



THE INFLUENCE OF THERMAL BARRIER COATING ON THE COMBUSTION AND EXHAUST EMISSION IN TURPENTINE OIL POWERED DI DIESEL ENGINE

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ABSTRACT

Several methods of coatings are used to protect various structural engineering materials from corrosion, wear, and erosion, and to provide lubrication and thermal insulation. Of these, Thermal barrier coatings (TBC) play the most important role in coating of internal combustion engines particular to the combustion chamber. Insulation of the combustion chamber components of low heat rejection (LHR) engines can reduce the heat transfer between the gases in the cylinder and the cylinder wall and thus increase the combustion temperature. This study concentrates on low heat rejection (LHR) engine in which yttria stabilized zirconia (YSZ) are coated to acquire the thermal barrier for the piston crown, cylinder head and valves which will vary depends upon the functional graded material (FGM). A layer of aluminum oxide coating is used to conduct extensive experiments in a single-cylinder Kirloskar TV 1 engine with every piston crown, cylinder head and valves are coated with a layer of ceramic, which consists of zirconia and yttria with varying of thick compositions. This study comprises about diesel blended with turpentine oil which is used in Engine performance measurements. Therefore the characteristics of emissions and combustion were analysed before and after the application of FGM coatings onto the piston crown of cylinder head and valves. To acquire more improved engine performance, cylinder pressure measurements were taken which provides direct comparison to cylinder pressure; maximum pressure and heat release diagrams between are figured to exhibit the base line which is coated with FGM.

Keywords: Thermal Barrier Coating, Functional Graded Material, Yttria Stabilized Zirconia.

INTRODUCTION

This study exhibits to stimulate the adiabatic engines in a signified combustion chamber by means of applying the Thermal barrier coating (TBC) to the internal combustion engine. The purpose of coating Thermal barrier is to reduce the in-cylinder heat and to maintain thermal fatigue protection on metallic surfaces, which further emulates the reduction of emissions that occurred in engines [1-4]. The actual purpose for applying TBCs is to reduce the heat in the engine cooling-jacket through the surfaces of cylinder head, liner, piston crown and piston rings. The combustion chambers which were coated with ceramics will be insulated in order to affect the combustion process and the exhaust emissions characteristics of the engines. The subject is quiet understandable through the first law of thermodynamics which explains in-cylinder heat rejection cannot be utilized for mechanical work, but emulates waste heat in the exhaust engine. By means of applying TBC there are some complications are possible which may increase fuel-air temperature in the combustion, it can further generates the ignition property to mix the fuel with air which applies mechanism to exhaust emission characteristics. The coated ceramic rough surface with its physical properties and its porous characteristic have direct influence on unburned or partially burnt hydrocarbons in terms of pore size or porosity, it also have effect on surface quenching and retention residual in the pores [5, 6].

The focus of this study is to increase the thermal efficiency and to reduce fuel consumption specifically of diesel engines, which will lead to adopt higher compression ratios and reduces in-cylinder heat. In the materials utilized for the combustion chamber generates mechanical and thermal stresses. In case of this durability of materials and the components of engine cylinders like pistons, rings and cylinder heads may be concerned, but it still prevents the in-cylinder temperature. The heat transfer in the underlying metal will be reduced by applying TBC to the surfaces of these components which also enhances temperature durability [5]. Karthikeyan and Mahalashmi [7, 8], Premanand *et al.*, [9] studied performance and emission characteristics with diesel and turpentine oil blends as a fuel. Nabiet *et al.*, [10] investigated the emission characteristics including particulate matter, mass and numbers, nitric oxide, total unburnt hydrocarbon, carbon dioxide and performance parameters including brake power, indicated power, brake mean effective pressure, indicated mean effective pressure, mechanical efficiency, brake thermal efficiency and brake specific energy consumption with four different blends of fuel. İşcan, and Aydın, [11] analysed with vegetable oil as a fuel in a low heat rejection diesel engine. [12] Abedin *et al.*, [12] examined the impact of different palm-jatropha-biodiesel blends in a diesel engine. The study of Literature shows that insulated engine exhaust gas temperature at various operating conditions even in the prescribed baseline when



it was not coated, this theory could be against the basic belief which explains that exhaust gas temperature should be higher in insulated engines. This study further induce to adopt and approach insulated combustion chambers with FGM coating, which can serve for the effect of TBC coating on the cylinder pressure that releases the heat and exhaust gas temperature in a diesel engine.

THERMAL BARRIER COATING

Chan [3] studied the effect of FGM thermal barrier coating applied to the piston crown on the engine characteristics. From the study, it is revealed that, by controlling the phases in the fabrication process zirconia ceramics have become strong and tough at room temperature. He also found that the knowledge in phase transition is crucial to determine the properties of zirconia ceramics, since zirconium dioxide (ZrO_2) has a monoclinic crystallographic structure at ambient temperatures. When he attempted to raise the temperature, the oxide undergoes phase transitions from monoclinic to tetragonal in the temperature of $1170^\circ C$, from tetragonal to cubic the transition temperature was $2370^\circ C$ and from cubic to liquid, the transition temperature would be $2680^\circ C$. The temperature was decreasing approximately $1170^\circ C$ when the monoclinic phase was transmitted from tetragonal which is disruptive and renders ZrO_2 as a high-temperature in structural ceramic. Further, it was observed that during the transformation from tetragonal to monoclinic phase, a disruption is caused by 6.5% expansion of volume, which could lead to structural failure of ceramic coating. As a matter of fact ZrO_2 forms of solid solutions which allow rare oxides such as CaO, MgO, Y_2O_3 and other oxides of earth. This process can be acquired by mixing the powders of ZrO_2 and Y_2O_3 as samples and pressed into solid body which sintered in temperature to promote inter-diffusion of the captions. When the temperature phases Yttria-dropped, zirconia behaves differently from pure ZrO_2 , in reaction to this tetragonal and cubic acts to stabilize temperature lower than $1170^\circ C$ and $2370^\circ C$, respectively. Therefore, dropping of the aforementioned aliovalent oxides serves as the stabilizing agent for the zirconia, in addition to this the fraction of stabilizer the cubic phase could stabilize the ambient temperature. The cubic structure of ambient temperature is stabilized by the addition of 9% mole fraction of yttria (Y_2O_3) or more to ZrO_2 . The further addition of 6% or less mole fraction of Y_2O_3 generates stabilized zirconia (PSZ) which consist the cubic matrix with dispersed tetragonal or monoclinic precipitates or even on both which completely depends upon the process of temperature history. With this background, this study concentrates on low heat rejection (LHR) engine in which yttria stabilized zirconia (YSZ) are coated to acquire the thermal barrier for the piston crown, cylinder head and valves which will vary depends upon the functional graded material (FGM).

METHODOLOGY

This study eludes the functions of material like piston crowns, cylinder head and valve which are coated in order to control engine emissions and combustion characteristics. A layer of aluminum oxide coating is used to conduct extensive experiments in a single-cylinder Kirloskar TV 1 engine with every piston crown, cylinder head and valves are coated with a layer of ceramic, which consists of zirconia and yttria with varying of thick compositions. This study used diesel blended with turpentine oil in various range i.e., B20 (Blend 20% turpentine), B40, B60, and B100 for measuring engine performance. Therefore the characteristics of emissions and combustion were analysed before and after the application of FGM coatings onto the piston crown of cylinder head and valves. To acquire more improved engine performance, cylinder pressure measurements were taken which provides direct comparison to cylinder pressure; maximum pressure and heat release diagrams between are figured to exhibit the base line which is coated with FGM.

CERAMIC COATING OF PISTON CROWN, CYLINDER HEAD AND VALVES

The phase stability in zirconia and thermal compatibility is based on the material which lies between the barrier coat and the coated aluminum alloy materials of the piston crown, cylinder head and valves, the properties of functionally graded material varied in the thickness of the coat. In this study, the ceramic consisting zirconia with different proportions of yttria doping its thickness is a layer of FGM. It displays continuous variation of compositions, else it microstructures definable geometric orientations and distances. In the microscopic level the grades continuously laminates comprised gradients of metals, ceramics, polymers or variations in porosity and density. While fabrication of FGM for structural application, different techniques are adopted. e.g., powder metallurgy, plasma spraying, self-propagating, high temperature synthesis, reactive infiltration, etc. To further process FGM films with nanometer composition gradients physical and chemical vapour deposition techniques are explored. For the further enhancement plasma spray was utilized and FGM are laminated by four sub-layers of zirconia-yttria with varying compositions from a pure zirconia ceramic to 25% zirconia.75%-yttria ceramic (see Table-1).

**Table-1.** Properties of FGM coating

Description	Density (g.m ⁻³)	Porosity (%)	Elastic modulus (GPa)
100%ZrO ₂	6.0374	12.16	53
75% ZrO ₂ /25%Y ₂ O ₃	6.2076	11.20	105
50% ZrO ₂ /50% Y ₂ O ₃	6.6264	10.01	158
25% ZrO ₂ /75% Y ₂ O ₃	6.9599	8.91	187

Plasma spray processing offers a flexible and relatively economic means for producing FGM. It has been used for many years to apply layered and graded deposits (bond coats) to enhance the survivability of engines. These graded coatings are applied to reduce discontinuities in thermal expansion coefficients in order to avoid mismatch-related failure in service. Before applying the thermal barrier coating in a manner of “functionally graded” onto the piston crown, cylinder head and valves a thickness of 200 microns of a new set of piston crown are to be machined off. In this study, the effect of ceramic coating on cylinder head, valves and piston crown face on the performance, emission and combustion characteristic of diesel engine is analysed. Ceramic layers were made by partially stabilized zirconia with aluminum oxide (Al₂ O₃ ZrO₂) by using plasma spraying method thickness about 200 microns[5] shown in Figure-1.

**Figure-1.** Thermal barrier coating on the piston crown, cylinder head and valves.**Figure-2.** Soot formation on thermal barrier coating.

Figure-2 shows the soot formation on thermal barrier coating after 50h running of engine.

EXPERIMENTAL SETUP

The experiment was conducted on Kirloskar TV-1 single cylinder direct injection diesel engine. Table-2 tabulates the specification of the engine while Figure-3 shows the schematic diagram of the overall arrangement of the test engine with thermal barrier coating on the piston crown, cylinder head and valves.

Table-2. Specification of the test engine.

Type	Single cylinder, vertical, water Cooled, 4-stroke diesel engine
Bore	87.5 mm
Stroke	110 mm
Compression ratio	17.5:1
Orifice dia	20 mm
Dynamometer arm length	195 mm
Power	5.2 kW
Speed	1500 rpm
Loading device	Eddy current dynamometer
Mode of starting	Manually cranking
Injection pressure	200bar

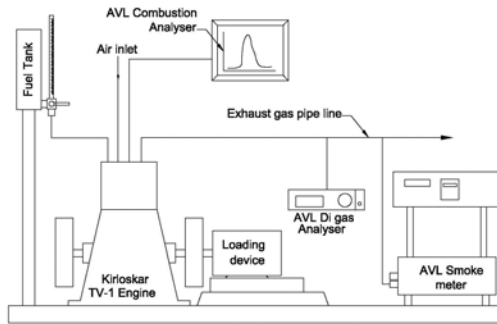


Figure-3. Schematic arrangement of the test engine.

For load testing the engine is coupled with eddy current dynamometer and the smoke density is measured by using a AVL smoke meter. NO_x emission is measured using AVL di-gas analyser. Combustion characteristics of engine are analyzed with AVL combustion analyzer. The experiments were carried out in different stages.

EXPERIMENTAL PROCEDURE

The engine speed is set at 1500 rpm and the piston crown, cylinder head and valves are insulated by using Al_2O_3 ZrO_2 and coating thickness of 200 microns. The fixed injection pressure of 200 bars was maintained. The test engine was fully instrumented and connected to eddy current dynamometer. The first stage of test is performed with different four loads viz, 25, 50, 75 and maximum load at constant speed. The experiments were conducted at the required engine load percentages in adjust by using the eddy current dynamometer. The engine was insulated and tested at base line condition. The second stage of the investigation was using various blends of turpentine oil as fuel blends. The concentration of 20, 40, 60 and 100 % is mixed with sole fuel and repeat the same experimental procedure.

The engine is operated with sole fuel at a constant speed for nearly 10 minutes to attain the steady state condition at the lowest possible load. The following observations were made twice for averaging/concordance. During the test various parameters such as brake thermal efficiency, smoke density, NO_x , CO_2 cylinder pressure, and heat release rate is obtained. The experiments were repeated for the Base engine and insulated engine as the following combinations

- Sole fuel and
- Sole fuel blend with various ratios of turpentine.

From the results of experiments the best concentration of fuel blend is determined among the various concentrations on the basis of the level of brake thermal efficiency, emission, cylinder pressure and heat release rate.

RESULTS AND DISCUSSIONS

A comparative experimental study is carried out between with and without ceramic coated piston crown, cylinder head and valves in same water cooled diesel engine. The results of brake thermal efficiency, heat release rate, smoke, CO_2 and NO_x emission obtained from the experiment compared with coating (WC) and without coating (WOC), coating for sole fuel and fuel blends. Effects of ceramic coating, without coating and fuel blends on brake thermal efficiency for function of engine loads is shown in Figure-4.

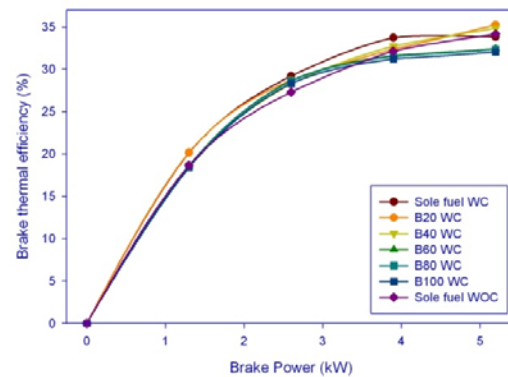


Figure-4. Effect of brake thermal efficiency on brake power.

The change in brake thermal efficiency is examined with 20, 40, 60 and 100% blends of fuel at different loads. It was found that there is a marginal difference between the brake thermal efficiency of coated and uncoated engine components. It's increased about 3% of brake thermal efficiency at maximum load. The effect of fuel additives there is slight improvement of brake thermal efficiency among the concentration. In addition the effect of ceramic coating, lower heat rejection from combustion chamber through thermally insulated components causes increase available energy. Hence the thermal efficiency of coated engine is slightly higher than the conventional engine.

Figure-5 depicts the effect of smoke density with brake power of the engine. From the results it was found that the smoke density increases with the coating and fuel blends. In ceramic coated diesel engine the combustion wall temperature increased more significantly. Hence there is an increase in compression air temperature which changes the ignition delay so that there is a changing combustion behaviour and therefore increase in the smoke density for ceramic coated engine. It was found that the 100% turpentine oil reduce the smoke density for coated piston. Hence it was clear observed that the smoke density is lower for all the concentration of fuel blends when compared to ceramic coated engine.

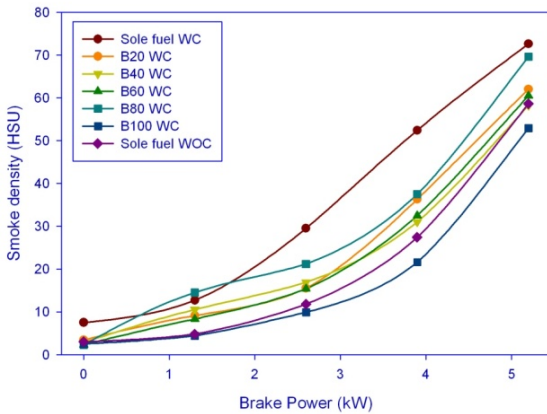


Figure-5. Effect of smoke density on brake power.

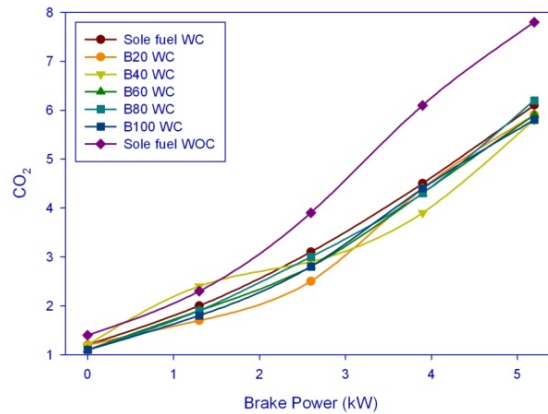


Figure-7. Effect of carbon dioxide on brake power.

Figure-6 shows the variation of NO_x emission with respect to coating and fuel blends. It is indicated that the level of NO_x is lower in case of ceramic coated piston when compared to conventional engine. This is due to the fact that the late combustion causes the heat to release at centroid to shift away from top dead center which results drop in peak pressure rise. Since the peak pressure rise is lower for the above reason and assuming the same value of mass, the peak gas temperature may also be lower near TDC, resulting reduced NO_x formation.

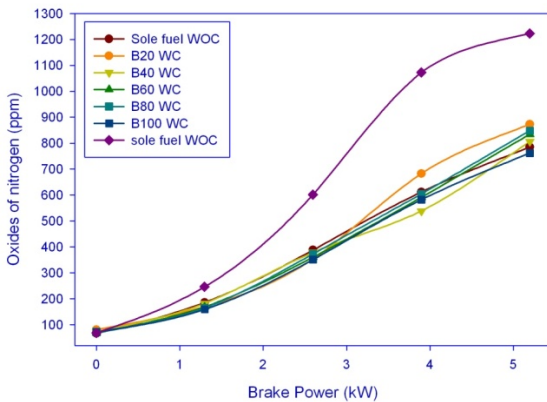


Figure-6. Effect of oxides of nitrogen on brake power.

It is seen that there is a marginal difference approximately 350 ppm reduce the effect of ceramic coating. Further it is found that effect of 100% turpentine oil as fuel with ceramic coating further reduced NO_x emission about 750 ppm at the maximum brake power of the engine.

Figure-7 shows the carbon dioxide on brake power of the engine, the CO₂ emission is reduced with turpentine oil blends with coating when compare to the sole fuel diesel without coating.

Figure-8 shows the effect of cylinder pressure with different concentration of fuel blends with ceramic coating at maximum brake power of the engine. It is found that same engine speed and load; the pressure slightly increased about 75.596 bars for coated engine. It is slightly higher than that of the conventional engine. This is due to shortening of diffusion combustion process.

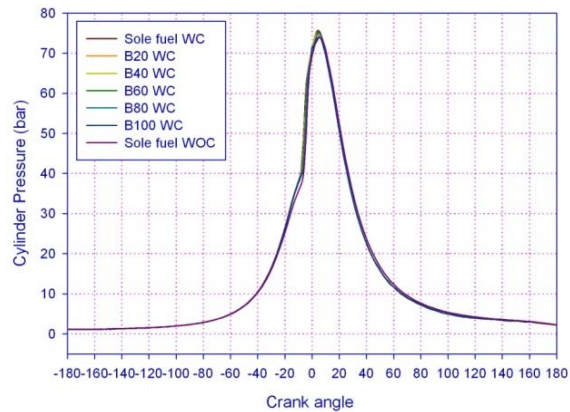


Figure-8. Effect of cylinder pressure on crank angle for various blends.

Figure-9 shows the heat release rate for different concentration of fuel blends and ceramic coating with maximum brake power of the engine. The rate of heat release for the ceramic coated engine slightly shifted from the top dead center due to reduced premixed combustion. The effect of fuel blends shows similar curve pattern.

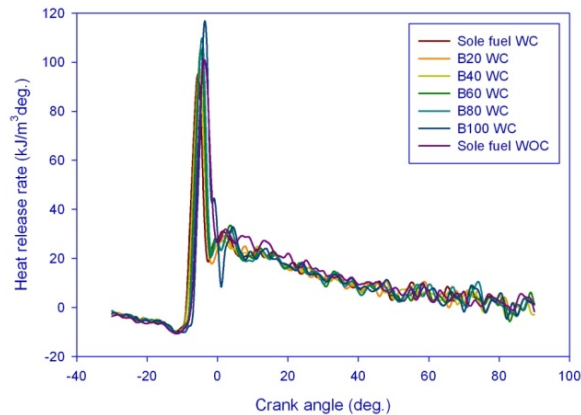


Figure-9. Heat release rate against crank angle.

Figure-10 shows the maximum cylinder pressure against number of cycles of the engine. The cylinder pressure is increased for the coated engine when compared to the baseline engine. The engine cylinder pressure is higher and also the brake thermal efficiency is increased.

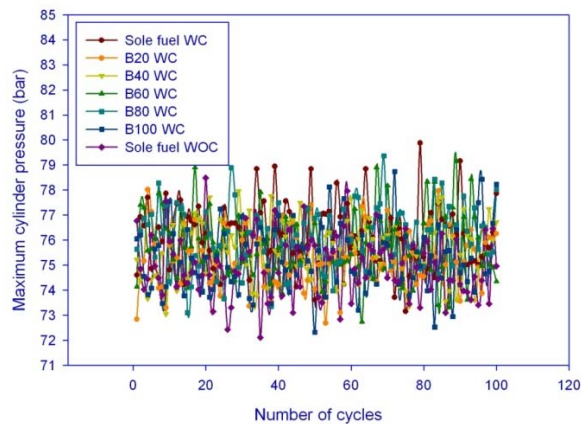


Figure-10. Maximum cylinder pressure against number of cycles.

CONCLUSIONS

The characteristics of emissions and combustion were analysed before and after the application of FGM coatings onto the piston crown of cylinder head and valves. From the study, it is concluded that the Thermal efficiency of the engine slightly improves with the ceramic coating. Also the 20% fuel blends shows better performance than the other concentration. Further, the smoke level slightly increases in both coating and fuel blends. The study also found that the reduction of NO_x level with coating is more promising. It is also observed that there is further reduction of NO_x emission with 100% turpentine oil. The CO₂ emission is reduced with

turpentine oil blends with coating when compare to the sole fuel diesel without coating and the heat release rate slightly decreases with coating and with fuel blends. Finally, it is observed that the cylinder pressure is increased for the coated engine. In the future study, suitable additives can be added in order to reduce the smoke density further.

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