Experimental Investigation of the effect of Ceria-Yttria Stabilized by Zirconia (CYSZ) thermal barrier coating on performance and emission characteristics of a DI diesel engine

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ABSTRACT

In the present study, the combined effect of piston bowl geometry and thermal barrier coating (TBC) on engine performance and emission characteristics of a single cylinder diesel engine was studied. The results indicated that bathtub bowl piston in diesel engine with TBC coating increased the brake thermal efficiency by 5.85%, and reduced brake specific fuel consumption by 4.32% compared with standard diesel engine, at 100% loading conditions. At part and medium load conditions, coated engine had shown better performance and reduced emission characteristics.The selected thermal barrier coating reduced the exhaust emissions such as carbon monoxide and hydrocarbons with an increment in emissions of nitrogen oxides.

Keywords: CI engine, Bathtub bowl, Piston geometry, Ceria-Yttria stabilized by Zirconia (CYSZ), TBC.

I. INTRODUCTION

From many years, researchers and technologies are working on IC engines to increase the thermal efficiency as well as decrease the fuel consumption and engine exhaust emissions to meet the framed very stringent regulations on pollution levels [1,2]. There are several systems are available to decrease emissions after combustion like SCR, catalytic converters etc. [3,4]. Although exhaust after treatment systems are capable of removing exhaust emissions but those are not beneficial to decrease fuel consumption and increase the thermal efficiency. Instead of after combustion emission reduction systems, in-cylinder reduction of emissions during combustion itself is more beneficial. Thermal Barrier Coatings (TBCs) [5] got researchers focus to improve emission, combustion and performance characteristics of an internal combustion engines. Early, TBCs are applied to gas turbine blades and aero engine for resisting the thermal shocks successfully.

Thermal barrier coating systems are one or two layers of duplex system coatings which have low thermal conductivity and high melting point act like advanced ceramic materials for example Yttria Stabilized Zirconia, Y2O3-ZrO2 (YSZ) [6]. TBC mainly consists of two layers; top layer is called as ceramic coat and bond coat is called as an oxidation and corrosion resistant layer. In case of IC engines [7], TBCS are applied mainly components of combustion chamber like piston’s top surface, cylinder head and valves. As per the thermodynamics, “An Adiabatic engine” [8] process means there is no heat transfer i.e., heat flow Q=0 when the system is in working condition. By insulating components of combustion chamber, improve power and thermal efficiency additionally from an adiabatic engine because heat energy loss to cooling medium and exhaust gases converted useful work. Wallace et al [9] analysed 6-cylinder high output truck diesel engine cycle in three cases, the results showed that an improvement in thermal efficiency for semi-adiabatic engine is 7% and for fully adiabatic engine 14%. Douglas H et al [10] in 1988 studied the TBCS in diesel engines over a bond coat consisting of MCrAlY. TBCS have three advantages in diesel engines i.e., reduction in operating temperature of metal surface, disincentive to corrosion caused by hot gases and improvement in thermal efficiency. Bruns et al [11] investigated the fuel economy of an “adiabatic” (uncooled) diesel engine in U.S. Army M813 5-ton truck with different three driving schedules. The results showed that, fuel economy improved 16 – 37% depending on the duty cycle with an uncooled engine in the test vehicle.

The main drawback of microstructural YSZ TBC is susceptibility to sulfur in the fuel and phase transformation from tetragonal to monoclinic phase at a temperature above 1200 °C. This point has got focus to new TBC generation such as Ceria–Yttria stabilized Zirconia (CYSZ). Basically, Ceria (CeO2) has lower thermal conductivity and higher thermal expansion coefficient than YSZ by addition of this rare-earth compound such as CeO2, in YSZ coating, 27.5CYSZ (% by wt. 2.5-Y2O3, 25-CeO2 and balance ZrO2is famous due to high corrosion resistance, effective for the enhancement of thermal cycling life and non-transformable tetragonal phase of these materials up to 1600 °C and 1400 °C and for 100h, respectively [14].

At low and high loading conditions of diesel engines, high levels of HC and CO are present this is due to incomplete combustion at these loads compared to medium load condition[15]. These levels of HC and CO are mainly depends on piston bowl geometry parameters such as crevice volumes and squish regions. In order to reduce HC and CO emissions and fuel consumption, a bowl geometry with less steep was named as 'Bathtub bowl' [16] is selected to reduce squish volumes with reduction in the piston bowl surface area coupled with less steep geometry enhances propagation of hot flame [17,18]. It is important to note that that designed piston bowl geometry was kept same compression ratio of hemispherical bowl piston, CR is 16.5:1.

A. Material and Methods

In the present experimental study, experiments were conducted on the engine with three different pistons. First piston used is as conventional piston with hemispherical bowl shaped, second piston used is a modified piston with bath tub shaped and the third piston used is bath tub shaped with CYSZ coated on piston crown. A thickness of 150 µm NiCrAlY alloy is used as bond coat and 300 µm thickness of CYSZ as top coat. A layer of 0.5 mm thickness wasremoved from the top surface of the piston crown bymachining especially, grinding to maintain the initial compression ratio with the coated piston. A commercially available bond coat material NiCrAlY powder 0.1 mm thickness was deposited by an 80 kWatmospheric plasma spray system on piston crown of CI engine using plasma torch. Then the ceramicpowder 27.5CYSZ (% by wt.) is sprayed on the piston crown surface to form a 0.4mm thin top coat. The snapshots of uncoated baseline engine piston and CYSZ coated bathtub pistons are shown in Fig.1.

Fig.1. Shows snapshots of two different pistons i.e., Hemispherical bowl (left), CYSZ Coated bathtub piston (Right)

B. Experimental Setup

In this study, a Single Cylinder Research Engine (SCRE), a four stroke, water cooled and naturally aspirated diesel engine with power output of 3.5 kW running at 1500 rpm was used for experimentation. The engine was coupled to single phase alternor which is connected to load resistance load bank as shown in fig.2.Throughout this study engine with hemispherical bowl piston is taken as standard or baseline engine. The specification of engine is listed in Table 1. A digital rotary encoder was used for measurement of RPM of the engine. The experimental setup has a stand panel consisting of air box, fuel tank, fuel measuring burette and manometer. The engine exhaust emissions were measured by online Manatec- (India) model, five-gas analyzer capable of measuring CO, HC, CO2, O2 and NO concentrations in the exhaust gas. The resolution, accuracy and range of emission parameters by using this analyzer are listed in Table 2. CO emissions are measured in molar percentage by NDIR method and NO, HC are measured in parts per million (ppm) by electro chemical method.

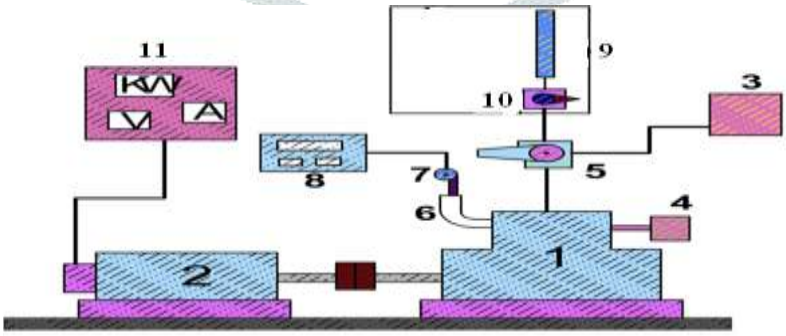


Fig.2. Schematic layout of experimental setup

1. Engine, 2. Alternator, 3. Diesel tank, 4. Air Filter, 5. Three way valve-1 6. Exhaust pipe, 7. Probe, 8. Exhaust Gas Analyzer, 9. Burette, 10. Three way valve-2 and 11.Control panel.

Table 1

Specifications of Single Cylinder Research Engine

Parameter	*Specification*
Product	Single Cylinder Research Engine (SCRE) setup

Type	4 Stroke, Diesel direct injection
Power	4.75 kW (@ 1500 ± 50 rpm)
Cooling system	Water cooled
Position of Cylinder	Vertical
Compression Ratio	16.5:1
Combustion Chamber	Bath bowl piston type
Engine loading	Single phase alternator of 5 kW
Fuel Tank	15 litres capacity
Bore	84.5 mm
Stroke	110 mm
Cubic Capacity	610 cc

Table 2
Specifications of Manatec Exhaust Gas Analyser

Parameters	*Resolution*	*Accuracy*	*Range*
CO	0.01vol.%	±0.3% < 25 vol. %	0 – 15 vol.%
CO_2	0.01vol.%	±0.3% < 25 vol. %	0 – 20 vol.%
NO_x	1ppm	±5 ppm < 100 ppm	0 – 5,000 ppm
HC	1 ppm	±400 ppm<4000 ppm	0 – 20,000 ppm
O_2	0.01 vol%	± 0.2 vol. %	0 – 25 vol%

C. Experimental Procedure

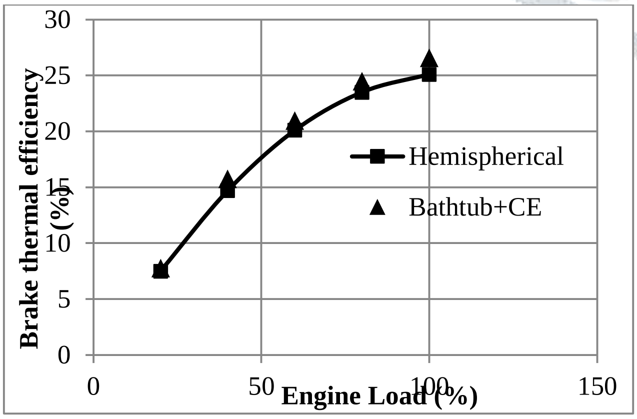
Initially the SCRE with hemispherical bowl piston was run at 20%, 40%, 60%, 80% and 100% loading condition. The experiment was repeated with the same experimental procedure and performance and emission characteristic of the engine was recorded for bathtub bowl piston with and without coating , the engine was dismantled after 100 hours of continuously engine operation to observe changes to piston TBC system.it was observed that the CYSZ coating layer had minor cracks at the edges of the piston crown, while in the remaining parts of the piston surface had neither any cracks and it indicated the stability of the CYSZ coating at all loading conditions of the engine operation.

II. RESULTS AND DISCUSSIONS

I. PERFORMANCE ANALYSIS

The performance analysis of an engine includes parameters like Brake thermal efficiency, Brake specific fuel consumption, and exhaust gas temperature etc. In this study, the effect of coating on piston bowl shape of an diesel engine performance characteristics was analysed under different loading conditions.

A. Brake Thermal Efficiency (BTE)



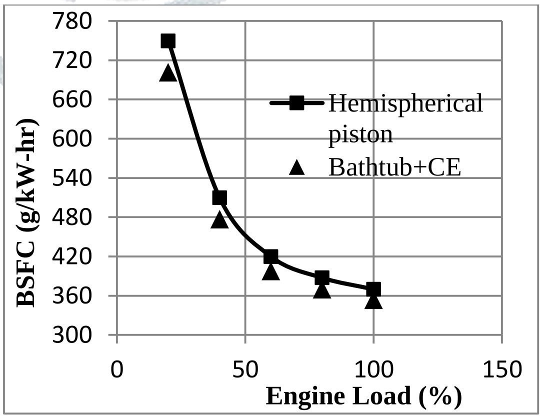


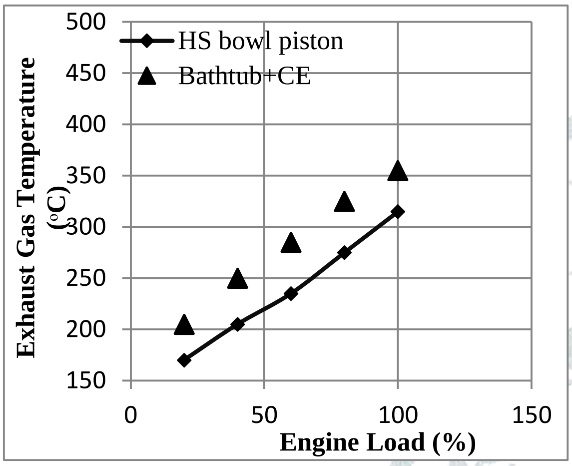
Fig.3. shows the variation of BTE Vs Load and Fig.4. Shows the trend of BSFC Vs Load for different pistons

The variation of BTE of TBC coated and uncoated piston engines with engine load are shown in Fig.3. The BTE increases in bathtub coated piston engine as compared to standard hemispherical piston diesel engine. The effect of reduced piston surface area of a bath tub piston resulted in complete oxidation of HCs. The improvement in BTE recorded for that of engine with coated bathtub piston increased by 5.85% at 100% of engine loading as compared to standard diesel engine. At part load conditions, combined effect of coating and bathtub bowl geometry in diesel engine exhibits 1.4% higher BTE than slandered engine. This agrees with the improvement in fuel consumption at part load conditions.

B. Brake Specific Fuel Consumption (BSFC)

The variation in BSFC of TBC coated and uncoated piston engines with engine load are shown in Fig.4. A reduction of BSFC was observed by coated bathtub bowl piston in diesel engine as compared to standard diesel as shown elsewhere. This is due to the improved energy conversion rate during combustion as a consequence of increase in combustion temperature, resulting in improved combustion leading to reduction in the fuel consumption. At part load conditions, coated bathtub bowl geometry piston in diesel engine has shown 6.44% lower BSFC than standard diesel alone. This indicates the improvement in part load performance of the engine due to elevated temperature of the combustion chamber. Coated Bathtub bowl geometry piston in diesel engine reduced the BSFC by 4.32%, at 100% engine load operation as compared to standard diesel operation with hemispherical bowl piston engine.

C. Exhaust Gas Temperature (EGT)



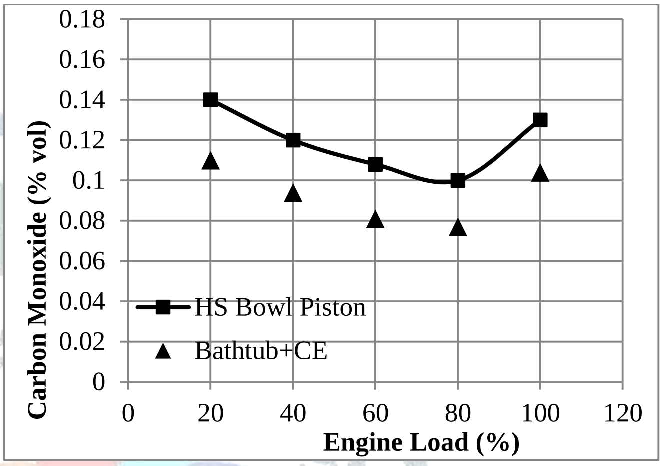


Fig.5. shows the trend of EGT Vs Load and Fig.6. shows the trend of CO emissions Vs Load and for different pistons

The variation of EGT of TBC coated and uncoated piston engines with engine load are shown in Fig.5. EGT increases in diesel engine with loading condition due to fact that the fuel burning rate increases as a result heat release rate increases. The engine with TBC shows an increase in EGT and it is due to the adiabatic effect of TBC that decreases the heat loss to engine cooling system and hence it leads to increase in the exhaust gas temperature. At 100% loading condition, The EGT values increased by 11.42% engine operated with coated bathtub bowl piston in diesel engine alone, than that of base line engine with hemispherical bowl piston.

II. Emission Analysis

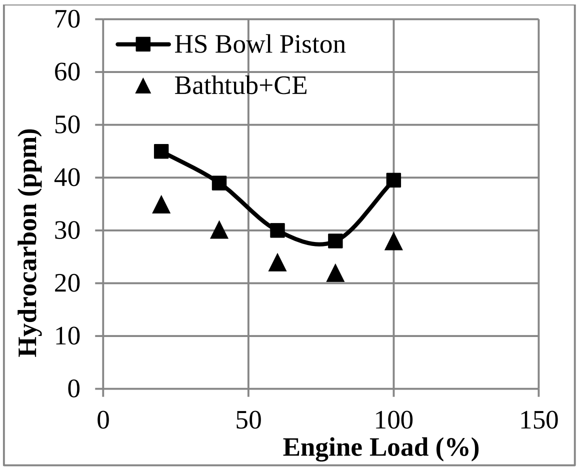
Presently EURO-6 emission regulation is implemented in most parts of the world. In this study, the emission analysis was carried out to understand the effect changes in crown shapes and coatings on top surface of piston on major exhaust gas emissions from an engine like CO, Unburnt hydrocarbons NO_x etc.

A. Carbon Monoxide (CO)

The variation of CO emission of TBC coated and uncoated piston engines with engine load are shown in Fig.6. CO formation is mainly due of lack of oxygen in the Air-fuel mixture. Engine with coated bathtub bowl geometry piston gives reduction in CO emission. Due to coated bathtub bowl piston geometry in diesel engine the CO emission is reduced by 23.07% for coated piston engine respectively at 100% engine loading operation as compared to standard diesel engine. This indicates that coated bathtub bowl piston in diesel engine gives a remarkable decrease in CO emission.

B. Hydro Carbon (HC)

The variation of HC emission of TBC coated and uncoated piston engines with engine load are shown in Fig.7. Incomplete combustion and oxygen deficiency leads to more HC emissions. The trends of HC emissions and explanation are similar to CO emissions. HC emission in coated engine is reduced significantly than uncoated engine, due to increase in combustion temperature during afterburning phase as a consequence of reduction in heat loss in coated engine. Diesel engine with coated Bathtub bowl piston geometry shows a reduction in HC emission by 29.11%, as compared to baseline diesel mode operation at 100% engine load.



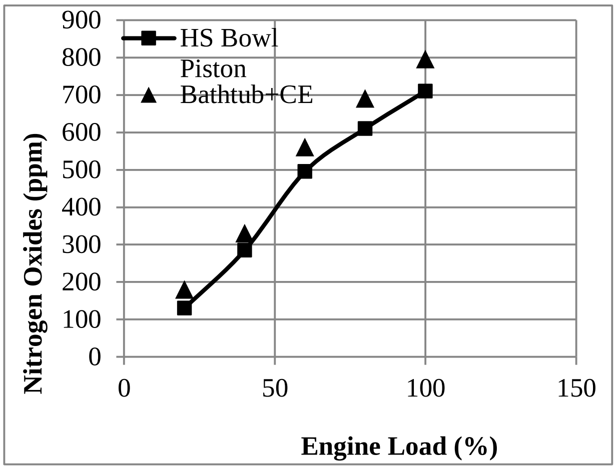


Fig.7. shows the trend of HC emissions Vs Load and Fig.8. shows the trend of NOx Vs Load for different pistons

C. Nitrogen Oxides (NO_x)

The variation in NO_x of TBC coated and uncoated piston engines with engine load are shown in Fig.8. The NO_x emissions increase with an increase in the engine loads. NO emission depends on two factors viz., combustion temperature and oxygen content. The NO emission of coated engine is comparatively higher, may be due to high combustion temperature leading to early start of combustion that shifts the peak pressure and temperature close to TDC. Diesel engine with coated bathtub bowl piston geometry shows an increase in NO_x emission by 11.97%, at 100% engine load condition as compared to standard diesel engine.

III. CONCLUSION

The influence of piston bowl geometry and TBC coating on performance and exhaust emission characteristics of a diesel engine were studied and the following observations are made,

1. Bathtub bowl geometry combined with 27.5% by wt. Ceria-Yttria stabilized Zirconia in the CI engine results an increase in BTE of the engine by 5.85% with a reduction in BSFC up to 4.32% compared to the engine is run by hemispherical bowl piston geometry.
2. Engine with 27.5 CYSZ coating has shown an improvement of BTE by 1.4% higher and reduction in BSFC by 6.44% at engine part load operation, while at medium load conditions; coated engine has shown better performance and emission characteristics.
3. There was decrease in CO and HC emissions and an increase of about 11.97% in the NO_x emissions while using coated or uncoated bathtub bowl engine when compared with standard diesel engine.

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