression ratio diesel engine with using single, four and five holes fuel injector nozzle. Jia *et al*. (2015) investigated about the effect of TiO_2 content on Al_2O_3 thermal barrier coatings on 6061 aluminum combination by plasma splashing. The erosion protection, thermal protection property and stage structure of these coatings were explored. The outcomes show that all the feedstock powders show stage change during the spray procedure. With the expansion of the TiO_2 content in the powder, the corrosion protection of the coating is improved however the heat protection property is diminished. Garud *et al*. (2017) determined that the peak cylinder pressures were increased up to 6 bars in a zirconium oxide ceramic coated piston crown LHR diesel engine and also they concluded that at low engine speed and low power output the unburnt hydrocarbon emission were increased with a TBC piston engine. Abedin *et al*. (2014) investigated that the temperature distribution and the effect of thermal barrier coated on engine piston as a function of various coating thickness. Finally, they concluded that 0.55mm coating thickness is the optimum coating thickness for diesel engine applications. Mingfa *et al*. (2018) investigated that the plasma spraying method was the familiar thermal spraying method for depositing TBC inside the engine cylinder walls due to its ability to melt the substrate at high temperature. In addition, high bond strength (15–25 MPa), lower porosity (1–7%), and wide range of coating thickness (300–1500 µm) are attainable by this process.

Based on the literature survey, it is concluded that YSZ are the reliable thermal barrier coating material on combustion chamber components in engine for improving the thermal performance, fuel consumption and also to reduce the emission characteristics in internal combustion engines. However, sufficient number of researchers discovered that the amount of NOx emission level was increased dramatically by using thermal barrier coating inside the combustion chamber. Pawlowski (2008) reported that stable phase structure at higher temperature conditions, low thermal conductivity, high Poisson's ratio and high coefficient of thermal expansion are the main requirements for good thermal barrier coating materials. Several researchers have used stabilized zirconia as a thermal barrier coating materials for piston crown and valves in the internal combustion engines. For improving the corrosion resistance of the coating in this work, the piston crown coated with 100 µm thickness of NiCrAl as lining layer and this layer was coated with 150 µm thickness of mixture that consists of 88% Yttria stabilized zirconia, 4% MgO and 8% TiO_2 by plasma spray coating method and the engine was tested for its performance and emission characteristics at various load conditions. With the expansion of TiO_2 and MgO content present in the YSZ powder, the corrosion opposition of the coating is improved. The potential reasons are that the melting point and brittleness of this mixture like MgO & TiO_2 are lower than those of YSZ, so it is simple for the mixture to scatter in the brittle YSZ substrate during spraying, in which these dispersively conveyed TiO_2 and MgO phases play a role of sealing hole, releasing stress and decreasing cracks on the piston crown due to high temperature at the time of combustion. The aim of this experimental work is to investigate how the mixture of Yttria stabilized zirconia, MgO and TiO_2 to improve the IC engine performance and emission characteristics.

2. PLASMA SPRAY TECHNIQUE

Thermal Barrier Coating techniques consist of different types such as physical vapour deposition method, chemical deposition method, atmospheric plasma spray method, and plasma arc method. Atmospheric Plasma spray method is the most suitable for this experimental study. The plasma spray is a process of providing coating on a metal surface by spraying molten metal on it. The powder form of material is infused into a high-temperature plasma flame, where it is quickly heated at very high speed. Plasma gas which contains helium, argon, hydrogen and nitrogen are streams through the anode and around the cathode which is formed as a nozzle. The plasma is started by a high voltage release which causes confined ionization and a conductive way for a DC arc to frame amongst cathode and anode. At first, the bond coat material like NiCrAl powder of 0.1 mm thickness coated on a piston crown by an 80 kW atmospheric plasma spray system. Then the composition of ceramic powder consists of 88% Yttria stabilized Zirconia, 4% MgO and 8% TiO_2 is coated on a piston crown to form 0.15 mm thin top coat. The spray parameters for both line coat and top coat are given in Table 1. The working of plasma spray coating is shown in Fig. 1. The pictures of uncoated piston and mixture of YSZ and MgO – TiO_2 coated piston are shown in Fig. 2. The detailed views of plasma spray specification are given in Table 2.

Table 1 Properties of thermal barrier coating materials [17]

Materials	Thermal Conductivity (W/mK)	Thermal Expansion 10^{-6} (1/K)	Melting Point (°C)
YSZ(80%-8% of mole of yttria remaining mole of ZrO_2)	1	10.9	2980
MgO (4%)	30	12	3135
TIO_2 (8%)	3.3	9.4	2123
NiCrAl (bond coat)	15	19	1673

Table 2 Specifications of Plasma spray coating

Coating parameters	Specifications
Plasma gun	3 MB plasma spray gun
Nozzle	GH Type nozzle
Organ gas pressure	100–120PSI
Organ gas flow rate	80–90LPM
Hydrogen gas pressure	50PSI
Hydrogen gas flow rate	15–18LPM
Feed rate of powder	40–45 g per minute
Distance of spraying	3–4in

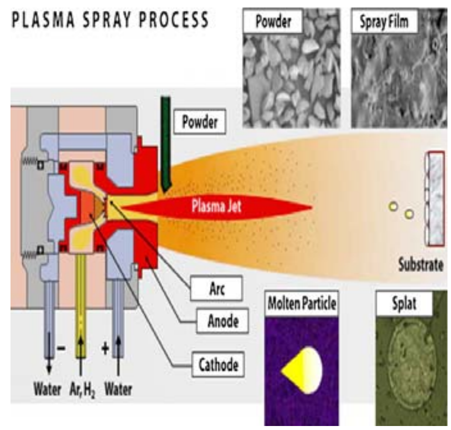

Fig. 1. Working of plasma spray technique.

3. EXPERIMENTAL SETUP

Technical specifications of experimental test rig are listed in Table 3. The experimental test rig consists of a variable compression ratio compression ignition engine, eddy current dynamometer, water cooling system, fuel supply system, lubrication system with computerized data acquisition system. The schematic diagram of experimental test setup is shown in Fig. 3. By using eddy current dynamometer the experiment were conducted at five different load conditions starting from no load level to full load level. By using AVL Five gas analyzer, the emission characteristics like carbon di oxide (CO_2), carbon monoxide (CO), unburnt hydro carbon (HC), and nitrogen oxide (NO_x) were measured. All the performance and emission characteristics were taken out using ARAI–EDACS controller setup.

Table 3 Specifications of the test engine

Parameters	Specification
General Details	Single cylinder, four stroke compression ignition engine
Stroke	110 mm
Bore	87.5 mm
Displacement	661 CC
Compression ratio	17.5
Rated output	5.2 kW
Rated speed	1500 rpm

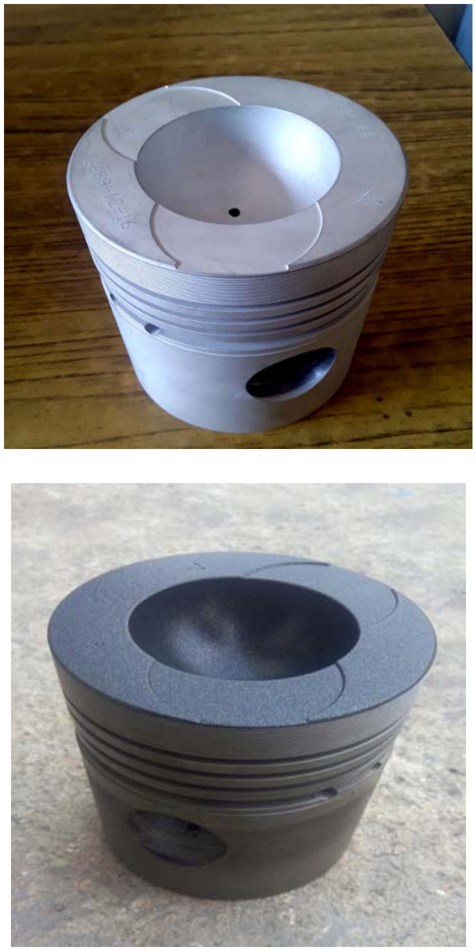

Fig. 2. Snapshots of uncoated piston and mixture of YSZ and MgO – TiO_2 coated piston.

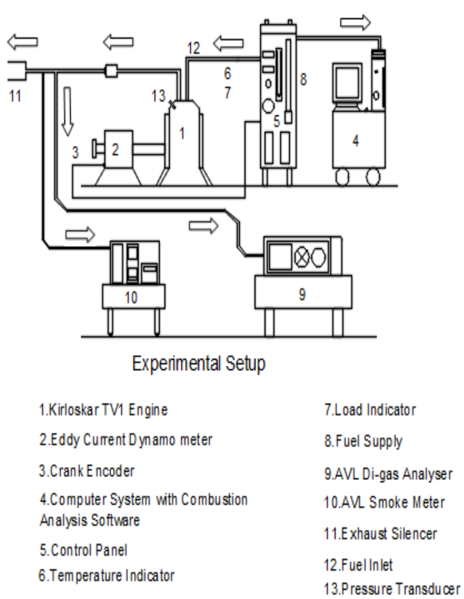

Fig. 3. Schematic diagram of Experimental Test setup.

Fig. 4. Photographic view of experimental setup.

The experiment setup enabling the evaluation of thermal performance parameters include brake power, brake thermal efficiency, volumetric efficiency, brake specific fuel consumption, heat equivalent of exhaust gas, heat equivalent of brake power, brake mean effective pressure and exhaust gas temperature. The accuracy of the instruments used in the experimental setup are listed in Table 4.

Table 4 List of instruments and its accuracy

S. No	Instruments	Accuracy
1	Gas analyzer	±0.02% CO ±0.03% CO_2 ±20 ppm HC ±10 ppm NO_x
2	Smoke	±0.1%
3	Temperature indicator	±1 °C
4	Speed	±10 rpm
5	Load	±0.1 kg
6	Burette for fuel measurement	±0.1 cc
7	Digital stop watch	±0.6 sec
8	Manometer	±1mm
9	Pressure pickup	±0.1
10	Crank angle encoder	±10

3.1 Error Analysis

In General, error analysis is carried out to examine the uncertainties in experiments. There are many uncertainties considered for the experiment as mentioned below: (a) Environmental and Experimental conditions, (b) Calibration of equipments, (c) Instruments used for experiment, (d) Observations during experiment. In accordance with Holman technique, the total uncertainty during experimentation was determined using propagation of error techniques. Table 5 shows the experimental uncertainty. The total uncertainty during experiment was found to be ±2.29%.

Table 5 Experiment Uncertainties

Parameters	Systematic Errors (±)
Speed	± 1 rpm
Load	± 0.1 N
Time	± 0.1 s
Brake power	± 0.15 kW
Temperature	± 1°C
NO_x	± 10 ppm
CO	± 0.03 %
CO_2	± 0.03 %
HC	± 12 ppm
Smoke	± 1 HSU

4. RESULT AND DISCUSSION

4.1 Engine Performance Characteristics

Engine performance characteristics like power, torque, and brake specific fuel consumption, brake thermal efficiency, volumetric efficiency and mechanical efficiency are measured and compared at different loading conditions maintained at constant speed.

4.1.1 Brake Specific Fuel Consumption

It is observed that, as compared to standard baseline engine, the BSFC is reduced by 9.8% and 17% at 25% load and full load conditions respectively as seen from the Fig. 5. Reduction in BSFC due to the lessening in the fuel utilization and enhanced energy change rate at all loading conditions in the TBC coated engine. This is due to the increase in temperature of the combustion chamber dividers, which builds the temperature of the supplied fuel from the heated fuel injecting nozzle which in turn reduces the fuel viscosity and better combustion of the fuel.

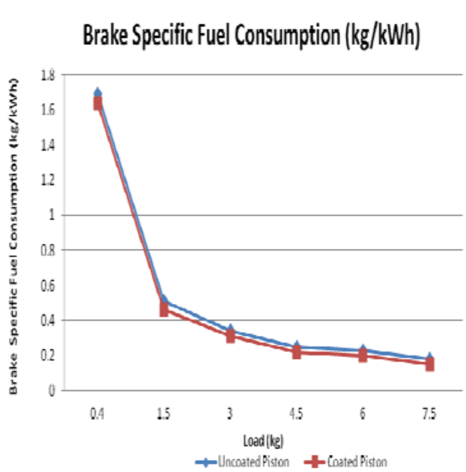

Fig. 5. Variation of baseline and TBC engine's BSFC under various load conditions.

4.1.2 Brake Thermal Efficiency

The peak level of brake thermal efficiency achieved for TBC coated engine and baseline engine is 36.4% and 33.5% respectively as depicted in Fig. 6. Maximum development of 10% in brake thermal efficiency is observed, when the engine is loaded at 75% of full load. This is due to fact that the thermal barrier coating does not permit to transmit the heat energy from the piston crown to atmosphere through cooling water or any other medium. Thus the fuel consumption is decreased, resulting increase in the brake thermal efficiency.

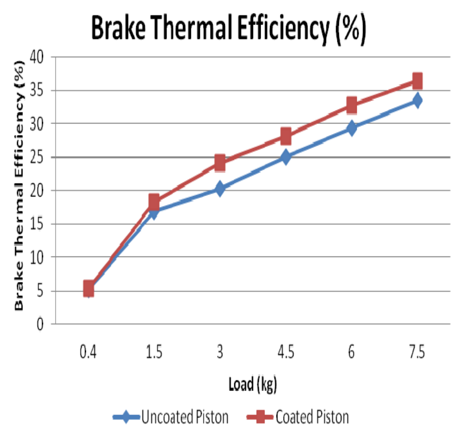

Fig. 6. Variation of baseline and TBC engine's Brake Thermal Efficiency under various load conditions.

4.1.3 Volumetric Efficiency

Figure 7 depicts the variation in volumetric efficiency of TBC coated engine and baseline engine under different load conditions. Inhalation capability of the engine is termed as volumetric efficiency based on atmospheric and operating conditions of the engine. The ceramic coating reducing the heat transfer which causes the raise of temperature of the combustion chamber walls of an LHR engines. The volumetric efficiency is decreased in the TBC coated engine. This is due to the reason that hotter walls and outer gas decreases the concentration of the inducted air.

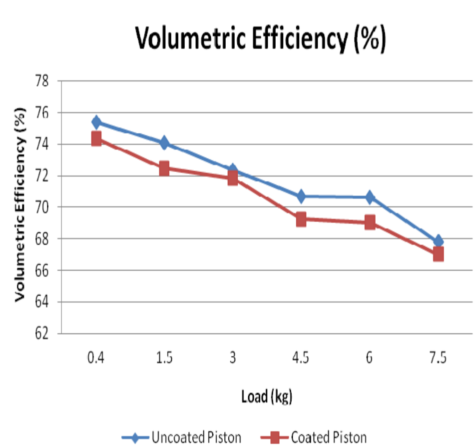

Fig. 7. Variation of baseline and TBC engine's Volumetric Efficiency under various load conditions.

4.1.4 Mechanical Efficiency

It is evident from the Fig. 8 that, TBC coated engine has higher mechanical efficiency than that of uncoated engine at all loading conditions. 77.3% and 64.3% are the maximum mechanical efficiency of TBC coated engine and baseline engine respectively.

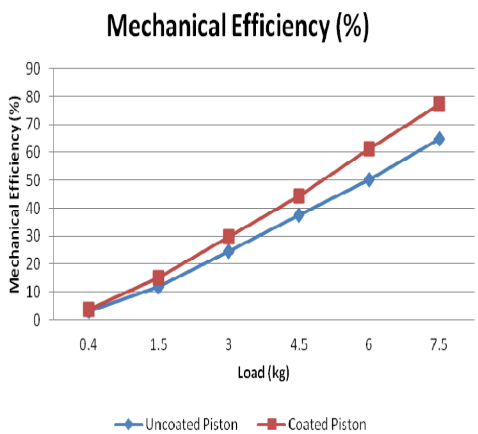

Fig. 8. Variation of baseline and TBC engine's Mechanical Efficiency under various load conditions.

At maximum loaded condition, there is an increase of 16.81% of mechanical efficiency. This is due to direct result of the expansion in energy due to TBC. The available energy for the work output will expand due to decrease the heat rejection to the walls of the engine cylinder, which builds the mechanical efficiency.

4.2 Emission Characteristics

The engine is tested with AVL five gas analyzer for characterizing the emission parameters. The weighted average of Nitrogen oxide, Carbon Monoxide, Carbon dioxide and Hydrocarbon emissions from the experimental data, are shown in Fig. 9. It is observed that the there is a reduction of about 28.2% of CO & 15.8% HC emissions in TBC coated engine in comparison with the baseline engine and the CO_2 emissions have elevated by 39.28% in the coated engine.

The weighted average of emissions like CO, CO2, HC, and NOx was calculated by the average value of each emission concerning each load condition that was calculated for both the TBC coated engine and baseline engine. After that, plot the weighted average emission graph for TBC coated engine and baseline engine.

4.2.1 Hydrocarbon Emissions (HC)

Hydro carbon emissions of the TBC engine are reduced by about 15.8% as compared to the standard baseline engine which is evident from the Fig. 10. In general, the hydro carbon is produced in the exhaust gases, when combustion processes are not fully completed. The experimental data clearly points out those local conditions like temperature, pressure, amount of oxygen, mixture ratio are maintained by the thermal barrier ceramic coating and makes the combustion continuous in diesel engines. The major reason for the reduction of hydro carbon emission in the thermal barrier coated engine is due to the successive boost in combustion temperature during after burning process and decrease in the heat loss, and also, due to higher combustion temperature the TBC helps to evaporate the fuel which results decrease in the concentration of hydrocarbon.

4.2.2 Carbon Monoxide Emission (CO)

The data obtained from the experiments of CO emissions for TBC and the baseline engines are shown Fig. 11. The CO emission decreases with increase in load condition and also lesser CO emission is the outcome of the improved fuel combustion. It is experimentally calculated that TBC engine decreases about 28.2% of CO emission as compared to the baseline engine. Complete burning of the fuel is the major reason for decrease in CO emission in the case of TBC engine. In common, diesel hydrocarbons are considered by lengthy carbon string and mainly saturated link. Therefore, using of TBC reduces the heat transfer and breaking of lengthy carbon string into small carbon string to reduce CO emissions.

4.2.3 Carbon di-oxide emission (CO_2)

Figure 12 shows CO_2 variations with respect to various load conditions. An increasing of CO_2 level was absorbed by thermal barrier coating on a piston crown. It is well known that improved fuel combustion increases the oxygen intake to the engine and hence the CO_2 emission is higher in TBC Engine. It was experimentally calculated that TBC engine causes an increase in CO_2 emission at every load conditions with a visible increase of 39.28% when compared to baseline engine.

4.2.4 Nitrogen Oxide Emission (NO_X)

Figure 13 shows that the NOx emissions increases with increasing the given load condition to the both TBC and baseline engine. In general, NOx level mainly depends on oxygen content present in the intake air to the engine and combustion temperature. It is clear from the experimental data that smoke level and NOx increases by 12% and 27% in TBC engine respectively, due to the high combustion temperature leading to early start of combustion that shift to peak pressure and temperature. From the literature survey, researchers have predicted that due to the larger combustion temperature and extended combustion duration, NOx emissions from LHR engine are generally higher and also the NOx emission level increased due to increase in after combustion temperature. It is evident that the temperature during the combustion in the TBC engine is high from experimental data. In the TBC engine, the NOx emission level will positively lift up in proportionate to the temperature of the after combustion.

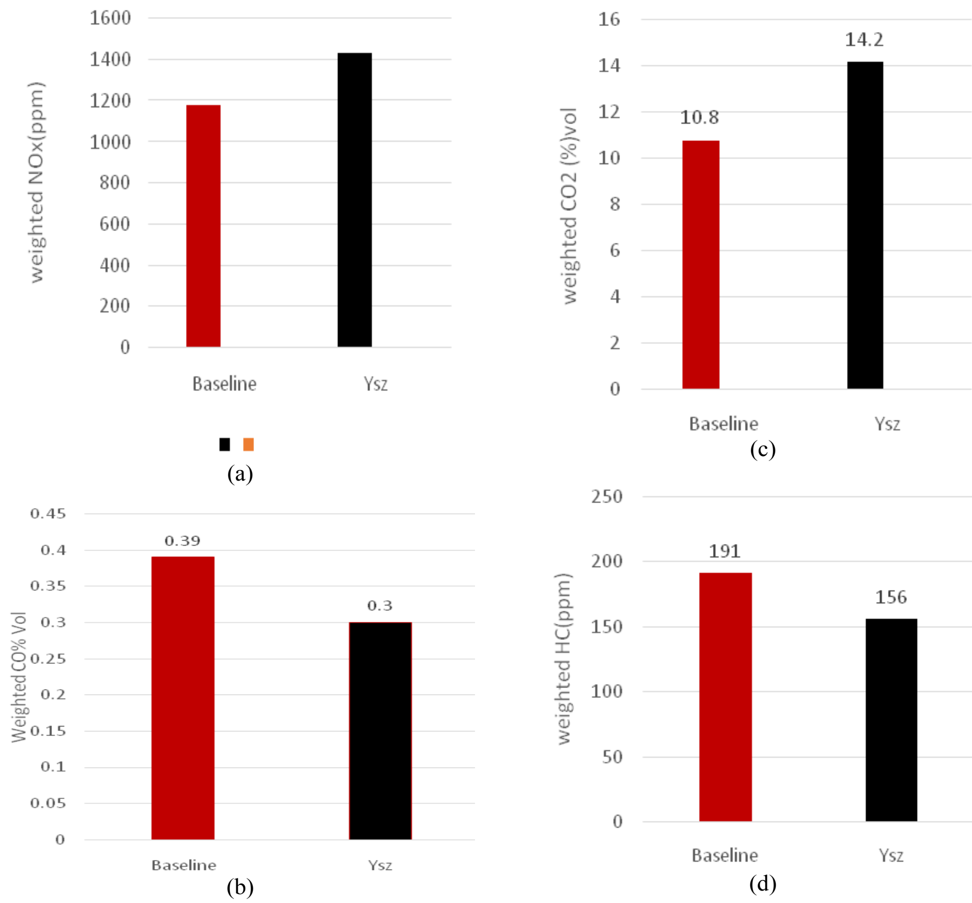

Fig. 9. Comparison of weighted average values of (a) NOx, (b) CO, (c) CO_2 and (d) HC emissions.

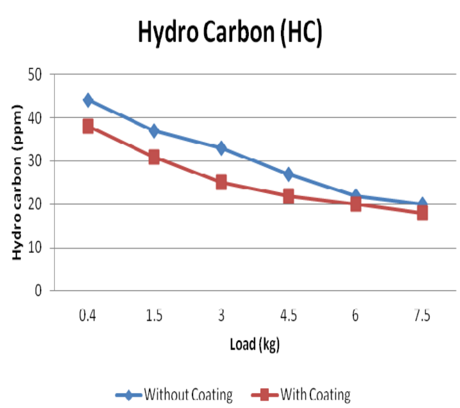

Fig. 10. Variation of baseline and TBC engine's Hydro Carbon emission under various load conditions.

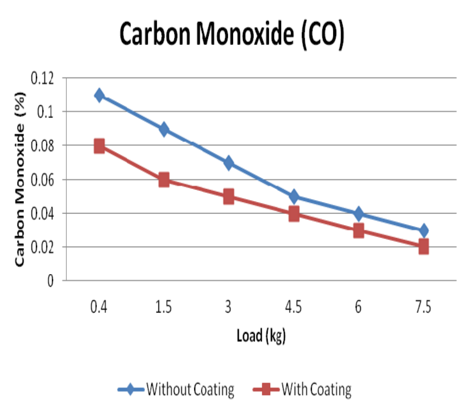

Fig. 11. Variation of baseline and TBC engine's Carbon Monoxide emission under various load conditions.

5. CONCLUSIONS

A 100 µm thickness bond layer of NiCrAl ceramic coating and 150 µm thickness mixture that consists of 88% Yttria stabilized Zirconia, 4% MgO and 8% TiO_2 were used by plasma spray method to convert a single cylinder diesel engine into LHR Engine. The results of TBC on its performance and emission characteristics of the engine are investigated by the measured value of various engine parameters emission characteristics. The following conclusions can be

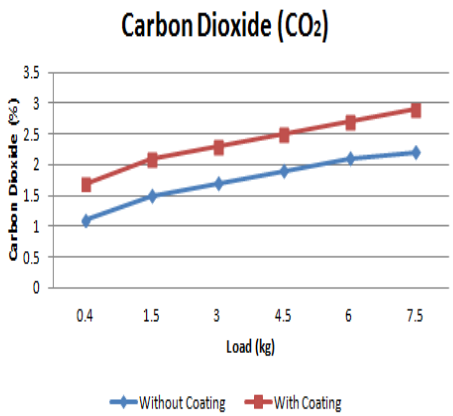

Fig. 12. Variation of baseline and TBC engine's Carbon Dioxide emission under various load conditions.

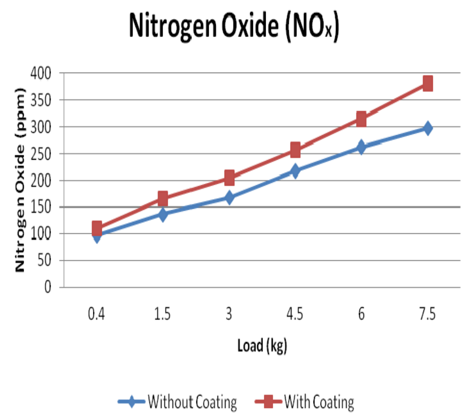

Fig. 13. Variation of baseline and TBC engine's Nitrogen Oxide emission under various load conditions.

drawn through the experimental findings of the present investigation.

- The brake thermal efficiency and BSFC of TBC engine have improved in comparison with the baseline engine.
- The brake thermal efficiency of TBC engine has good impact at all loads conditions ranging from 1.14% to a maximum of 10% at 75% of load condition.
- The SFC of TBC engine reduces by 9.8% and 17% at 25% and 100% load conditions respectively when compared to the baseline engine.
- Carbon monoxide and Hydrocarbon emissions were reduced by 28.2% and 15.8% respectively in the TBC engine and Carbon dioxide emission increased by 39.28%.
- NOx emissions of the TBC engine increased due to the increase in exhaust gas temperature at all loading conditions.

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