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ORIGINAL ARTICLE

Investigation on effect of Yttria Stabilized Zirconia coated piston crown on performance and emission characteristics of a diesel engine

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Abstract Experimental investigation is carried out under different loading conditions in a three cylinder diesel engine with its piston crown coated with Yttria Stabilized Zirconia (YSZ) to understand the influence of the thermal barrier coating (TBC) on performance and emission characteristics in comparison with baseline engine characteristics. YSZ is chosen as the candidate material for coating the piston crown because of its desirable physical properties such as high coefficient of thermal expansion, low thermal conductivity, high Poisson's ratio, and stable phase structure at higher temperature conditions. For the measurement of emission characteristics, ISO 8178-4 "C1" 8 Mode testing cycle procedure is followed. Experimental results revealed that the heat loss to the cooling water is reduced up to 5–10% and the thermal efficiency is increased by 3–5% with reduction of brake specific fuel consumption by up to 28.29%. Experimental results also revealed that Hydro carbon (HC) emission is reduced up to 35.17%, carbon monoxide (CO) by up to 2.72% and Carbon di-oxide (CO_2) emission is increased by up to 5.6%.

1. Introduction

Diesel engines play a major role in the automotive industry. It has assumed a dominating role in both transport and agricultural industry due to its higher fuel economy and low running cost. However the heat carried away by the coolant and exhaust gases carry considerable amount of fuel energy from the combustion chamber even in diesel engines leaving only 30–40% of the total energy for conversion into useful work. The engine cooling system absorbs combustion and friction-generated heat energy and dissipates it to the surroundings to ensure engine temperature always remain below the safe level. The lubrication system and exhaust gases are the other sources which carry away the heat from the combustion chamber.

Researchers are continuously striving to improve the performance and emission characteristics of the Internal Combustion engines due to the continuous demand from the industry for some technological and environmental requirements besides rapid increase in the cost of the fuel. On the other hand the improvements in engine materials become increasingly

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important by the introduction of new alternative fuels. Thermal barrier coating is predominantly used by many researchers to increase the heat resistance inside the combustion chamber and thereby improving the thermal efficiency of the existing engines. Ceramic coatings not only act as heat resisting medium, but also prevent the thermal fatigue and shocks in protecting the substrates. Ceramic coating also helps in reducing the emission levels of Hydrocarbon and Carbon Monoxide. The application of TBC reduces the heat transfer through the cooling water [5] and hence assists the engine for better combustion inside the combustion chamber. Due to the increased after combustion temperature, the exhaust gas temperature also raises proportionately. While there have been numerous research papers in the recent years describing the theoretical benefits obtained from the use of ceramic components in reciprocating engines, the amount of the literature that describes practical results is very limited.

Generally in LHR engines, the thermal barrier coating is done on Cylinder head, cylinder liners, piston crowns and valves. Most of the researchers have concluded that the thermal efficiency of TBC coated Low Heat Rejection (LHR) engines is higher with better brake specific fuel consumption [3].

According to second law of thermodynamics, insulating the combustion chamber of an internal combustion engine will theoretically result in improved thermal efficiency. Kamo et al. [3] by experimental determination predicted that thin thermal barrier coated engine could improve its thermal efficiency by 5–6% in comparison with the standard engine. Bruns et al. [1] predicted that fuel economy could be improved in the range of 16–37%. The results of Wallace et al. [2] indicated a gain of 14% in the indicated thermal efficiency for fully adiabatic condition and 7% for semiadiabatic condition. The investigation of Havstad et al. [10] has shown improvements ranging from 5% to 9% in ISFC of an insulated engine over a baseline engine. The investigation of Kamo [7] has shown that TBC engine with its piston and cylinder head coated with 0.1 mm thickness of YSZ and the cylinder liner coated with 0.5 mm thickness of YSZ improved the fuel efficiency by 5–6% at all loads and speeds. Investigation of Miyairi et al. [11] reported higher fuel consumption by the LHR engine coated with Mg–ZrO_2.

The efficiency of most commercially available engines can be improved by coating the piston crown with an insulating material such as stabilized zirconia. The main requirements of the thermal barrier coating materials include low thermal conductivity, resistance to corrosive and erosive environments, co-efficient of thermal expansion high enough to be compatible with metal and thermal shock resistance. Various TBC materials and its characteristics are given in Table 1. The plasma sprayed stabilized zirconia was used extensively in aero engines as an ideal thermal barrier coating material. Morel et al. [9] determined that Yttria was the preferred stabilizing agent for zirconia. The stabilized zirconia has been successfully tried by several investigators as thermal barrier coating agent for piston crown.

Based on the open literature review, it is found that Low Heat Rejection engines with thin TBC on combustion chamber components coated with YSZ are the most effective one in terms of improving the Thermal efficiency and fuel consumption [5] of Internal Combustion engines. However significant number of literatures revealed that NO_x emission levels were increased due to the application of Thermal Barrier Coating inside the combustion chamber. In the present work, the piston crown is coated with 100 micron thickness of YSZ by plasma spray coating method and engine is tested for its performance and emission characteristics at various loads and speeds as per **ISO 8178-4 "C1" 8 Mode test cycle** for off road vehicles [17].

2. Plasma spray technique

Thermal Spraying technique consists of different types such as Chemical deposition method (CVD), plasma arc method, Physical vapor deposition method (PVD), Plasma spray method. From the above four methods, plasma spray method is adopted in our experimental study. The main objective in plasma spraying was to constitute a thin layer that has high protection value over other exposed surfaces. Yttria Stabilized Zirconia (YSZ) is sprayed in powder form molten in ionized gas rapidly on the piston crown surface to form a 100 μm thin TBC coating. A typical Plasma spray coating system is shown in Fig. 1. The Snapshots of uncoated baseline engine piston (left) and YSZ coated piston (right) are shown in Fig. 2. The system primarily consists of power unit, powder supply unit, gas supply unit, cooling system, spraying gun and control unit. The coating material is made up of 8 mol% of Yttria (Y_2O_3) and remaining mole% of fully stabilized Zirconia (ZrO_2). The plasma spray specifications are mentioned in Table 2.

3. Experimental test setup

A four stroke, direct injected, water-cooled, Three cylinder, naturally aspirated diesel engine is used for investigation. The base engine specifications are presented in Table 3.

The Schematic of experimental setup is shown in Fig. 3. The experiments were conducted at four load levels, viz. 25%, 50%, 75% of full load and full load using Eddy current dynamometer at five different speeds viz. 1200, 1400, 1600, 1800 and 2000 rpm. The mass flow rate of air is measured using a manometer setup by Air Box method. Fuel flow rate is measured by a gravimetric type Fuel consumption meter. Pressure and temperature sensors are mounted at important locations in engine exhaust, water inlet, water outlet, air intake, lube oil for online recording of pressure and temperature values using a Digital Dyno Controller unit and Data Acquisition System. Emission characteristics such as Carbon monoxide (CO), Hydro carbon (HC) and carbon dioxide (CO_2) were measured by using AVL Di-gas 444 Gas analyzer as per **ISO 8178-4 "C1" 8 Mode testing cycle** for off road vehicles [17]. All the readings were carried out using ARAI–EDACS controller setup and the readings were stored in a personal computer automatically.

4. Results and discussion

Experimental result shows that reduction in heat rejection to cooling medium had resulted in an increase in exhaust energy at all load levels. In case of Thermal Barrier Coated engine, there is a increase in the volumetric efficiency of the engine at different loadings and speed conditions.

Table 1 TBC materials and their characteristics [3].

Materials	Advantage	Disadvantage
YSZ	1. High thermal expansion co-efficient $10 \times 10^6\,°C^{-1}$ 2. Low thermal conductivity 2 $W\,m^{-1}\,K^{-1}$ 3. High melting point 2800 °C	1. Sintering above 1473 K 2. Phase transformation 1443 K
Mullite	1. High corrosion resistant 2. Low thermal conductivity 3. Not oxygen transparent	1. Crystalization (1023–1273 K) 2. Very low thermal expansion-coefficient
$MgZrO_2$	1. Low thermal conductivity 2 $W\,m^{-1}\,K^{-1}$ 2. High fracture toughness 3. High Young's Modulus	1. Low Melting point 1600 C 2. Very low thermal expansion-coefficient
Alumina	1. High corrosion resistance 2. High hardness value 3. Not oxygen transparent	1. Phase transformation (1273 K) 2. High thermal conductivity 3. Very low thermal expansion-coefficient

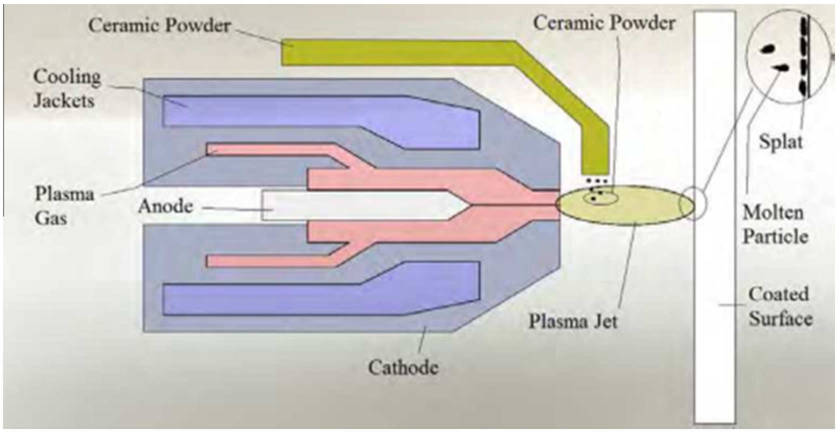

Figure 1 Plasma spray Technique [4].

Figure 2 Snapshots of uncoated baseline engine piston (left) and YSZ coated piston (right).

4.1. Engine performance characteristics

Engine performance characteristics are measured and compared in terms of power, torque, brake specific fuel consumption, brake thermal efficiency and heat balance sheet at different loadings and speed conditions.

4.1.1. Brake specific fuel consumption (BSFC)

Fig. 4 shows the variation in brake specific fuel consumption of TBC coated engine and baseline engine with respect to the

Table 2 Plasma spray coating specifications.

Coating parameters	Specifications
Plasma gun	3 MB plasma spray gun
Nozzle	GH Type nozzle
Pressure of organ gas	100–120 PSI
Flow rate of organ gas	80–90 LPM
Pressure of hydrogen gas	50 PSI
Flow rate of hydrogen gas	15–18 LPM
Powder feed rate	40–45 g per minute
Spraying distance	3–4 in.

Table 3 Baseline engine specifications.

Parameter	Specifications
Bore & Stroke	108 & 120 mm
Rated power	50 HP @ 2150 rpm
Rated torque	180 Nm @ 1200 rpm
Compression ratio	18.5:1
Connecting rod length	208 mm
Crank radius	60 mm
Capacity	3.3 L
Aspiration	Natural
Type of injection	Direct injection
Type of operation	Four stroke
Maximum inlet valve lift	10.52 mm

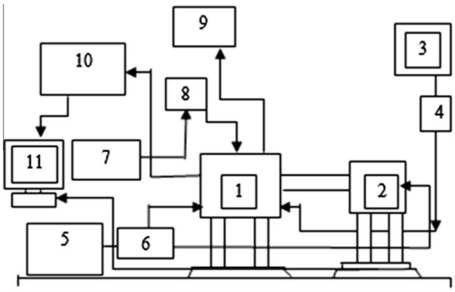

Figure 3 Schematic diagram of Experimental Test setup (Left), Photograph of experimental setup (Right) 1. Engine, 2. Dynamometer, 3. Fuel tank, 4. Fuel filter, 5.Water tank, 6. Water Filter, 7. Manometer setup, 8. Air filter, 9. AVL Di-Gas 444 gas analyzer, 10. Sensor junction box, 11. ARAI EDACS Dyno controller, Throttle controller & Monitor setup.

variation in load. It is observed that, as compared to standard baseline engine, the BSFC is reduced by 3.38% and 28.59% at full load and 25% of the full load conditions respectively. Decrease in BSFC is due to the reduction in the fuel consumption and improved energy conversion rate at all loading conditions in the TBC coated engine. This may be due to the increased temperature of the combustion chamber walls, which increases the temperature of the fuel issuing from the heated fuel injecting nozzle resulting in the reduced fuel viscosity and better combustion of the fuel. Experimental results showed that the reduction in BSFC trend is monotonically increasing while decreasing the applied load conditions. The predicted trend is consistent with the findings of various researchers [8].

4.1.2. Brake thermal efficiency

Fig. 5 shows the variation in brake thermal efficiency with increasing load for TBC coated engine and baseline engine. It is significant that TBC coated engine has higher efficiency than that of base line engine at all loading conditions. This may be due to thermal resistance on the piston crown which cannot allow the heat energy to the coolant and other medium. This can clearly be seen from (Table 4) that the percentage of heat loss to coolant got reduced significantly for all loading conditions. The maximum brake thermal efficiency obtained for TBC coated engine and baseline engine is 34.05% and 33.49% respectively. Maximum improvement of 8.84% in brake thermal efficiency is observed, when the engine is loaded at 50% of full load. This is due to the fact that the reduction in fuel consumption for the same power output helps in increasing the brake thermal efficiency.

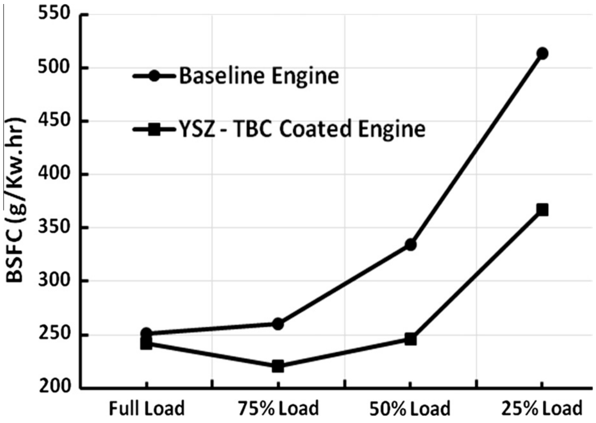

Figure 4 Variation of BSFC of baseline engine and TBC engine under different load conditions.

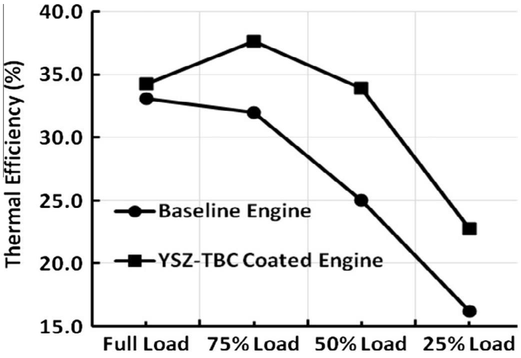

Figure 5 Variation of thermal efficiency of baseline engine and TBC engine under different load conditions.

4.1.3. Power

It is observed that power and torque developed in the thermal barrier coated engine is reduced at all loading conditions when compared to the baseline engine as shown in Fig. 6. Though the TBC layer reduces the heat loss to the cooling medium, it affects the compression ratio of the engine which in turn reduces the power and torque developing capacity of the engine.

4.1.4. Volumetric efficiency

Volumetric efficiency is an indication of breathing ability of the engine. It depends on the ambient conditions and operating conditions of the engine. Reducing the heat rejection with the addition of ceramic insulation causes increase in the temperature of the combustion chamber walls of an LHR engines. Fig. 7 shows the variation in volumetric efficiency of baseline engine and TBC coated engine under different load conditions. Increase in volumetric efficiency is observed in the TBC coated engine, as the hotter walls and residual gas decrease the density of the inducted air. The similar findings were found by the previous researchers; Gatowski [14], Suzuki et al. [15], Sudhakar et al. [16] and others on LHR engine.

Table 4 Variation in heat distribution of baseline and TBC coated engines.

Loading condition	Total heat (Q) (KW)	Useful heat (Q1) (%)	Heat loss to coolant (Q2) (%)	Exhaust heat (Q3) (%)	Unacconted heat (Q4) (%)
Baseline engine heat distribution					
Full Load	88.355	24.309	32.507	21.631	21.551
75% Load	63.351	34.019	30.600	29.579	5.800
50% Load	43.749	24.283	37.648	21.629	16.439
25% Load	31.489	17.282	42.119	23.252	17.346
YSZ TBC coated engine heat distribution					
Full Load	84.750	25.148	30.435	25.317	19.097
75% Load	61.712	25.966	27.832	30.652	15.548
50% Load	45.425	23.577	35.891	21.883	18.647
25% Load	32.284	16.683	41.383	24.086	17.846

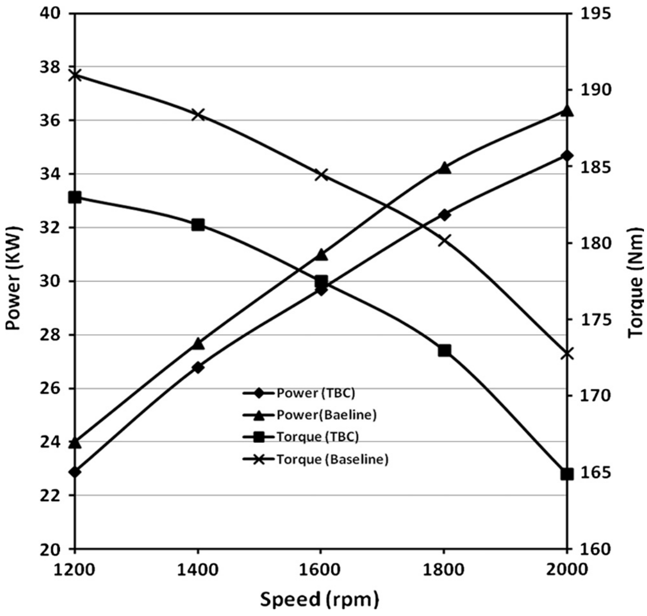

Figure 6 Variation in Power and Torque of baseline engine and TBC engine under different load conditions.

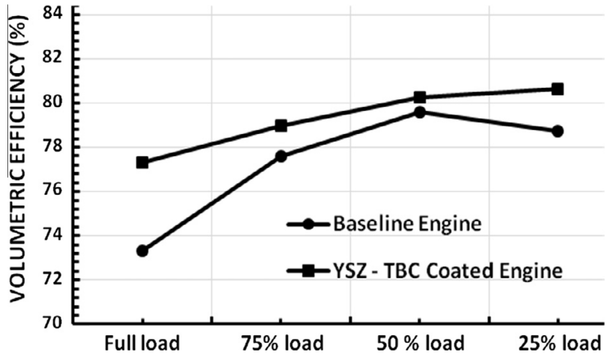

Figure 7 Variation in Volumetric efficiency of baseline and TBC coated engines.

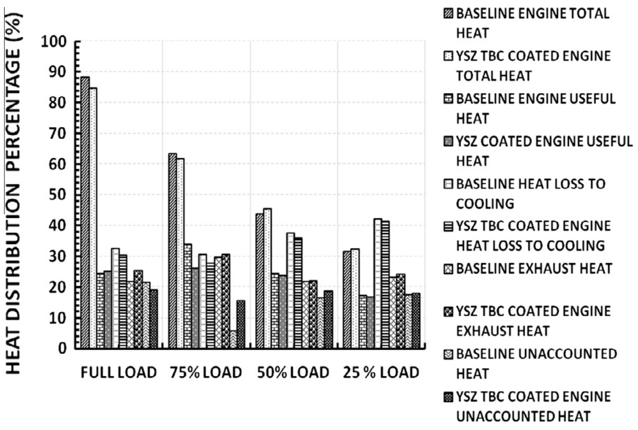

Figure 8 Variation in heat distribution of baseline and TBC coated engines.

4.1.5. Thermal balance

The thermal balance sheet for the baseline engine and the thermal barrier coated engine was prepared and is presented in Table 4. Thermal balance sheet illustrates the distribution of total heat energy developed into various forms such as useful work, heat lost to cooling water, heat lost through exhaust gas, and other unaccounted losses (heat carried away by the lubricating oil, radiation, vapor in the exhaust). The comparison of thermal balance sheet for the baseline engine and TBC coated engine under different load and speed conditions is shown in Fig. 8. At higher load conditions (100%, 75% load) the total heat produced is more in baseline engine when compared with the TBC coated engine. However the heat produced in TBC coated engine is higher at lower loads (50%, 25% loads). This is due to the reason that, the fuel consumption is reduced at higher loads and increased at lower loads in TBC coated engine. It is also observed that, the heat energy available at the exhaust is increased at all loading conditions.

4.2. Emission characteristics

The engine is tested as per ISO 8178-4 “C1” 8 Mode test cycle for off road vehicles, for its emission characteristics. From the experimental results, the weighted average of Hydrocarbon, Carbon Monoxide and Carbon dioxide emissions is calculated and shown in Fig. 9. It is found that the CO & HC emissions

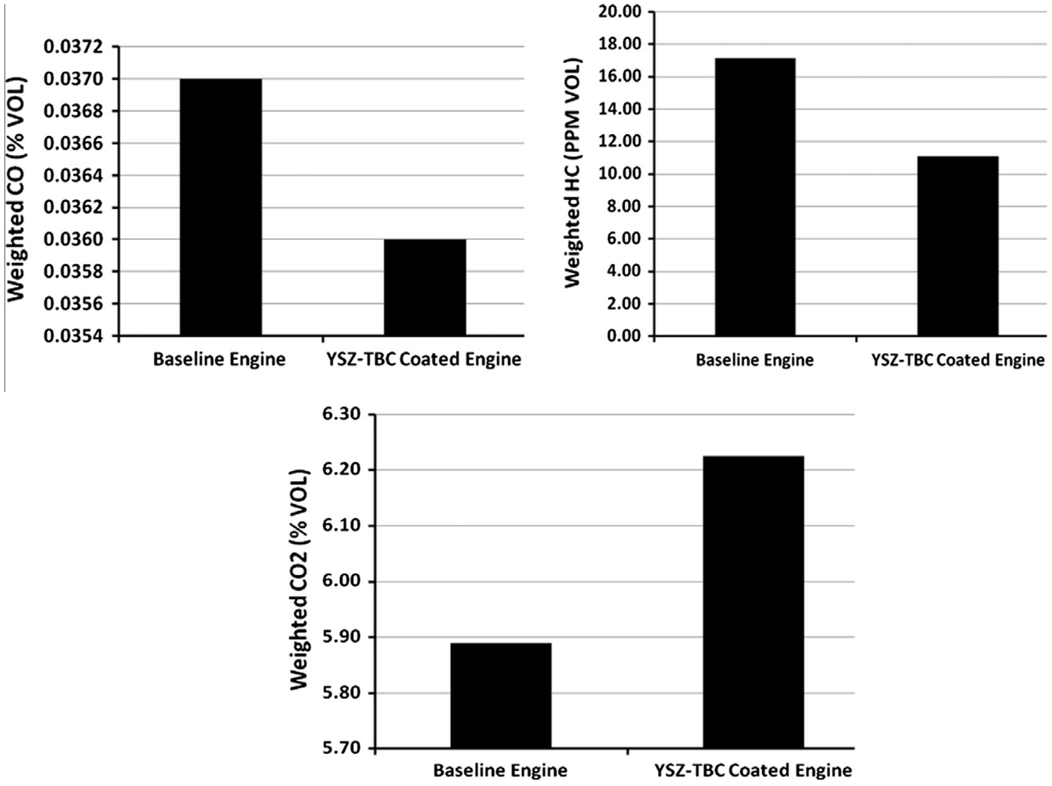

Figure 9 Comparison of weighted average values of CO, HC and CO_2 emissions.

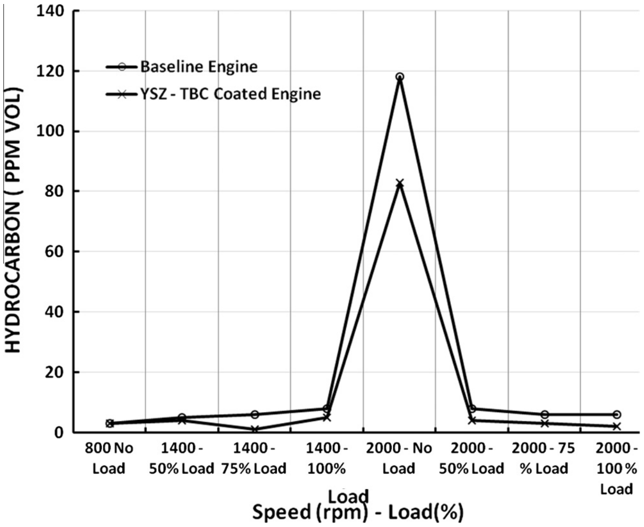

Figure 10 Variation in Hydrocarbon emissions of baseline and TBC coated engine.

are reduced by 2.70% & 35.27% respectively in TBC coated engine when compared to the baseline engine. The CO_2 emissions are increased by 5.68% in the TBC coated engine.

4.2.1. Hydrocarbon emissions (HC)

Fig. 10 shows variations in HC emissions. HC emissions are low in the TBC coated engine when compared to the standard baseline engine. In TBC coated engine, the hydrocarbon emission is reduced by up to 35%, when compared to the baseline engine. The decrease in HC emission in the TBC coated engine is due to the decrease in the heat losses going to the cooling system and subsequent increase in the after-combustion temperature. The experimental results clearly indicate that the ceramic coating improves the local conditions specifying temperature, pressure, mixture ratio, amount of oxygen and makes the combustion continuous in diesel engines.

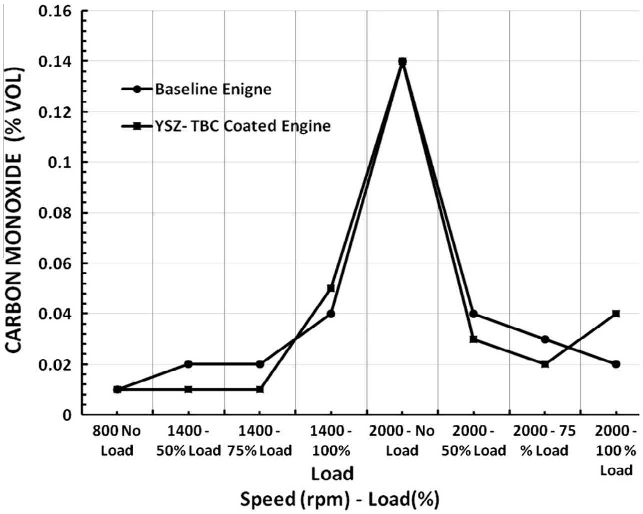

Figure 11 Variation in Carbon monoxide emissions of baseline and TBC coated engines.

4.2.2. Carbon monoxide emission (CO)

The measured CO emissions for TBC coated engine and the baseline engine are shown in Fig. 11. It shows CO variations with respect to various load and speed conditions as per ISO 8178-4 "C1" 8 Mode cycle for off road vehicles. It is well known that better fuel combustion usually results in lower CO emission. It was experimentally determined that TBC coated engine causes a 2.72% reduction in CO emission at various load and speed conditions. The reduction in CO emission is due to complete combustion of the fuel.

4.2.3. Carbon di-oxide emission (CO_2)

Fig. 12 shows CO_2 variations with respect to various load and speed conditions. CO_2 emission from diesel engine is related to the fuel properties as well as combustion characteristics. It is well known that better fuel combustion increases the O_2 and hence the carbon di-oxide emission is higher in Thermal Barrier coated Engine. It was experimentally determined that TBC coated engine causes a increase in CO_2 emission at all loads and speed conditions with a noticeable 5.6% hike at 75% of full load and 2000 rpm.

4.2.4. Exhaust gas temperature

Fig. 13 shows variations in exhaust gas temperature for different load conditions. Exhaust gas temperature increases as the engine load increases and this trend was found by previous researchers [1–16]. The exhaust temperature for the baseline engine is 524 °C at full load condition whereas for the TBC coated engine exhaust temperature reached a peak value of 558 °C for the same operating conditions. This is due to the higher after combustion temperature and reduced heat loss to the coolant in the TBC coated engine, which is evident from Table 4.

4.2.5. Nitrogen oxide emission (NO_x)

In general, NO_x level varies in direct proportion with the in-cylinder temperature of the engine. Azadi et al. [12] predicted that NO_x emission in TBC coated engines is higher than that in baseline engine. Morel et al. [9] predicted that Smoke levels increases by 12% and NO_x levels increases by 19% in TBC coated engine. Most of the earlier investigations also showed that NO_x emissions from LHR engine are generally higher. This could be due to the higher combustion temperature and longer combustion duration.

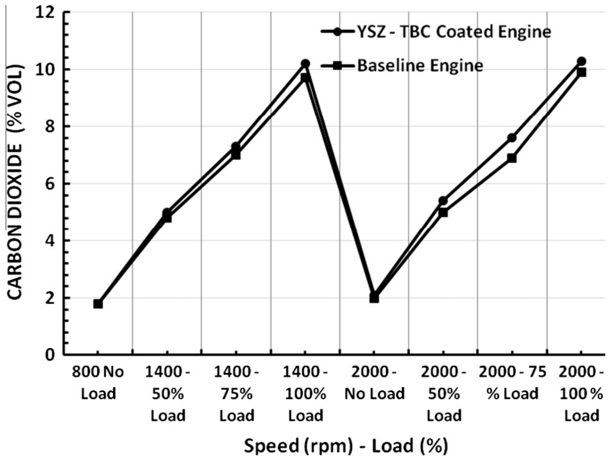

Figure 12 Variation in Carbon Dioxide emissions of baseline and TBC coated engines.

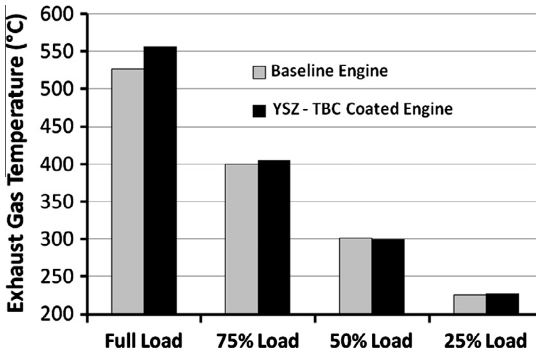

Figure 13 Variations of the Exhaust gas temperature of baseline and TBC coated engine.

Due to the better combustion of the air–fuel mixture in the TBC coated engine, the combustion temperature is higher. An increase in after-combustion temperature causes an increase in NO_x emission level. All factor facilitating and accelerating the reaction between oxygen and nitrogen increases NO_x formation at higher temperature. Experimental results show that the combustion temperature in the TBC coated engine is high, which is evident from the values of exhaust gas temperature (see Table 4) when engine runs at 2000 rpm. The exhaust temperature of the baseline engine is 181 °C at no load and 534 °C at full load Condition whereas for the TBC coated engine the exhaust gas temperature is increased to 199 °C at no load and 586 °C at full load Condition, as shown in Fig. 13. The authors suspect that, the NO_x emission level will certainly raise up in the TBC coated engine in proportionate to the after combustion temperature.

5. Conclusion

A conventional three cylinder diesel engine was converted to a LHR Engine by coating its piston crowns by a 100 μm layer of Yttria Stabilized Zirconia by plasma spray method. Engine parameters, namely brake thermal efficiency, brake specific fuel consumption, power and emission characteristics were measured to investigate the effects of YSZ on its performance and emission characteristics of the engine. The following conclusions can be drawn from the experimental results.

- The TBC coated engine shows better Brake thermal efficiency and better BSFC compared to the baseline engine.
- Brake thermal efficiency is improved at all loads and speed conditions in the TBC coated engine. The improvement is ranging from 1.14% to a maximum of 8.84% at 50% of full load condition.
- TBC coated engine reduces the specific fuel consumption by 3.38% and 28.59% at full load and 25% of the full load conditions, respectively when compared to the baseline engine.
- Hydrocarbon emissions were reduced drastically by 35.27% in the TBC coated engine, whereas Carbon monoxide emission is reduced by 2.7% and Carbon dioxide emission is increased by 5.27%.

- Exhaust gas temperature increased monotonically at all loading conditions which in turn increased the NO_x emissions of the TBC coated engine.

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