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Experimental study on Yattria Stabilized and Titanium Oxide Thermal Barrier Coated Piston effect on Engine Performance and Emission Characteristics

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A B S T R A C T

Most of the energy was being lost through the cooling system and exhaust gas, to utilize that energy and convert it to a useful job thermal barrier coatings is widely used. Tests were conducted on a four stroke, single cylinder diesel engine for which its piston crown was coated with a thickness of 100/100 microns YSZ/TiO_2 over 100 microns NiCr bond coat with plasma spray coating technology and then the results were juxtapose with uncoated piston. Thermal barrier coating was used for better performance, emission and combustion characteristics. The tests were performed at different load conditions using both the pistons and compared the results. At maximum load there is a rise in Brake Thermal Efficiency (BTE) and reduction in Brake Specific Fuel Consumption (BSFC), CO,hydrocarbons (HC) emissions compared to uncoated piston at maximum load. With use of coated piston NOx emissions were increased and the smoke opacity is decreased compared to uncoated piston. Finally, the results convey that thermal barrier coated piston is more efficient than uncoated piston.

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NOMENCLATURE

BSFC	Brake Specific Fuel Consumption	TBC	Thermal Barrier Coated
BTE	Brake Thermal Efficiency	TiO_2	Titanium Oxide
HC	Hydrocarbons	YSZ	Yttria Stabilized Zirconia
CO	Carbon monoxide	HBP	Heat converted to useful Barke Power
NOx	Nitrogen Oxide	HJW	Heat rejected to Jacket cooling Water

1. INTRODUCTION

Environmental protection and fuel economy are the most important concerns especially in the transport sector with an increasing demand in usage of diesel engine vehicles [1-3]. In the internal combustion engines, combustion chamber walls and the piston absorb most of the heat generated at the process of combustion. This causes heat loss in walls and piston. Which lowers the generated power in engine and the performance. The temperature will be maintained in the combustion chamber to required level, unburnt gases will be burned which will reduce the polluted exhaust because of a decrease in heat loss in the piston [4,5]. In TB coating a bond coat and a top coat will be casted on piston. To improve the coating union between TBC and substrate metal bond layer is used. TBC materials have some basic requirements like low thermal conductivity, low sintering rate of the porous microstructure, no phase transformation, high melting point, thermal expansion match with the metallic substrate, chemical inertness and good adherence to the metallic substrate. To enhance the performance, different TBC materials were used for IC engines by various researchers. It has an effective effect on exhaust emission and the power of the engine [6-8]. Yttria-stabilized zirconia of 400 microns was cast-off for top coat and

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NiCrAl of 100 microns was cast-off for bond coat. Holes were made of 2, 3, 4 and 5 mm diameter to the exterior of coating and temperature distribution was examined. Results appear that for coated piston there is a rise in temperature of top exterior and drop in substrate. Extra raise in temperature of the top exterior appears when on coating surface holes are made, i.e. 9.5% raise and 2.7% drop with 2 mm diameter holes aimed at top and substrate temperature. With the enlargement of holes diameter, it can be noticed that substrate and top exterior temperatures are dropping. Thermal analysis was performed on an uncoated diesel piston on ANSYS, finished with aluminium silicon alloy and steel [9]. Again, on a piston coated with $MgZrO_3$, the results of 4 different pistons are compared with one another. The material with low thermal conductivity is appeared that the utmost surface with coated piston was improved around 48% for AlSi alloy and 35% for steel. The utmost surface temperature of base metal of coating piston for AlSi and steel are 261 °C and 326 °C [10]. TiO_2 of 100 microns thick was sprayed to the piston crown using a plasma spray method. There is 3% and 2% raise in brake thermal efficiency and mechanical efficiency and also fuel consumption is low compared to uncoated piston [11]. The Diesel engines combustion chamber was encased with mixture of 20% Lead Zirconate Titanate (PZT) and 60% Cyanate modified Epoxy system. Results appeared that 15.89% specific fuel consumption dropped due to the consequence of TB coatings on Diesel engine performance [12]. $FeCl_3$ as catalyst was used to diesel fuel and YSZ coating was encased on valves and piston crown. The outcomes they got were that $FeCl_3$ with a YSZ diesel engine raised the brake thermal efficiency to 2.7%, and has fallen brake specific fuel consumption to 8.3% and for 3-cylinder diesel engine there is 3-5% gain in thermal efficiency with 28.29% fall BSFC [13,14]. Fly ash with composition of silica (45%), alumina (30%), iron (10%) and magnesium (0.5%) were used as TBCs for cylinder head, piston crown, cylinder liner, inlet and exhaust valves for diesel engine. There was 3.4% raise in BTE and 10.3% drop in (Specific Fuel Consumption) SFC compared to uncoated [15]. Two different piston top coatings were used, CeO_2/8YSZ and Al_2O_3/ 8YSZ and bond coat as CoNiCrAlY. Results revealed brake thermal efficiency has raised to 3.37% and specific fuel consumption was 3.45% less in CeO_2 /8YSZ TBC coated engine than that of Al_2O_3/ 8YSZ TBCs [16]. To investigate the temperature of the exterior built on coating thickness experiment was conducted by coating an aluminum piston crown with magnesia-stabilized zirconia. Tests were performed for different coating thicknesses from 0.2mm to 1.6 mm eliminating the bond coat layer. Maximum temperature at the crown center is 32.70%, 55.80%, 72.50% and 84.80% for 0.4 mm, 0.8 mm, 1.2 mm and 1.6 mm thick coating compared with the uncoated piston [17]. To calculate the temperature gradients a steady state thermal analysis was conducted in the two different partially stabilized ceramic coated pistons using Yttria Stabilized Zirconia (Y-PSZ), Magnesium Stabilized Zirconia (Mg-PSZ) compared with standard engine by using Abaqus finite element (FE) software. Results display that there is 18% raise in temperature value of Y-PSZ coated piston and 48% raise in Mg-PSZ coated piston compared to the uncoated piston [18]. $CaZrO_3$ and $MgZrO_3$ were plasma sprayed on the base of the NiCrAl bond coat. The uncoated piston was tested at different loads and speed conditions then the combustion chamber, piston crown faces, valves and cylinder head were coated with thermal barrier coatings. The results at all load levels and engine speed, show a 2-7% reduction in bsfc and the effective efficiency development of about 2%, 5% and 3% at low, medium and full loads. It is known that the coating surface temperature rises with increasing thickness. Utmost temperature at 0.5 mm thick coating was established to be more in $MgZrO_3$ by 34% compared to uncoated piston. [19,20]. Motor tests were conducted using the MEZ VSETIN test bench with a DS 736-4/V DC dynamometer. In MAO-coated pistons inside temperature falls at least 45 °C when compared with non-MAO pistons. Comparing pistons with different thickness i.e. 76 and 108 microns of MAO layers finalizes that thickness will not have a major effect on thermal state of pistons [21]. Through plasma spray technique the piston top was coated with partially stabilized zirconia of thickness 125microns, following with alumina (Al_2O_3) and NiAl as bond coat. Finally the total thickness to achieve is 250 microns. Results observed a 4 bar increase in peak pressure, 4.6% raise in BTE, 12.6% in exhaust gas temperature and 15.67% increase in nitric oxide emission compared with uncoated piston in the engines [22]. 6-8%Yttria stabilized zirconia (YSZ) TBCs of different thicknesses (100, 125 and 150µm) on 50 to 75µ thick NiAl bond coat was applied on Aluminium – silicon alloy flat plates. It was observed 40ºto 48º C by 100 and 125µm thick coating and nearly 40% increase in the drop value i.e. 57 to 68º C was observed for just 25µm raise in coating thickness i.e. 150µm. It is observed that temperature drop raises with the thickness of YSZ coating. [23]. NiCr coating of 100 microns and Aluminium Oxide coating of 150 microns was covered on piston crown. Two different varrities of biodiesel combination (Lemongrass biodiesel and pongamia pinnata methyl ester) was used. At 100% load condition it was proved that the blend combination with TBC piston (i.e D80 PME 10 LGB 10), BTE is improved by 29.2%, BSFC also improved by 0.23 kg/kW-h. Whereas the emission characteristic was dropped in CO, HC and smoke, slightly raised in NOx emission. [24].

From the literature survey it is revealed that the performance of engines with thermal barrier coated pistons is improved. Few researchers worked with YSZ with different thickness ratios. In the present work, the performance and energy balance study of diesel engine is carried out using piston coated with YSZ + TiO_2 materials with 100mm thickness each and the results are discussed.

2. COATING PROCESS

Kirloskar TV1 alloy of aluminium piston of diameter 87.5mm with stroke length 110mm was coated using Plasma spray method used in this experiment. The piston was cleaned with kerosene to remove the dust particles. The coating specifications were shown in Table 1. Grit blasting was done with the help of compressed air at 3.5 kg/cm^2 pressure to create rough exterior on crown hence the mechanical bond in between substrate and coating remains strong. The nozzle used is of GH type and sprayed with distance of 2-3 inches. The process of coating is done with 490- 500amps current and 60-70 volts. To offer good bonding for coating material, NiCr of 100 microns was applied as a bond coat. TiO_2 is used as coating material which has low thermal conductivity of 4.8W/m-k. Then TiO_2 in powder form was sprayed with a gun on to the piston crown of thickness 100 microns and then 100 microns of Yttria stabilized zirconia was sprayed on TiO_2 layer. YSZ is casted as coating material for its low thermal conductivity, which is anticipated for substrate to diminish the thermal fatigue. Thermal conductivity is 2.2W/m-k for YSZ and it has good thermal insulation property, the stability is high at high temperature. The powder feed of YSZ and TiO_2 is 40-50g/min. Table 2 indicates the properties of YSZ and TiO_2. TiO_2 was sprayed at pressure of 100-120 psi and YSZ at pressure of 50 psi. The powder feed was 40-50 g/m. Coated and uncoated pistons before testing are shown in Figure 1 and coated piston after testing is shown in Figure 2.

3. EXPERIMENTAL PROCEDURE

Tests were conducted on Kirloskar TV1, 5.20 kW rated power at 1500 rpm, 1-cylinder, four stroke water cooled, loaded with eddy current dynamometer diesel engine.

TABLE 1. Specifications of coating parameters [14]

Coating parameters	Specifications
Plasma gun	3 MB plasma spray gun
Nozzle	GH type nozzle
Pressure of hydrogen gas	50 psi
Flow rate of hydrogen gas	15-20 SCFH
Pressure of argon gas	100-120 psi
Flow rate of argon gas	80-90 SCFH
Spraying distance	2-3 inches
Powder feed rate	40-50 g/m

TABLE 2. Properties of YSZ and TiO_2 [11,14]

Properties	YSZ	TiO_2
Allowable temperature °C	1000	1840
Density gm/cm^3	5.2-6.1	4.23
Thermal Conductivity W/m-K	2-3.8	4.8-11.8
Specific heat J/kg-K	400-700	683-697
Thermal expansion coefficient	8.0-11.4	8.4-11.8

The photograph of the engine used is shown in Figure 4 and specifications were listed in Table 3. Tests were conducted at varying the loads i.e. 25, 50, 75 and 100%. The parameters like BSFC, BTE were obtained and the emission parameters like CO, HC, NOx and smoke opacity were studied. There is a possibility of ±0.1 % uncertainty in the results with the equipments used.

4. RESULTS AND DISCUSSION

4.1. Brake Specific Fuel Consumption

Figure 3 shows variation in BSFC for uncoated and coated piston at different loads. Decrease in BSFC was obtained with rise in brake power for both the pistons, but associated to uncoated piston there is 6.94% reduction in fuel consumption at higher load condition for coated piston. This is caused by high temperature increase in the combustion chamber walls leads to high fuel vaporization causes reduction in physical delay and BSFC drops with coated piston. i.e YSZ and TiO_2 is more efficient and against the exiting.

TABLE 3. Specifications of tested engine

Type of the Engine	Kirloskar TV1
Number of cylinders	1
Number of Stroke	4
Bore and stroke	87.5mm, 110mm
Rated Power	5.2 kW @1500 rpm
Compression Ratio	17.5 :1

Figure 1. Uncoated and Coated Piston before testing

Figure 2. Coated piston after testing

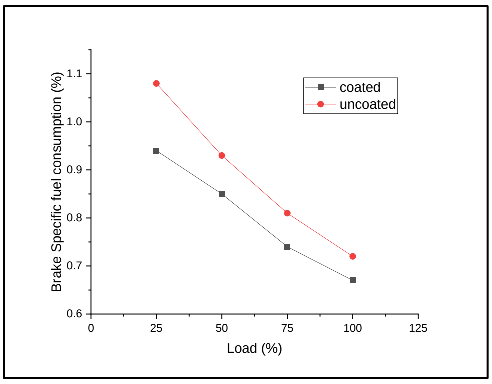


Figure 3. Variation in BSFC for coated and uncoated pistons

4.2. Brake Thermal Efficiency

The variation in BTE is shown in Figure 4 for both uncoated and coated pistons at various loads. It was observed that there is 3.128% raise in brake thermal efficiency compared to uncoated piston at higher load. This is due to the TBC on the piston i.e. YSZ of thermal conductivity 1.4 W/m c and TiO_2 of thermal conductivity 4.8W/m-K. which lowers the heat energy rejection and cannot be allowed to coolant and that energy is transformed as more available work and then BTE increased.

4.3. HC Emission

Figure 5 indicates the deviation in HC emissions in the thermal barrier coated piston and the uncoated piston at different loads. There is 16.92% decrease in the HC emission of the coated piston. In thermal barrier coatings the combustion temperature is higher and also the amount of oxygen. This reduces the hydro carbon emissions and reduces the heat loss going to coolant. The TBC raises the temperature of local heat high and leads to decomposition of fuel molecules. It is because of the presence of radicals, the combustion enhances

4.4. CO Emission

At various load conditions the CO emissions are determined for both TBC piston and uncoated piston graphically is shown in Figure 6 and is observed that CO emission were decreased by 14.92% with growth in load compared to uncoated piston. In general incomplete combustion auses the formation of CO emissions and is more at higher loads. But TBC lowers the heat transfer and fuel combustion gets better which leads to decrease in CO emissions.

4.5. NOx Emissions

Figure 7 indicates the variance in NOx emissions at different lods for both thermally coated engine and uncoated engine. The NOx emissions were visibly increased for both pistons with increasing load. But in TBC coated piston there is 6.93% raise in NOx emission associated with uncoated piston. This is because the combustion chamber has a high flame temperature. When increasing the load the fuel consumption is greater and there will be high combustion for thermal barrier coated piston.

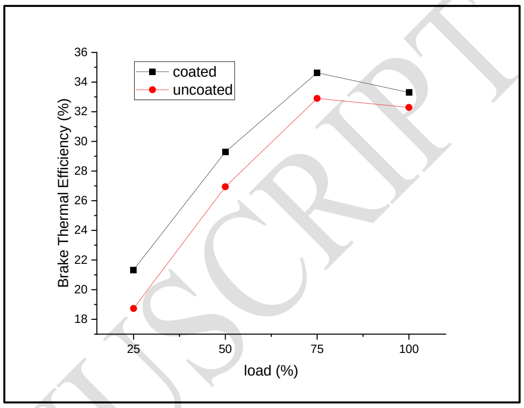


Figure 4. Variation in BTE for coated and uncoated piston

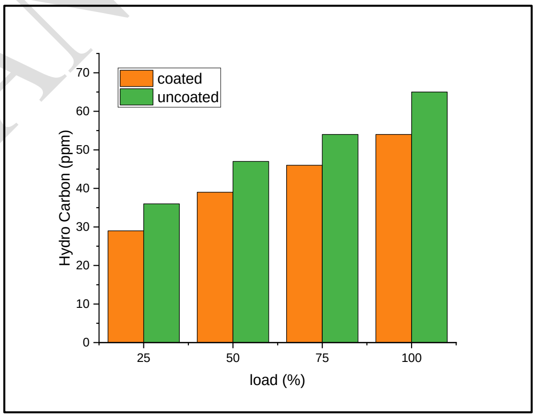


Figure 5. Variation in HC emissions for coated and uncoated pistons

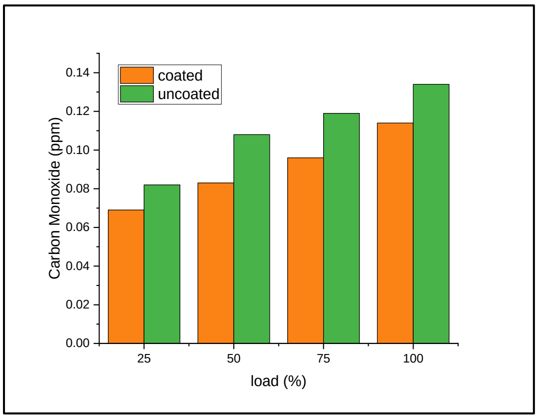
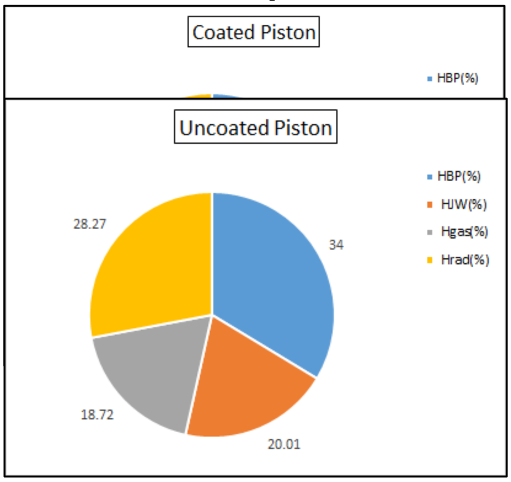


Figure 6. Variation in CO emissions for coated and uncoated pistons



4.6. Smoke Opacity

Figure 8. Energy balance for coated uncoated piston

Figure 8 shows the variation of smoke opacity and it shows that the smoke opacity upsurges with load. But compared to uncoated piston the smoke opacity is lower for TBCoated piston. At higher load conditions there is a 12.4% decrease in smoke opacity for YSZ and TiO_2 coated piston. This is due to a steady increase in combustion chamber temperature for thermally coated piston, and a great drop in smoke opacity

4.7. Energy balance

Energy balance of coated and uncoated is shown in Figures 9 and 10. Due to TBC, the heat rejected to through the piston which is not useful to the engine was reduced. By the lower heat loss, more brake thermal energy is converted into useful work out as brake power.

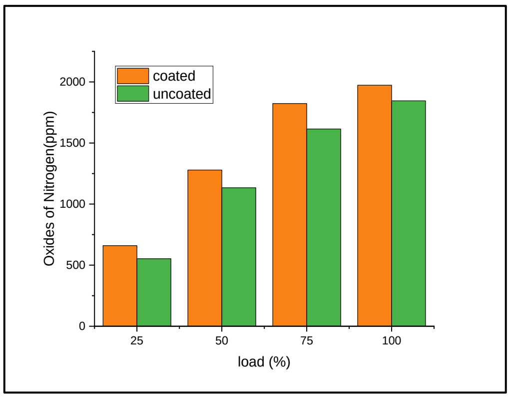


Figure 7. Variation in NOx emissions for coated and uncoated pistons

Figure 9. Energy balance for coated uncoated piston

There is an 8.2% raise in HBP compared to uncoated piston. The HJW difference was found by 14.64% drop in coated engine as the rejection of heat is cleared by temperature rise of the coolant. The decrease in thermal rejection of loads leads to increase in exhaust gas temperature in coated engines, and hence there is 28.1% increase in exhaust gasses temperature. From the experiment the HRad (unaccounted losses) were decreased by 10% in coated piston compared to uncoated piston. Unaccounted losses mainly caused because of energy losses like radiation, conduction and convection removal of heat from the engine to atmosphere.

5. CONCLUSION

From the experimental work done on the diesel engine using YSZ and TiO_2 coated piston, and uncoated piston the following conclusions were observed.

- The TBC coated piston shows a great result of increase in brake thermal efficiency and decrease in brake specific fuel consumption compared to the uncoated pistion.
- At higher load condition there is 3.12% increase in brake thermal efficiency in TBC coated piston compared to the uncoated piston.
- In TBC coated piston there is 6.94% decrease in brake specific fuel consumption when differentiated with uncoated piston.
- There was 14.9% and 16.9% drop in CO emission and HC emission in TBC coated piston whereas NOx emissions were increased by 6.93%.
- Smoke opacity is decreased by 12.4% in the TBC coated pistons.

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غالبا انرژی از طریق سیستم خنک کننده و گازهای خروجی از بین می رود ، برای استفاده از این انرژی و تبدیل آن به یک کار مفید ، پوشش های مانع حرارتی به طور گسترده ای مورد استفاده قرار می گیرد. آزمایشات بر روی موتور دیزلی تک سیلندر چهار زمانه انجام شد که تاج پیستونی آن با ضخامت ۱۰۰/۱۰۰ میکرون YSZ/TiO2 با پوشش میکرومتر ۱۰۰ میکرون NiCr با فناوری پوشش پاشش پلاسما پوشش داده شد و سپس نتایج با پیستون بدون روکش کنار هم قرار گرفت. به پوشش حرارتی برای عملکرد بهتر ، ویژگی های انتشار و احتراق استفاده شد. آزمایش ها در شرایط بار مختلف با استفاده از هر دو پیستون انجام شد و نتایج مقایسه گردید. در حداکثر بار افزایش BTE و کاهش انتشار BSFC، CO، HC در مقایسه با پیستون بدون روکش در حداکثر بار وجود دارد. با استفاده از پیستون پوشش داده شده ، انتشار NOx افزایش یافته و کدورت دود در مقایسه با پیستون بدون روکش کاهش می یابد. در نهایت ، نتایج نشان می دهد که پیستون با روکش حرارتی کارآمدتر از پیستون بدون روکش است.