Use of Thermal Barrier Coating in Diesel Engine

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Abstract : The Experimental work is carried out under different loading conditions with same compression ratio on the Research Engine Set-up, single cylinder, four stroke, water cooled, multi fuel variable compression ratio (VCR) diesel engine, with its piston crown, cylinder head and valve top surface coated with Nickel Chromium Aluminum (NiCrAl) as bond coat and Yattria Stabilized Zirconia (YSZ) as a top coat to understand the effect of thermal barrier coating on the performance and emission characteristics in comparison with baseline engine characteristics.YSZ material is taken as the top coat material because of its desirable properties such as the high coefficient of thermal expansion, low conductivity, low heat capacity, high resistance to fatigue stress, creep stress, thermal shock stress, high Poisson ratio and stable at the high temperature condition. Performance characteristics are found out by using I.C. Engine combustion analysis software, smoke and exhaust gas emission is measured by AVL smoke meter and AVL Di-gas analyzer respectively. Experimental results show that there is improvement in the performance and reduction in the emissions. It shows slightly increase in the Nitrogen oxide emission (No_x).

IndexTerms – TBC Engine, Thermal barrier coating in diesel engine.

I. Introduction

Diesel engine is mostly utilized in both transport and agriculture industry due to its low fuel cost. Energy release in diesel engine is by the chemical process in a combustion chamber which is then converted into mechanical energy by work. Out off total fuel energy generated in a combustion chamber of diesel engine only convert one third of energy is used for work and remaining two third of energy is lost as the waste energy through coolant, exhaust gas and friction. Approximately 60 to 70 % of energy is lost out off total fuel energy generated in the combustion chamber. [1] Efficiency of the diesel engine is generally in the range of 30 to 40 %. Approximately 30% of fuel energy is carried out by the exhaust gas and 50 to 60 % energy is carried by the Cooling water. [2] The engine cooling system should absorb energy to keep the working temperature of the material below the safe temperature.

In order to save the energy which is lost to the coolant, it need to make some insulation on the internal part of the combustion chamber such that energy pass through material is reduced. In order to provide the insulation on the material of the IC engine parts, it need to make the coating on the material by the thermally insulated layer known as Thermal Barrier Coat (TBC) which protect the material against high temperature. It means to make the IC engine as a Low Heat Rejection (LHR) Engine. In LHR engine cylinder head, piston crown, top surface of valve is coated with insulating material. This will reduce heat transfer through the engine wall, piston surface and cylinder head. The major effect of the TBC engine is to increase the thermal efficiency and reducing the cooling system. A simple first law of thermodynamics analysis of the energy conversion process within diesel engine would indicate that if the heat rejection to the coolant system was eliminated or reduced then the thermal efficiency of the engine could be increased.

Thermal barrier coatings were used not only for reduced in-cylinder heat rejection and thermal fatigue protection of the underline metallic surface, but also for possible reduction of engine emissions. It allow engine to work at high temperature and compression ratio. Thermal insulation work according to second law of thermodynamics, improve the engine efficiency and reduce the fuel consumption. [3]

Base on the literature survey Wallace et al. [4] shows the increase in the 7 to 14 % in the indicated thermal efficiency for fully and partially adiabatic conditions respectively. Kamo et al. [5] shows by its experimental work that thermal efficiency of thermal barrier coated engine compare to that of baseline engine increase by 5 to 6 %. By L.Bruns et al. [6] fuel economy can be achieved up to the 16 to 37 %. R.Kamo. [7] shows by its experimental work increase in the fuel economy by 5 to 6 % when piston and cylinder head coated with yattria stabilizes zirconium (YSZ) having 0.1 and 0.5 mm thickness respectively.

II. Thermal Barrier Coat (TBC) Material

There are number of TBC materials are available for the coating. [8] Most desirable properties of TBC material involved high thermal coefficient of expansion, resistance to corrosion, low thermal conductivity, sustained to high temperature, low heat capacity and resistance to high temperature stress. Base on the open literature survey YSZ is most effectively used as the TBC [3] material since approach to the desirable properties of TBC material. T Morel et al. [9] shows that Yattria used as stabilizing agent for zirconia. The stabilize zirconia has been mostly used by several investigator as thermal barrier coating for piston crown. In the present work YSZ used as the TBC material and Nickel Chromium Aluminum (NiCrAl) as a bond coat material. The bond coat layer is used between the TBC and the metal substrate. The bond coat material is an intermetallic alloy that provides oxidation resistance at high temperatures and aids in the adhesion of the TBC layer to the substrate. Properties of YSZ and NiCrAl are given in table 1.

Table1. Materials and their property

Parameter	YSZ	NiCrAl
Melting point	2800 °c	2800 °c
Apparent Density	2.3 ± 0.2 g/cm^3	1.4–0.4 g/cm3
Recommended coating processes	APS	APS
Thermal conductivity	0.8 – 1.3 W/mK	16.1W/mK
Specific Heat	450 ± 20 J/kgK	450 J/kg K

III. Atmospheric Plasma Spray Coating (APS)

Thermal spraying technique consist different types of materials deposition process such as Detonation spraying, Wire arc spraying, Flame spraying, High velocity oxy-fuel coating spraying (HVOF),Warm or cold spraying and Atmospheric plasma spray (APS). From the above methods plasma spray process is adopted in our experimental study. Plasma process is recommended by the OERLIKON METCO for the deposition NiCrAl and YSZ materials. Snap shot Plasma spray coating system is shown in fig 1. APS system consist of the power feed unit, power supply unit, job holding mechanism, control unit and gas supply unit. In APS powder is melted in the ionized gas and spray molten powder form with high velocity on the surface to be coated. In the present work two layers of coatings are provided on the piston and cylinder head. First is made of NiCrAl material. This layer is known as bond coat layer. Second layer is made up of the YSZ known as top layer. YSZ consist of the 8 % mole yattria and remaining mole % is zirconia. This combination of the layers is known as the TBC layer. Snapshot of coated cylinder head and piston top is shown in figure 2 and figure 3 respectively.

Table2. Plasma spray coating specification

Parameter	Specification
Plasma gun	3 MB
Pressure of argon gas	100-110 PSI
Flow rate of argon gas	60-70 LPM
Current	600 A
Voltage	60-70 V
Arc temperature	15000 °c
Particle size	20-40 um

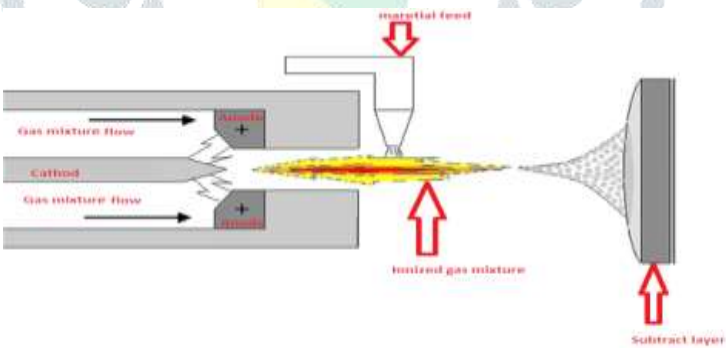

Fig 1.Snap shot of plasma spray coating.

Fig 2.Snapshot of coated piston top

Fig 3.Snapshot of coated cylinder head

IV. EXPERIMENTAL TEST SETUP

Experimental test set up consist of the four strokes, single cylinder, water cooled diesel engine connected with eddy current dynamometer for loading. Experimental set up is shown in figure 4. Diesel engine is the variable compression engine. Engine specification is given in table 3. Variable loads applied on the engine using eddy current dynamometer. Fuel flow rate to the engine is measure using gravimetric type fuel consumption meter. Air flow rate to the engine is measured using monometer attached to air box. Temperature and pressure at various positions in the engine is measure by using various sensor mountains at proper positions. Various performance and combustion parameters are calculated using software package known as "Engine soft" which take the input from various sensors mountain on engine. Emission from the engine such as carbon monoxide (CO), carbon dioxide (CO_2), hydro carbon (HC) and nitrogen dioxide (NO_x) are measured by using AVL Di-gas analyzer. Smoke opacity is measure by using smoke meter.

Fig 4.Experimental set up

Table 3 Base line Engine Specification

Parameter	Specification
Stroke	110 mm
Bore	87.5 mm
Capacity	661 cc
Power	3.5 Kw
Speed	1500 rpm
Connecting Rod length	234 mm
Fuel tank capacity	15 Liter

V. RESULTS AND DISCUSSIONS

In experimental results comparison of baseline engine and TBC engine has been done for various performance and emission characteristics at different loading such as 0, 4, 8, 12 and15 kg with constant speed 1500 rpm and constant compression ratio 18. Experimental result shows that heat losses to the cooling medium are reduced as the thermal conductivity of the TBC material is low which result into increase in the exhaust energy. This increase in exhaust energy reduced emission.

5.1 Performance Parameters

Engine performance parameters such as brake power, indicate power, brake specific fuel consumption, thermal efficiency of TBC engine are measure and compare with the base line engine for different loading at constant speed.

5.1.1 Brake Power

Figure 5 shows the variation of the brake power for the TBC engine and base line engine with respect to the variation of the load at the constant speed and constant compression ratio. In the TBC engine heat losses to cooling water are reduced which increases temperature and pressure in the combustion chamber. This reduction in heat losses to cooling water leads to increase in brake power in TBC compared to baseline. The graph shows up to seven percent of brake power increase in TBC engine compare to the base line engine. It also shows that maximum percentage of increase in the brake power is occur at lower load compare to higher load in TBC engine compared to the baseline engine.

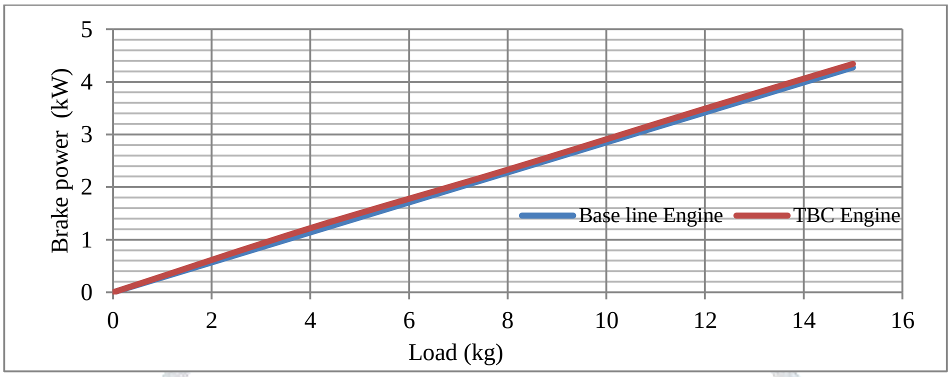

Fig 5.Variation of brake power vs. load

5.1.2 Brake Specific Fuel Consumption (BSFC)

Figure 6 shows the variation of the brake specific fuel consumption in TBC engine compare to base line engine at constant speed for the variable loads. In TBC engine, temperature and pressure is increases in combustion engine due to decrease in the heat losses through the combustion chamber and cylinder head. This increased temperature in combustion chamber lead to increase the temperature of the fuel incoming in combustion through the injector. This makes the better combustion of the fuel which decreases the fuel consumption in TBC engine. This result into decreasing the brake specific fuel consumption in TBC engine compare to the base line engine. The maximum percentage of decrease in BSFC is up to 39 for TBC engine compare to baseline engine at partial load. It also shows that maximum percentage of decrease in BSFC is at lower load in TBC engine compare to baseline engine.

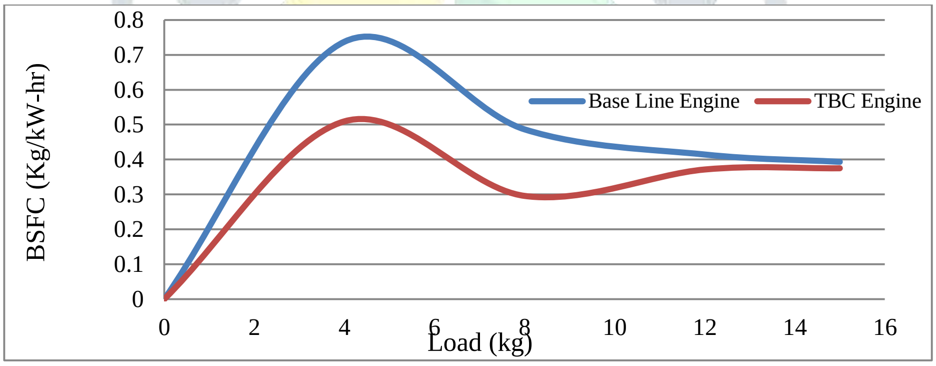

Fig 6.Variation of BSFC vs. load

5.1.3 Brake Thermal Efficiency (BTE)

Figure 7 shows the variation of the brake thermal efficiency in TBC engine compare to the baseline engine for variable load at constant speed. It shows increase in the brake thermal efficiency in TBC engine compare to baseline engine. This is due to reduction in heat losses to the coolant water due to thermal resistance to the flow of heat. This thermal resistance decreases the heat losses and increases the temperature in combustion chamber which results into increase in brake thermal efficiency in TBC engine compare to the baseline engine. The increase in the percentage brake thermal efficiency in TBC engine compare to the baseline engine is varying with the load. The average increase in brake thermal efficiency is 25 percent in TBC engine compare to the baseline engine.

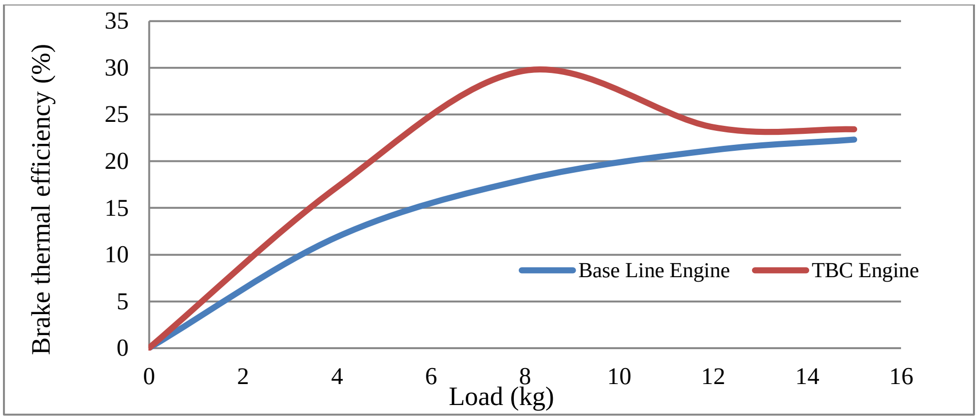

Fig 7.Variation of BTE vs. load

5.1.4 Fuel Consumption

The figure 8 shows the variation of the fuel consumption for TBC engine compare to the baseline engine. It shows the reduction in the fuel consumption in TBC engine compare to baseline engine. This is due to the decreased in the heat losses to surrounding due to the thermal resistance created by the thermal barrier coating in TBC engine. This decreased losses in the TBC engine result into better utilization of the fuel for the output. This lead to decrease the fuel consumption in TBC engine compare to baseline engine

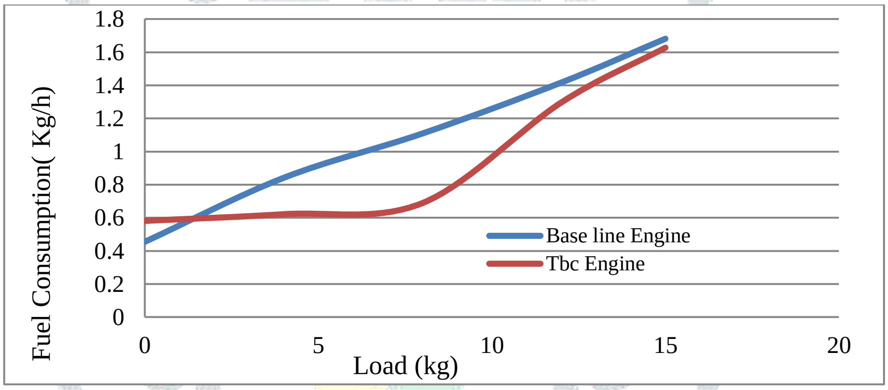

Fig 8.Variation Fuel consumption vs. load

5.2 Emissions Characteristic

Emission characteristics such hydrocarbon (HC), carbon monoxide (CO) and Nitrogen Dioxide (NO_x) are compare for TBC engine and Base line engine at different load with constant speed and constant compression ratio. Exhaust temperature in the TBC engine increase due to that emissions decrease in TBC engine compare to base line engine except NO_x emission.

5.2.1 Carbon Monoxide (CO)

The measured CO emissions for TBC coated engine and the baseline engine are shown in Figure 9. It shows CO variations with respect to various load and constant speed. It is well known that better fuel combustion usually results in lower CO emission. It was experimentally determined that TBC coated engine causes a 14 to 15 % reduction in CO emission at various load conditions. The reduction in CO emission is due to complete combustion of the fuel.

5.2.2 Hydrocarbon (HC)

The measured HC emissions for TBC coated engine and the baseline engine are shown in Figure 10. 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 27%, 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.

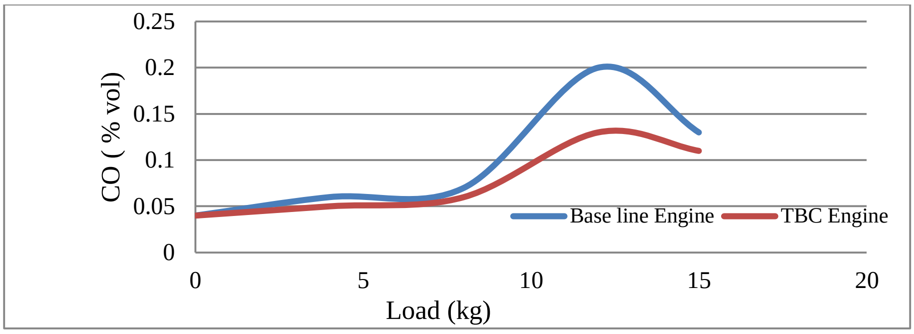

Fig 9.Carbon monoxide vs. Load

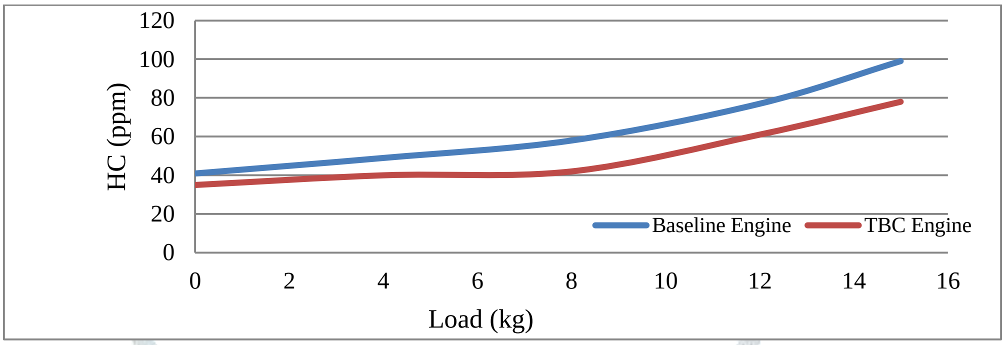

Fig 10.Hydrocarbon vs. Load

5.2.3 Nitrogen Oxide (No_x)

The measured No_x emission for the TBC engine and baseline engine is shown in fig 11. Experimental result shows the temperature of exhaust gas is more in TBC engine compare to the baseline engine. No_x emission is directly proportional to the temperature. Experimental result shows No_x emission in the TBC engine is more than the baseline engine. No_x emission in the TBC engine is 12 percent more than the baseline engine.

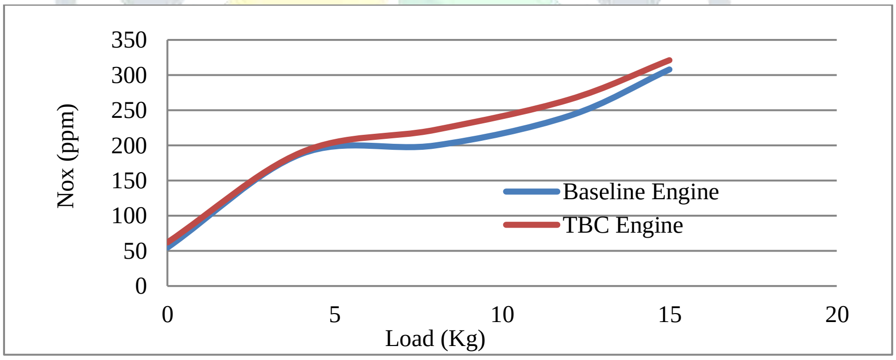

Fig 11.Nitrogen dioxide vs. load

VI. CONCLUSIONS

A conventional baseline engine is converted to a TBC engine by coating piston top and cylinder head by thermal barrier coating. Yattria stabilized zirconium is selected as a Thermal barrier coating material. Performance parameters such as brake power, brake specific fuel consumption, fuel consumption, heat rejection and air fuel ratio for both baseline engine and TBC engine is calculated. Following conclusion can be drawn from the results.

1. Brake power for the TBC power is more than that of TBC engine. Up to 7 percent of brake power increase in TBC engine compare to baseline engine.
2. Brake specific fuel consumption for the TBC engine is lower than the baseline engine. Brake specific fuel consumption for the TBC is 39 to 4.6 percent lower than baseline engine at lower load and full load respectively.
3. Brake thermal efficiency for the TBC engine is higher than the baseline engine. Brake thermal efficiency for the TBC engine is 4 to 40 percent more than baseline engine at higher and lower load respectively.
4. Air fuel ratio for the TBC engine is more than the baseline engine. Air fuel ratio for the TBC engine is 3 to 28 percent more than baseline engine at higher load and lower load respectively.

5 It was experimentally determined that TBC coated engine causes a 14 to 15 % reduction in CO emission at various load conditions.
6 In TBC coated engine, the hydrocarbon emission is reduced by up to 27%, when compared to the baseline engine.
7 No_x emission in the TBC engine is 12 percent more than the baseline engine.

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