

A Review Study on Thermal Barrier Coatings for Diesel Engine Performance and Emission with Tribological Analysis

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Abstract

In the automotive industry, enhancing diesel engine performance while simultaneously controlling exhausts emissions in compliance with environmental regulations has become increasingly important. The thermal barrier coatings applied on diesel engine combustion chamber parts is a promising approach to achieving these objectives. Based on the literature reviewed in this study, key parameters of TBC like as low thermal conductivity, low specific heat capacity, high melting point, high porosity, phase stability and high fracture toughness are considered in the selection of suitable ceramic coating materials. Numerous researchers have applied 8YSZ as upper layer and NiCrAlY as intermediate layer between top coat and substrate upto 500 μm thick in coating system by atmospheric plasma spray coating method. The reported results indicate increases the coated engine performance and improved exhaust emission except NO_x emission. The surface morphology of the coated system including porosity distribution, microcracks, and surface texture has been extensively examined by FE-SEM, Similarly the phase stability and elemental composition of coating system evaluated by XRD and EDS colour mapping respectively. Thermal cycling and microhardness evaluations have shown that the addition of Al_2O_3 whiskers, CeO_2 , and other such oxides Nd_2O_3 , Gd_2O_3 , and Yb_2O_3 enhances coating durability by reducing thermally induced stresses between both coating layers, thereby extending coating life. Tribological experiments conducted on a piston–liner interface using an engine tribometer revealed a reduction in friction coefficient and wear rate for TBC-coated liners, indicating that the ceramic coating effectively promotes improved lubrication behavior. Furthermore, CFD based combustion chamber models validated with experimental results demonstrated increases combustion pressure and temperature with higher heat energy generated rate for coated engines compared to uncoated engines. Most experimental investigations reported that the reduction in heat loss through the cooling system due to TBC application gives higher brake thermal efficiency, less brake specific fuel consumption (BSFC), and higher side exhaust gas temperature. The exhaust gas emissions of coated engines consistently exhibited reduced HC, CO, and smoke opacity, although higher NO_x emission found, primarily due to elevated combustion gas temperatures.

Key Words: Diesel Engine, Thermal Barrier Coating, Coating Material Characterization, Thermal Cycling Life, COF and Wear Rate, CFD Simulation, Brake Thermal Efficiency, BSFC and Emissions.

Nomenclature

YSZ	Yttria Stabilized Zirconia
TBC	Thermal Barrier Coating
PSZ	Plasma Spray Zirconia
B.P	Brake Power
BSFC	Brake specific Fuel Consumption
BTE	Brake thermal efficiency
C_v	Calorific Value
HC	Hydrocarbon
PPM	Parts per million
XRD	X-Ray Diffraction
FE-SEM	Field Emission Scanning Microscopy
EDS	Energy Dispersive Spectroscopy
CPS	Count per Second

1. INTRODUCTION:

In the current scenario, meeting the growing energy demand and addressing emission concerns are major challenges faced by society. Therefore, the automotive industry is required to adopt advanced technologies that improve engine efficiency with decreasing fuel consumption and exhaust gas emissions. There are many ways to improve engine working in above aspects, like as modifications in engine design to improve mechanically efficient and reduction of frictions in different moving parts. The reduction of heat energy from engine via cylinder wall, cooling system and exhaust gases by application of thermal barrier coating which acts as adiabatically in combustion chamber resulting maximum heat energy converted into work done of engine. The development and application of thermal barrier coatings on diesel engine combustion chamber components like as pistons, valves, cylinder heads, and cylinder liner walls, is not a recent concept. Such advancements were introduced prior to 1980 but the practical implementation of TBC technology in the automotive industry remained limited, the widespread adoption was restricted mainly due to the high cost associated with ceramic coating processes for multiple engine components, along with durability and reliability challenges of ceramic coatings under severe operating conditions [1][2]. A.H. Pakseresht et al introduce the whisker reinforced thermal barrier coating, top coat YSZ 300 μm thick is deposited by atmospheric plasma spray coating including Al_2O_3 whisker on Ni based super alloy, The alumina whisker uniformly distributed on coating and maintained integral structure with YSZ during coating deposited but the surface found very rough and porous in nature caused by fragmented splash splat during adhesion of coating process. On other side, also found splats boundaries, pore, micro cracks and fine debris on coating surface due to rapid solidification of molten droplets[3][4]. The thermal conductivity difference between substrate metal and coating material is main cause of generation of micro cracks [5][6]. It is noticed that the micro cracks and splash debris are common defects in atmospheric plasma spray coating process which are play important role to decrease the mechanical strength of coating layer. So the ceramic fibers are needed to add to reduce the above defects during plasma spray coating process. The outcome demonstrate that the density and porosity of composite coating (YSZ+ Al_2O_3) are ($5.02 \text{ g/cm}^3 \pm 0.007$) and ($12.7\% \pm 0.5$) respectively. Similarly, conventional coating YSZ shows density is $5.15 \text{ g/cm}^3 \pm 0.005$ and porosity is $11.5\% \pm 0.5$. The composite coating has lower density and high porosity which required lower power to feed stock the deposited coating[7]. Joop Somhorst et al examine an investigation of thermal barrier coated piston of light duty single cylinder diesel engine via atmospheric plasma spray method of two different material yttria stablized zirconia and hard anodized aluminum. The coating thickness for both materials was maintained at 200 μm . Hard anodized aluminum exhibits thermal conductivity lies between 0.7 to 1.3 W/mK and a specific heat capacity between 860 and 890 J/kgK. In comparison, the yttria-stabilized zirconia coating shows thermal conductivity lies between 0.8 to 1.3 W/mK, with a specific heat capacity of approximately 440 to 460 J/kgK. The experimental values of fuel consumption of coated engine 1% higher than non coated diesel engine due to high surface roughness which increases heat energy dissipated in wall and retarded in combustion process where as the polished coated piston significantly less fuel consumption than uncoated diesel engine [8]. Serkan Özel et al studied the different coating material Al_2O_3 13% TiO_2 , Cr_2O_3 , and Cr_2O_3 25% Al_2O_3 deposited through plasma spray coating process method on piston and valves of air cooled four stroke single cylinder diesel engine and found the results of same engine on torque, brake power and fuel consumption with experimentally and statistically with Taguchi method for optimization. The engine was operated at a brake power of 26 kW, a torque of 80 Nm, and a speed of 5000 rpm, the cylinder pressure crank shaft angle measurements system enclosed with experimental setup [9]. Wellington Uczak de Goes et al deposited various coating with suspension plasma spray coating, here three layers employed bond coat, top coat and sealing coat with three different architecture material used to obtain desired results. The substrate material of alloyed steel with vanadium (38MnSiVS5) is used in piston of heavy duty diesel engine; the diameter of sample is 25.4 mm and has thickness is 6 mm. The first

architecture is coated with yttria stabilized zirconia through atmospheric plasma spray coating process adopt for both layers upper and lower coat used as base sample for compression with other material coating system. The second architecture YSZ or gadolinium zirconate (GZO) applied through suspension plasma spray coating on highly dense bond coat which is applied by the high velocity air fuel (HVOF) process and other side third architecture is GZO sealed with (GZO-C means ceramic seal layer, GZO-M means metallic seal layer and GZO-PM means thick porous metallic seal layer) by suspension plasma spray coating. The eight samples prepared to investigation of this approach with different thickness of top coat and different coating method employed above. The finding described that the YSZ coating has lowest thermal effusivity with plasma spray coating and followed by GZO with suspension plasma spray process. In the third architecture system the GZO-C has lowest thermal effusivity which is followed by GZO-M, and while exhibited the highest effusivity among the coatings produced by suspension plasma spray coating process. The best thermal cycling performance compared to the other coating systems exhibited by GZO coating system deposited by the suspension plasma spray method [10].

Anders Thibblin et al investigated fuel efficiency of heavy duty diesel engine have thermal barrier coating system with different material. The 8YSZ ceramic material of various microstructure deposited on the heat flux probe act as substrate made up of 36CrNiMo6 steel materials with atmospheric plasma spray coating process, and The Fe24Cr8Al0.5Y material applied as a bond coat in all coating system. The conventional YSZ, YSZ sealed porosity, Nano YSZ, Segmented YSZ, lanthanum zirconate ($\text{La}_2\text{Zr}_2\text{O}_7$, LZ) and gadolinium zirconate ($\text{Gd}_2\text{Zr}_2\text{O}_7$, GZ) different top coat applied on substrate. The heat generated flux measured in combustion chamber decreases 4.7% with gadolinium zirconate ($\text{Gd}_2\text{Zr}_2\text{O}_7$, GZ) as compare to uncoated surface. On other side YSZ and lanthanum zirconate ($\text{La}_2\text{Zr}_2\text{O}_7$, LZ) are less effective to resist heat losses. The results obtained of sealed porosity layer on top coat increased heat flux and increased thermal radiation. As per result conclude that the conventional YSZ coating is most promising as thermal barrier coating [11]. Anders Thibblin et al investigate the different microstructure of YSZ coating applied with atmospheric plasma coating process and plasma spray physical vapour deposition (PS-PVD) on heavy duty diesel engine components. The substrate material used for piston is alloyed steel 38MnSiVS5 and exhaust manifolds material is cast iron SiMo51. A disc shape sample of size diameter 25 and thickness is 15 mm used to evaluate the thermal life test and ability of adhesion test. The results conclude that the conventional and nano structured coating is most promising for thermal barrier coating in heavy duty diesel engine combustion chamber due to lower thermal conductivity and higher heat reflectance in all direction [12]. Debasish Das et al applied multilayer coating of YSZ, Cr_2O_3 , and Al_2O_3 different composition and different thickness on substrate of common material aluminum alloy A336, Si12%, Ni2.5%, Mg1.0%, Cu 1.0% in Indian hatchback diesel engine car piston with 100 μm thick NiCrAlY for bond coat with help of atmospheric plasma spray coating process. The thermal fatigue results show that the YSZ coat was survive at thermal shock above 350 cycles without failure upto 300 μm coating system. It is identified with scanning electron microscopy study with increases coating thickness the crack formation developed and also lattice strain increased of specimen. The result analysis concludes that the YSZ coating with optimum thickness is promising four thermal barrier coating at high temperature working environments[13]. Onur Biyikligö lu et al applied thermal barrier coating inside cylinder liner of heavy duty diesel railway engine 16 cylinder 1770 kW power at 1400 rpm of different material $87\text{Al}_2\text{O}_3/13\text{TiO}_2$, $75\text{Cr}_3\text{C}_2/13\text{NiCr}$, and $80\text{Ni}/20\text{Cr}$ with plasma spray coating process principal. The coating thickness is adopted on substrate of $\text{Al}_2\text{O}_3/\text{TiO}_2$ is 240 μm , $\text{Cr}_3\text{C}_2/\text{NiCr}$ is 208 μm and NiCr is 220 μm . The substrate has 255N/mm² tensile strength and 250HB hardness. The hardness measured of coated and non coated samples with Vickers hardness test arrangements and the wear test performed with reciprocating motion at dry working condition on ball-disk arrangements. The size of disk is 30 mm diameter and 25 mm thickness. The results show that the all coated samples have lower wear, lower coefficient of friction and higher hardness than uncoated samples. The COF_{rms} of non coated sample is 0.337, the least COF of $\text{Al}_2\text{O}_3/\text{TiO}_2$ coating is one third of noncoated sample and the COF of $\text{Cr}_3\text{C}_2/\text{NiCr}$ is one half of uncoated sample. It is conclude that the $\text{Al}_2\text{O}_3/\text{TiO}_2$ and $\text{Cr}_3\text{C}_2/\text{NiCr}$ coating system performed better as compared to NiCr and non coated sample for wear and hardness aspect results [14]. Xiong Yang et al

developed ceramic coating as base material Cr_2O_3 in composite coating is deposited with different doping material like Cr_2O_3 -7wt.% Mo(C7M), Cr_2O_3 -7wt.% Nb_2O_5 (C7N), Cr_2O_3 -4wt.% MoO_3 -3wt.% Mo(CMM), and Cr_2O_3 -4wt.% Nb_2O_5 -3wt.% Mo(CNM) using plasma spray coating process. The substrate prepared in plate shaped steel material in different size $30 \times 10 \times 2$ mm for SEM analysis and $43 \times 30 \times 5$ mm for wear test respectively. The characterization of composite coating analyzed through XRD, FE-SEM and EDS mapping, and hardness of same by Vicker's hardness instruments. After that the sample is taken for wear test arrangements of sliding method of ball on plate. The coating plate specimen fixed on movable platform in reciprocating motion paired with WC-Co or Si_3N_4 fixed ball diameter of 6.35 mm at room temperature with applied load of 5N or 50 N in vertical direction. It is conclude that the composite coating CNM performed best wear and has higher hardness than other coating system [15]. Jian Rong et. al found tribological investigation of Al_2O_3 and Al_2O_3 - Y_2O_3 composite coating 450 μm thickness applied with plasma spray coating process on stainless steel (1Cr18Ni9Ti) substrate plate of size is $16 \times 27 \times 1.3$ mm. The experiment work done on tribological testing machine with block on ring arrangements at room temperature working conditions. The stainless steel ring has outer most diameter is 40 mm and inner diameter is 16 mm whereas 10 mm is thickness which is coating thickness is 450 μm above said material and the graphite block size is $30\text{mm} \times 7\text{mm} \times 6\text{mm}$, respectively. The load applied on block is 1000 N and the angular speed of ring is 400 rpm like as sliding velocity of 0.84 m/s. The results show that the composite coating Al_2O_3 - Y_2O_3 have lower wear rate as compared to Al_2O_3 [16].

Sabino CAPUTO et. al examined the effect of 100 μm coating of YSZ and anodized aluminum on diesel engine piston top. The temperature swing effect discussed that which is heat loss reduction in combustion chamber due to lower temperature difference exist between combustion gas and cylinder wall. One dimensional engine model develops couple with engine thermal model. In this way piston, liner, valves, heads are discretizes with equivalent thermal nodes represented by parameters including mass, material density, effective area, thermal conductivity, specific heat capacity, and temperature. In this model found temperature swing through transient heat conduction approach. The results of numerical simulation is the high temperature swing effect found in anodized aluminum coating system as compare to YSZ coating because the low thermal conductivity, low heat capacity[1]. Mingfa Yao et al found experimental and simulation study of thermal barrier coating $\text{La}_2\text{Zr}_2\text{O}_7$ applied with thickness of 500 μm on piston and cylinder head. The conclusion of both mathematical model and experimental results are show that the heat losses reduced, soot emission reduced but NO_x emission increased and redistribution of temperature in chamber the adiabatic effect developed in rich mixture region [17]. V. Guruprakash et al cerium stabilized zirconia (CSZ) applied with plasma spray coating on cylinder liner water cooled single cylinder 5.2 kw diesel engine at 1500 RPM and found better results compare to standard engine increases of brake thermal efficiency and brake specific fuel consumption decreases. Similarly, emissions of coated engine have lower compare to standard engine at different load conditions except NO_x is increases with O_2 [18]. Vikrant Garud et al YSZ coating material deposited to piston of four stroke single cylinder water cooled diesel engine and found improvements in performance and emissions as compared to non coated engine. The output power is high and increased pressure 6 bar in engine with increasing of NO_x and O_2 also. S. Saravanan et al examined study of single cylinder four stroke water cooled diesel engine piston coated with YSZ thermal barrier coating thickness of 250 μm with NiCoCrAlY bond coat through atmospheric plasma spray coating process. The second coating is applied with SiC high porosity range and good structural strength. The results observation show that the thermal barrier coated piston with YSZ reduces heat loss in cooling system and found brake thermal efficiency 36.5% where as 34.5% brake thermal efficiency of non coated engine. The coated piston engine reduces the 14% CO and 38% HC emission. High temperature in combustion chamber by TBC coating cause increase NO_x about 21%. On other side the porous medium coated piston reduces remarkable emission of NO_x about 21% but the HC and CO emissions increases. It is concluding that the porous medium and thermal barrier coating reduction of NO_x , carbon dioxide gas CO_2 and smoke opacity. Similarly from the energy and exergy the heat loss in coolant, exhaust and accessories of engine reduce with both case of porous medium and thermal barrier coating compared to non coated engine [19].

2. REVIEW STUDY OBJECTIVE AND NOVELTY

As evident from the available literature, thermal barrier coating (TBC) technology is not a new approach; however, the large production of TBC coated components is not able to penetrate in the market of automotive industry. This gap is attributed to several contradictory and negative aspects reported by researchers; these are porosity on the TBC surface, increased surface roughness, formation of splash splats, inter splat boundaries, micro-crack initiation, generation of fine debris, development of thermally grown oxide (TGO) layers, and the risk of coating fracture. Furthermore, the application of TBCs has been associated with potential reductions in volumetric efficiency and an increase in NO_x emissions, which are additional challenges for emission norms.

In this review, the objective is to critically address the aforementioned issues through a detailed analysis of thermal barrier coatings on different combustion chamber components of diesel engine. The study systematically examines key aspects, including substrate selection for engine components, surface preparation techniques, selection of coating materials, coating processes, and optimization of coating thickness. Furthermore, the sustainability and durability of TBCs are evaluated using experimental investigations and CFD-based modeling. The performance and emission analysis of a diesel engine equipped with thermal barrier coating system are found and compared with non coated engine by considering different ceramic coating materials and varying coating thicknesses. In addition, the tribological behavior of TBC-coated diesel engine cylinder samples is investigated, with a comparative assessment of wear rate and coefficient of friction against non-coated samples.

Based on a comprehensive review, it is recommended that yttria-stabilized zirconia (YSZ) ceramic material with doping of Al₂O₃/8YSZ, CeO₂/8YSZ, Al₂O₃ + 13% TiO₂, and Al₂O₃ + 25% Cr₂O₃ is a promising for thermal barrier coatings on diesel engine components like as the piston, cylinder liner, and valves. A coating thickness of approximately 500 µm, deposited using atmospheric plasma spray (APS) or suspension plasma spray (SAPS) techniques, appears to be suitable for automotive applications. However, the literature lacks a unified investigation addressing the performance, emission, and tribological characteristics for a single coating material under identical operating conditions. Therefore, systematic experimental studies, supported by CFD-based validation, are required to comprehensively evaluate the thermo-mechanical behavior, engine performance, emission characteristics, and tribological response of YSZ-based TBCs.

3. Surface Preparation of Substrate

To remove extraneous foreign material particles from the surface to initiate effective contact between coating and substrate, the preparation of surface was carried out by various methods like vapour degreasing, oven baking, acid pickling, ultrasonic cleaning, abrasive blasting, and air-blasting systems operated in siphon and gravity feed modes. The surface should be sufficiently rough to promote strong mechanical bonding at interface of coating and substrate. Grit blasting is commonly employed in all thermal spray processes to generate the required surface roughness and improve coating adhesion. In grit blasting, the average size of 125 µm abrasive particles is propelled onto the substrate surface using compressed air at 80 psi pressure and working distance is 100 mm. The effectiveness of the grit blasting process depends on several parameters, including grit size and its distribution, air pressure, spray distance, number of passes, spray angle, and diameter of nozzle. Continue in this series, need to degreased grit blasted substrate surface and clean with trichloroethylene vapour. After cleaning of grit blast of sample surface pre-heat with plasma torch to remove condensate and adsorbates [20][7].

4. Coating Process Method

As per literature, there are different coating process method like Electron beam physical vapor deposition method, Atmospheric plasma spraying, Plasma enhanced chemical vapor deposition method, Electrostatic spray assisted vapour deposition method, Solution precursor plasma spray method, Sol-gel method and Suspension plasma spraying method. The most common, economical and thermal stable is Atmospheric plasma spraying method which is used to produce thermal barrier coating on substrate. In this process, the powder of coating material is deposited in higher temperature environments and drive particles towards surface of substrate. The heated droplets of

ceramic material spread in form of splats and quenched on surface. In every pass, There are ceramic material accumulated on surface in form splats and increases the thermal barrier coating thickness by repeating of such passes. As per literature know that the microstructure of thermal barrier coating surface is dependent on such coating process parameters which are illustrated in Table 1 [21]. The optimum parameters of coating process resulted improve mechanical properties of coating system with regulateng of such as phase compositions, thermal stability and improve corrosion resistance [22].

Table 1. Plasma Spray Coating Parameter [21]

Parameter	NiCrAlY	YSZ
Voltage (V)	65	68
Current (A)	600	600
Spray Distance (mm)	120	105
Powder feed rate (g/min)	38	38
Ar gas (l/min)	32	32
H ₂ gas (l/min)	15	15

5. MATERIAL SELECTION AND CHARACTERIZATION

As per literature review the selection of coating material on bases of low thermal conductivity, lower specific heat capacity, high melting point, high porosity, phase stability and high toughness because use of thermal barrier coatings in high temperature environments. Zirconia base material is suitable for this application, in high temperature zirconia under goes in phase transformation. It has a monolithic structure upto 1170 °C after this attains tetragonal structure upto 2379 °C and transformed into cubic structure. Due to this transformation volumetric change developed causes failure of coating, So other materials like as CaO, MgO, Y₂O₃ and other rare oxides elements are added into zirconia base material [19][23]. Ytria stabilized zirconia used in most experimental studies to overcome the zirconia physical properties deficiency. There is to attain long life cycle of coating, YSZ cannot suitable for high temperature application. The mullite has lower coefficient of thermal expansion and higher thermal conductivity, it is intermediate compound of aluminum and silica (3Al₂O₃2SiO₂) in adequate composition. It has lower and which reduce the stress in coating due to thermal gradient generated throughout the coating [1]. Other ceramic coating materials are evaluated with thermal barrier coating are 8wt %Y₂O₃-ZrO₂ on Aluminum alloy with NiCoCrAlY bond coat [24], the reinforced Al₂O₃ whisker on Ni based super [7]. The coating samples used 20Al₂O₃ + 80 YSZ and 20CeO₂ + 80YSZ as top coat on Aluminum substrate respectively with CoNiCrAlY used as bond coat [25]. In YSZ coating additionally doped with rare oxide like as Nd₂O₃, Gd₂O₃ and Yb₂O₃ to improve its stability and have low thermal conductivity [5] and other average sizes of ZrO₂, Al₂O₃, TiO₂, CeO₂ [25], cerium stabilized zirconia (CSZ) [18] and hard anodized aluminum [8] have added in coating system.

The piston liner surface was coated using a thermal spray process with a NiCrAlY alloy as the bond coat and YSZ as the top ceramic layer. The FESEM showed a well-adhered dual-layer coating structure, and the YSZ top coat appeared porous and columnar in morphology, as shown in Figure 1(a). The YSZ layer exhibited micro-pores and inter-splat boundaries, which contribute to strain tolerance and thermal insulation. The bond coat demonstrated good adhesion to the substrate, with a smooth transition at the interface. The EDS analysis confirmed that the top coat showed strong signals of Zr, Y, and O, whereas the underlying bond coat region revealed the presence of Al, indicating proper layering and compositional integrity of the coating, as depicted in Figure 1(b). XRD analysis of the coated piston liner revealed prominent diffraction peaks at $2\theta \approx 30.2^\circ$, 34.8° , and 50.2° , corresponding to the (101), (112), and (211) planes of tetragonal zirconia (t-ZrO₂, ICDD card no. 50-1089), confirming the presence of YSZ as the top coat, as depicted in Figure 1(c). However, minor peaks observed around $2\theta \approx 59^\circ$ and 62° were attributed to the (220) and (221) planes of the Ni-based γ -phases from the NiCrAlY bond coat (ICDD card no. 47-1405). Quantitative phase analysis by Rietveld refinement revealed >98% tetragonal phase in YSZ, verifying high structural stability and

phase purity; absence of undesired secondary phases, such as monoclinic zirconia or oxide impurities, was detected. Average crystallite sizes were calculated as 18 ± 1.5 nm for tetragonal ZrO_2 and 35 ± 2 nm for the NiCrAlY bond coat, matching the ranges reported for plasma-sprayed TBC coatings. The intense peaks indicate high crystallinity and phase stability, with sharpness and intensity comparable to other optimized multi-layer TBC studies [26][27][28]. Surface roughness measurements indicated a higher Ra value ($0.099 \mu\text{m}$) compared to the uncoated liner ($0.072 \mu\text{m}$), attributed to the topographic features of the plasma-sprayed ceramic YSZ layer, as depicted in Figure 1(d). This increased roughness promotes better mechanical interlocking and thermal insulation performance.

The coating thickness was measured using an Elcometer 456 right-angle probe, confirming a dual-layer structure comprising a NiCrAlY bond coat ($150 \mu\text{m}$) and a YSZ ceramic top coat ($350 \mu\text{m}$) applied using Atmospheric Plasma Spraying method. The $150 \mu\text{m}$ bond coat provides remarkable adhesion with substrate and effective oxidation prevention, whereas the $350 \mu\text{m}$ ceramic top coat offers strong thermal insulation and durability under repeated thermal cycling. These thicknesses fall within widely adopted design ranges for thermal barrier coatings, optimizing bond strength, coating lifetime, and resistance to cracking under harsh engine service conditions. The SEM and EDS cross-sectional analysis (Figure 1(e)) clearly distinguishes the dual-layer structure of the coating. The YSZ top coat is primarily composed of Zr, Y, and O, confirming the presence of ZrO_2 stabilized with Y_2O_3 . The NiCrAlY bond coat shows strong signals of Ni, Cr, Al, and Y, indicating a dense and adherent interlayer. The cylinder liner substrate is dominated by Fe, consistent with its base alloy. Minor elemental overlap between adjacent layers was observed, which is attributed to material transfer during cross-section sample preparation and cutting. However, EDS mapping distinctly separates the each layer of coating such as top coat, bond coat and substrate. The thickness values measured from microstructural analysis closely match those obtained using the Elcometer, validating coating uniformity, structural integrity, and effective adhesion [21].

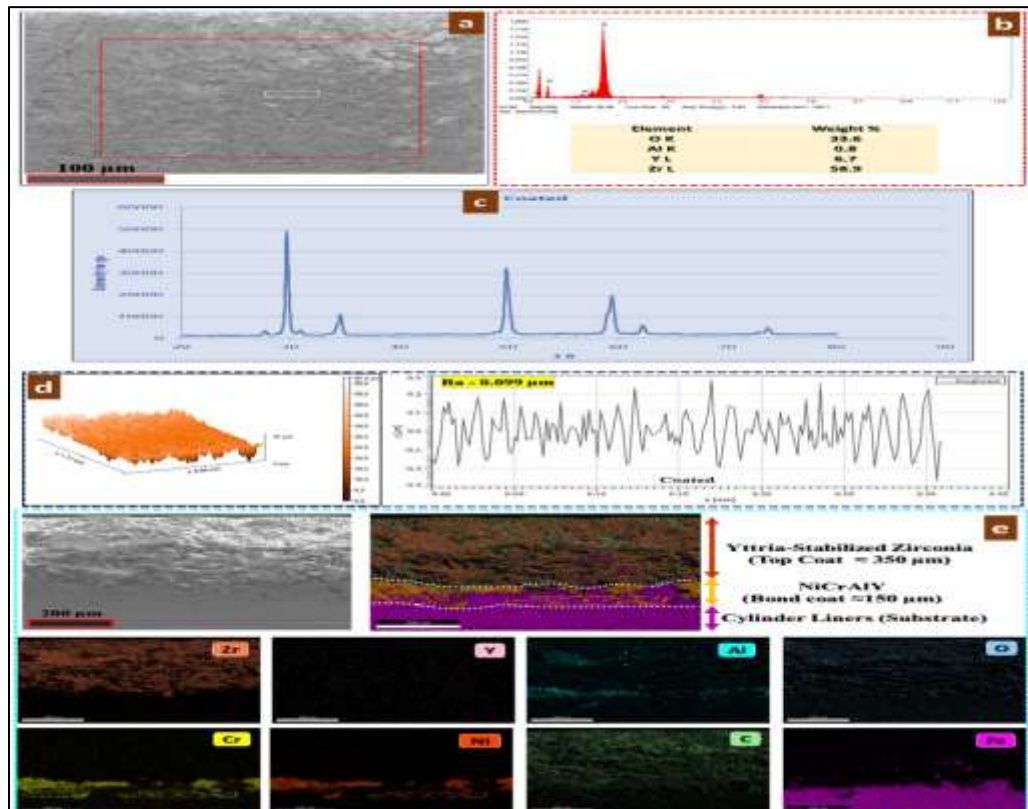


Figure 1 Coated liner before wear test [21] (a) FESEM image, (b) EDS, (c) XRD pattern, (d) 3D surface morphology and roughness profile, and (e) EDS mapping of cross-section of coated liner

6. Heat Transfer in TBC Model

Figure 2(b) shows the one-dimensional thermal barrier coating model of the engine combustion chamber. Various assumptions are adopted based on thermal barrier coating properties to optimize the simulation complexity. First of all, the coating thickness is not included in the three-dimensional numerical grid because it is much smaller than the grid scale. Secondly, the surface roughness of the thermal barrier coating is assumed constant, resulting in maintained flow restriction within the near-wall region. Thirdly, perfect bonding between the cylinder wall and the TBC bond coat is assumed, with no thermal contact resistance. Finally, all thermodynamic properties of the thermal barrier coating are assumed to remain constant in the high-temperature region, including density (ρ), thermal conductivity (λ), porosity (ϵ), and specific heat capacity (c_p). [29][30]. Based on the above assumptions, the TBC model is proposed as follows. A thermal boundary heat flux model was constructed considering the thermal resistance contribution of the thermal barrier coating:

Based on the above assumptions, the energy conservation relationship for the thermal barrier coating boundary region is taken by considering the influence of heat capacity.

$$Q_{tot} = Q_{TBC} + Q_{gas \rightarrow wall} \quad (1)$$

The heat energy in TBC in the above Eq. (1) is:

$$Q_{TBC} = c_p \rho A \delta \Delta T_{TBC} \quad (2)$$

Where A is area and δ is thickness of thermal barrier coating.

Moreover, the heat capacity of the TBC alters the transient surface temperature response, thereby influencing the in-cylinder thermodynamic behavior. To account for this effect, heat flux redistribution is performed through the implementation of the TBC energy conservation equation. The corresponding algorithm is outlined below:

- Calculation of the average temperature in thermal barrier coating by energy conservation. By taking the derivative of Equation (1), the corresponding difference equation can be obtained, where the average temperature of the TBC is expressed as

$$T_{TBC}^n = 0.5 * (T_{wall} + T_s^n) \quad (3)$$

T_s is temperature of coating surface for n th cycle.

- Calculate the surface temperature of TBC.

$$T_s^{n+1} = 2 T_{TBC}^{n+1} - T_{wall} \quad (4)$$

- Determine the net heat flux for a single computational cycle.

$$flux_{tot} = \left\{ -\frac{\bar{\lambda} \rho c_p u^* (T - T_w)}{Pr y^+ \bar{\lambda} + \rho c_p u^* \delta} y^+ \right\} \quad (5)$$

$\bar{\lambda}$ is denotes the harmonic average thermal conductivity of the porous thermal barrier coating, y^+ is dimensionless height, u^* is denote frictional velocity

- All TBC temperatures are updated and replaced, followed by recalculation of the total heat flux. The heat flux is redistributed and evaluated using the above algorithm, which accounts for the thermal influence of the TBC on the near-wall gas region. The proposed model is an improved version previously developed model [17]. To investigate the effect of the TBC on engine performance, the developed model and algorithm are applied to the entire wall surface of the computational grid, indicating that the coating is implemented throughout the inner cylinder wall, as illustrated in Figure 2(a).

$\text{La}_2\text{Zr}_2\text{O}_7$ used in engine as TBC for better heat resistance and anti fracture performance for above work, which have appropriate thermodynamic and other structural parameters.

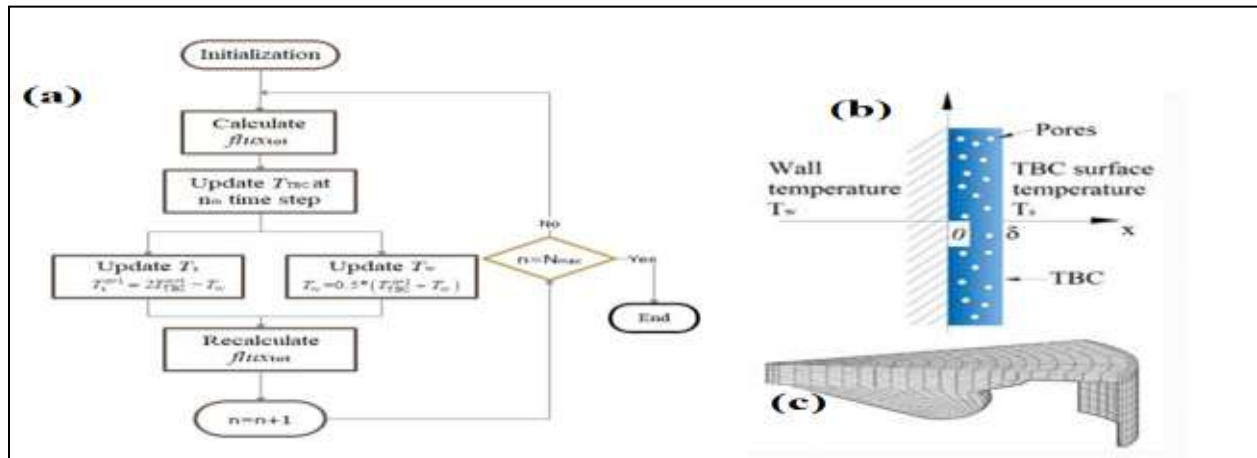


Figure 2 (a) Heat Flux Algorithm of TBC [31] (b) Thermal barrier Coated Model [2] (c) Computational Grid of Chamber [2]

Yang Wang et. al analyzed simulation with 1/8 sector of the combustion chamber was carried out by considering geometric symmetry shown in Figure 2(c). The mesh structure developed in computational domain with 11,152 cells with 2 mm uniform grid size. The Reynolds Averaged Navier Stokes equation employed to analyze the fuel dynamics droplets in form of spray, including atomization, droplet collision, and spray-air interaction within the combustion chamber. The simulation of combustion process carried out a reduced chemical kinetic mechanism based on Toluene Reference Fuel (TRF), coupled with droplet breakup dynamics and discrete multi component evaporation modeling [32][33][34][35]. The cylinder pressure was recorded using a Kistler 6125A piezoelectric pressure sensor connected to a charge amplifier. The measurements were averaged over 100 engine cycles, and the sensor provided a pressure resolution of 0.5 °CA in experimental work, the pressure curve shown in Figure 3 demonstrate the compression of pressure variation of experimental values with simulated values with and without coating. From about -30° to 0° crank angle all three curves follow a similar nature, indicating good consistency between the experimental data and simulation results before start of combustion. Near top dead center, a rapid rise in pressure is observed due to fuel ignition and combustion. The simulation with whole TBC shows the maximum cylinder pressure whereas the experimental curve showing slightly lower peaks, comparatively simulation results without TBC demonstrate lower peak. The higher peak pressure in the TBC configuration is mainly due to reduced heat losses through the combustion chamber walls, which enhance cylinder temperature. Heat transfer loss is determined by integrating the boundary heat flux.[2][31].

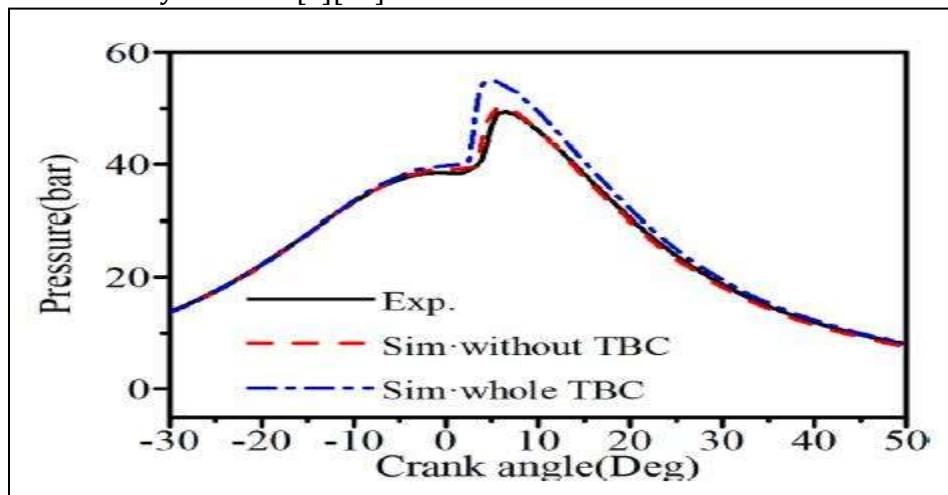


Figure 3 Compression of Both Experimental and Simulation Results of Pressure with Crank Angle [2]

7. Sustainability and Durability

Lijian Gu et. al the ceramic coating material 8YSZ top coat thickness varies from 100 μm to 1000 μm and NiCoCrAlY 100 μm bond coat applied on disk shape 12 mm diameter and 6 mm thickness. The hardness polished cross section of measured by Vickers hardness measurements (FM-700, Future-Tech) and the residual stress obtained by deformation of coating based on chemical removal method. The porous nature developed on ceramic coating with plasma spray coating process measured by metalloscope, the high porosity zone built up near 300 μm thick bond coat. The surface hardness increases with increases of thickness of coating while porosity and surface roughness decreases as show in Figure 4 during increases of ceramic thickness [36]. Similarly, the hardness was measured using the Rockwell method, yielding a value of 60.6 HR15N at a load of 15 Kgf, corresponding to an indentation depth of 39.4 μm . This enhanced hardness confirms the improved mechanical strength imparted by the dual-layer coating system. The conventional uncoated cast iron cylinder liners typically exhibit hardness values in the range of 200-250 HV (45-50 HR15N). The improvement in the hardness of the coated sample is attributed to the high intrinsic hardness of zirconia-based ceramics, their resistance to plastic deformation, and the role of the bond coat in distributing stresses and enhancing adhesion[21].

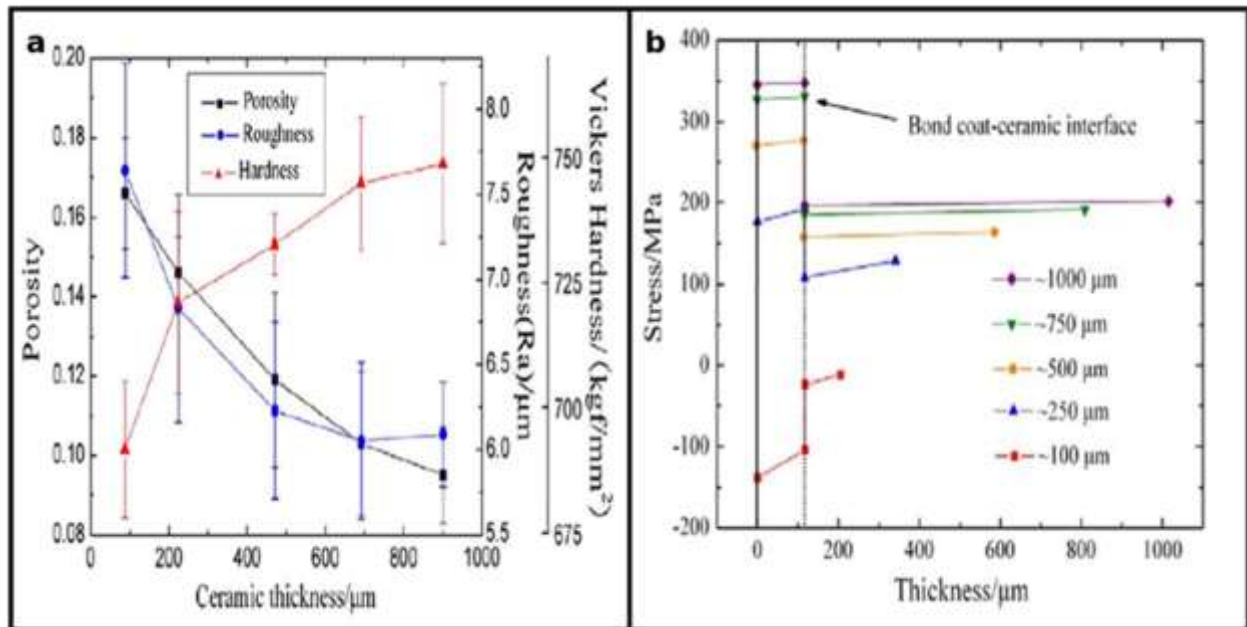


Figure 4 Variation of properties with TBC thickness [21]

The powder particles exhibited an average size distribution in the range of 5–50 μm supplied to feedstock for depositing on substrate. The first and second coating samples used 20 wt% Al_2O_3 – 80wt % 8YSZ and 20 wt% CeO_2 + 80 wt%8YSZ as top coat with 300 μm thicknesses of each on Aluminum substrate respectively. The CoNiCrAlY used as bond coat with 150 μm thickness for both samples. The thermal cycling test conducted of sample size 15mmx10mmx5mm heated in electric furnace upto 800 $^\circ\text{C}$ and kept in furnace for soaking time 5 minutes. After heating upto desired temperature quenched this sample with water to achieve 25 $^\circ\text{C}$. Again same sample put inside furnace upto same previous temperature and quenched. Repeat this process again and again for 100 cycles. The coated piston installed in above engine and has done experiment at 200 bar injection pressure and kept constant 1500 rpm at different load 0 to 100 % working conditions. The thermal stress induced in TBC coating caused by the formation of a thermally grown oxide (TGO) layer, phase transformation from tetragonal (t) to monoclinic (m) zirconia, and thermal expansion mismatch between the top layer and intermediate layer of coating system. The stress generation and thermal mismatch in coating region are causes of TBC failure during thermal cycling test[37][38]. The CTE is main factor out of three found in many research studies. Mainly the substrate surface has high CTE

which cause residual stress found different in coating and substrate during atmospheric plasma spray coating process. When increase coating thickness, the smaller temperature rise on surface of substrate causes lower thermal conductivity of TBC during deposition of coating. Resulted the residual stress turned into tensile stress, however the stress gradient was reduced at the substrate bond coat interface, while it increased at the bond coat top coat interface.. Since the fracture move towards ceramic top coat, thus at high porosity segments and bond coat top coat interface have decreases bonding strength which gives the fracture path if coating thickness increased to 0.5 mm [36][25]. The results of thermal cyclic test of sample 20%Al₂O₃ + 80 %8YSZ is initiated the spallation first on corner and edges. After initiated these points then spreads on adjacent areas of samples which caused thermal stress and this defect is call edge defect. The outcome of thermal cycling test found better of CeO₂ /8YSZ with improved life of this coating because of CeO₂ doping with YSZ which induced lesser stress at the interface of top layer and bond coat [39][40]

8. Tribological Study

K.Singh et al the tribological tests were performed on engine tribometer, focused to analysis tribological analysis of tribopair surface like friction coefficient and the wear loss at different load and constant sliding velocity and compare results of coated liner with uncoated case at wet (lubricated with SAE 15W40 Oil) and dry working conditions. During the test, the sliding velocity was 0.8 m/sec, 960 m sliding distance, and 40 mm stroke length for a period of 20 minutes; all test parameters are shown in Table 2.

Table 2. Experimental test parameter [21]

Conditions	Load (N)	Lubrication Condition
TestsNC ₁ , & C ₁	20	Dry
TestsNC ₂ , & C ₂	40	Dry
TestsNC ₃ , & C ₃	60	Dry
TestsNC ₄ , & C ₄	20	Wet (SAE 15W-40 Oil)
TestsNC ₅ , & C ₅	40	Wet (SAE 15W-40 Oil)
TestsNC ₆ , & C ₆	60	Wet (SAE 15W-40 Oil)
Temperature (°C)- Room Temperature		
Sliding velocity- 0.8 m/sec		
Sliding Stroke- 40 mm		

As per Archard's wear equation (1), the wear rate was measured in this work.

$$W = \frac{V}{P \times L} \quad (6)$$

Whereas W is the rate of wear (mm³/N.m), V is the removed material volume (mm³), P is the applied normal load (N), and L is the distance (m) covered during the experiment in a sliding nature[41]. The wear rate of coated and uncoated diesel engine liners under dry and wet sliding conditions across varying loads is depicted in Figures 5(a) and 5(b). Under dry sliding conditions, the uncoated liner (NC₁-NC₃) exhibits progressively increasing wear rates with load, increasing from 42.237× 10⁻⁶ mm³/Nm at 20 N to a maximum of 61.810× 10⁻⁶ mm³/Nm at 60 N. However, the coated liner (C₁-C₃) shows significantly lower wear rates under dry sliding conditions, increasing from 8.437 × 10⁻⁶ mm³/Nm (C₁) at 20 N to 38.656 × 10⁻⁶ mm³/Nm (C₃) at 60 N. This represents a reduction of up to 46% in wear at the highest load due to the YSZ ceramic top coat, which acts as a thermal and mechanical barrier. The coating minimizes direct contact, reducing material removal under abrasive and adhesive wear mechanisms common in dry sliding.

In lubricated sliding, the overall wear rates are lower due to the presence of a lubricating oil film. The uncoated liner (NC₄-NC₆) again shows increasing wear with load-from $9.560 \times 10^{-8} \text{ mm}^3/\text{Nm}$ at 20 N to $18.845 \times 10^{-8} \text{ mm}^3/\text{Nm}$ at 60 N. However, the coated liner (C₄-C₆) maintains wear rates between $1.744 \times 10^{-8} \text{ mm}^3/\text{Nm}$ to $2.467 \times 10^{-8} \text{ mm}^3/\text{Nm}$, showing significantly improved resistance. The YSZ-coated surface improves oil film retention due to its higher roughness and porosity, enabling better lubrication.

The lower coefficient of friction (COF) observed for the YSZ-coated liner indicates that the ceramic surface enhances lubrication efficiency by promoting the formation of a stable oil film and reducing asperity-to-asperity interactions. The inherent porous topography of the coating, along with its thermal insulation capability, helps maintain a consistent lubrication regime by retaining lubricant and minimizing direct metal-to-metal contact under operating conditions. The performance difference is more subtle than in dry conditions, indicating that thermal barrier coatings are beneficial even under lubricated conditions, reducing friction.

The wear rate shows in Figure 5(c) at different load conditions and found that composite coating have higher wear resistance compare to the conventional coating due to higher porosity and lower density. It is observed that the wear rate is increased with increasing of applied load in both cases but significantly decrement in wear during composite coating loading conditions. The analysis of the top surface, cross sectional and fracture section conclude that the adoption of alumina whisker in coating surface increases the strength of cohesion and adhesion. The wear results show the value decreased from $58 \times 10^{-3} \text{ mm}^3/\text{Nm}$ to $43 \times 10^{-3} \text{ mm}^3/\text{Nm}$ with adding 10% wt Alumina whisker in coating powder at above loading conditions.

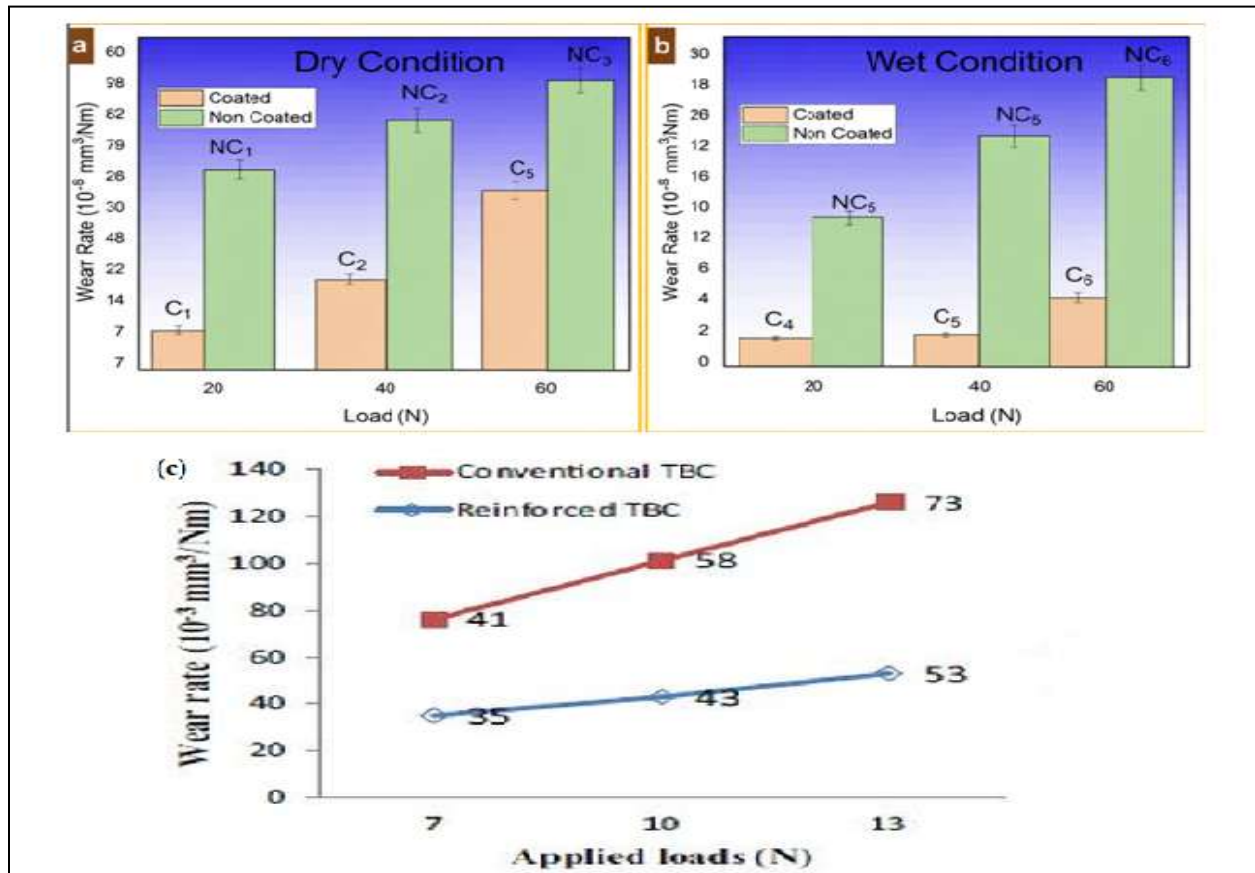


Figure 5 Wear rate with applied load (a) Dry Condition working conditions [21] (b) Wet Working Conditions [21] (c) Conventional TBC v/s Reinforced TBC [7].

The coefficient of friction demonstrates at 10 N applied load with function of sliding distance in Figure 6 (a) and (b). The obtained results shows the value of coefficient of friction lies between 0.5 and 0.9 for both cases but after 80 meter sliding distance found fluctuation in conventional coating compare to the composite whisker reinforced coating. The fluctuation in COF in composite coating is smooth and steady state upto end of wear test. The reduction of fluctuation in COF because of splat delaminating decreases and effect of exfoliation mechanism decreases also which due to better inter locking and better adhesion in coating surface. As per the exfoliation mechanism the micro meter sized defect like crack between two splats and pores in coating region causes of cracking agents. The reinforced splats have better interlocking interface and adhesion between splats which delaminates delay in coating structure [7].

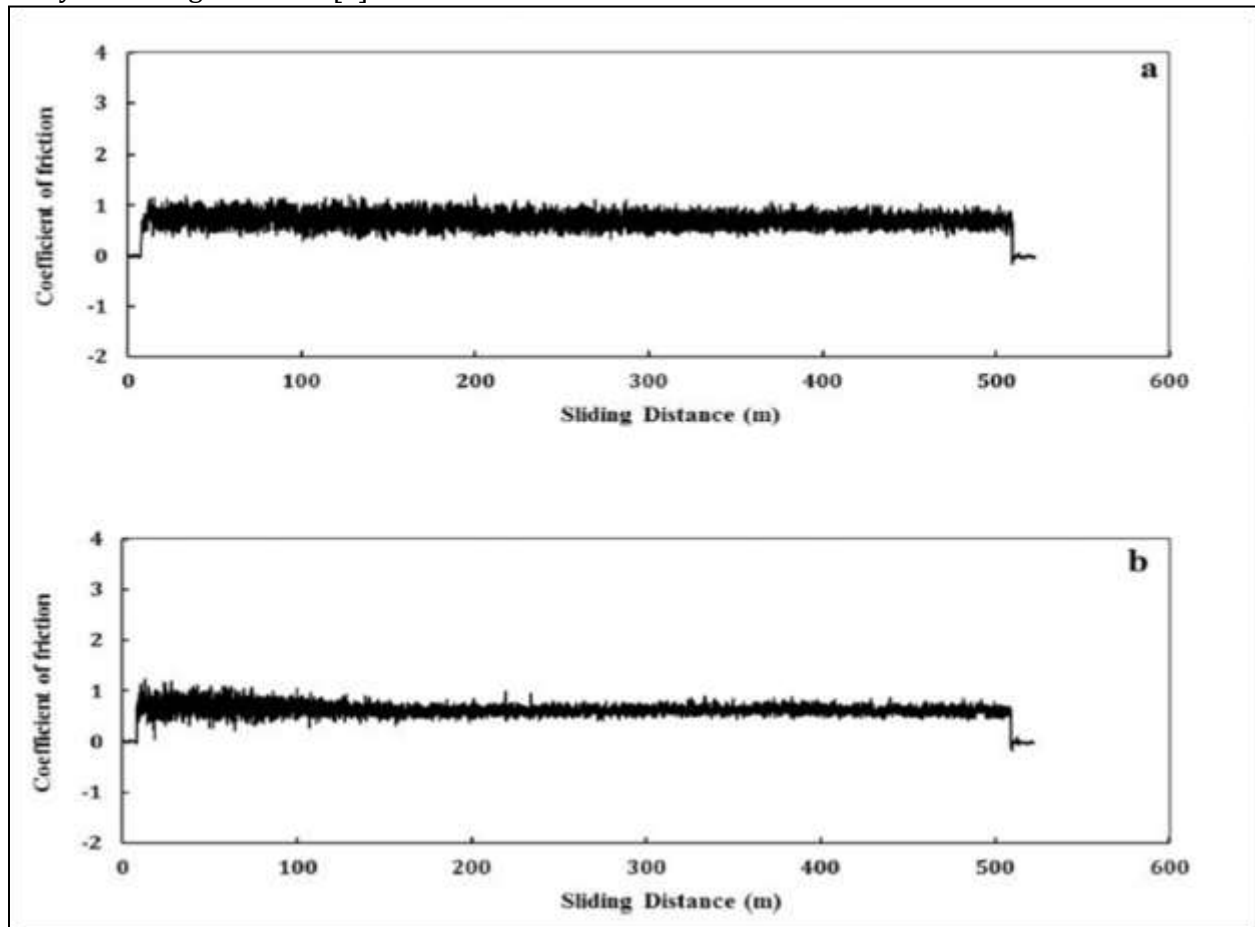


Figure 6 Coefficient of Friction with Sliding Distance (a) Conventional Coating (b) Reinforced Coating [7]

9. Performance and Emission

9.1 Heat Transfer Rate

It is found that the cylinder pressure varies significantly during fuel combustion process with respect to the crank angle. The measured pressure crank angle and volume data are used to evaluate important combustion variables including heat release rate, combustion chamber temperature, rate of pressure rise, and ignition delay, based on the assumptions of average thermodynamic properties, negligible leakage during compression, chemical and thermal equilibrium, and uniform mixing of fuel-air charge at 100 kPa pressure and 25 °C intake temperature. As shown in Figure 7 (a), the piston coated with $\text{Al}_2\text{O}_3 + 13\% \text{TiO}_2$ exhibits the highest peak cylinder pressure of 45.70 bar at 361°C, whereas the uncoated piston engine shows the lowest peak in-cylinder pressure of 40.46 bar at the same crank angle [9]. Similarly, the maximum pressure 70.99 bar developed inside cylinder with $\text{CeO}_2/\text{8YSZ}$ coating and 66.43 bar with $\text{Al}_2\text{O}_3/\text{8YSZ}$ coating on diesel engine piston in Figure 7(b)

[25]. As discussed above the thermal barrier coated engine have better combustion by advanced ignition and shorter delay gives higher instantaneous heat energy rate is 20.89 (j/°CA) at 377 °CA angle of $\text{Al}_2\text{O}_3 + 13\% \text{TiO}_2$ coated piston shown in Figure 7 (c), Similarly $\text{Al}_2\text{O}_3 + 13\% \text{TiO}_2$ and $\text{CeO}_2/\text{8YSZ}$ coated piston engine release heat rate 10% higher than non coated engine in Figure 7 (d)

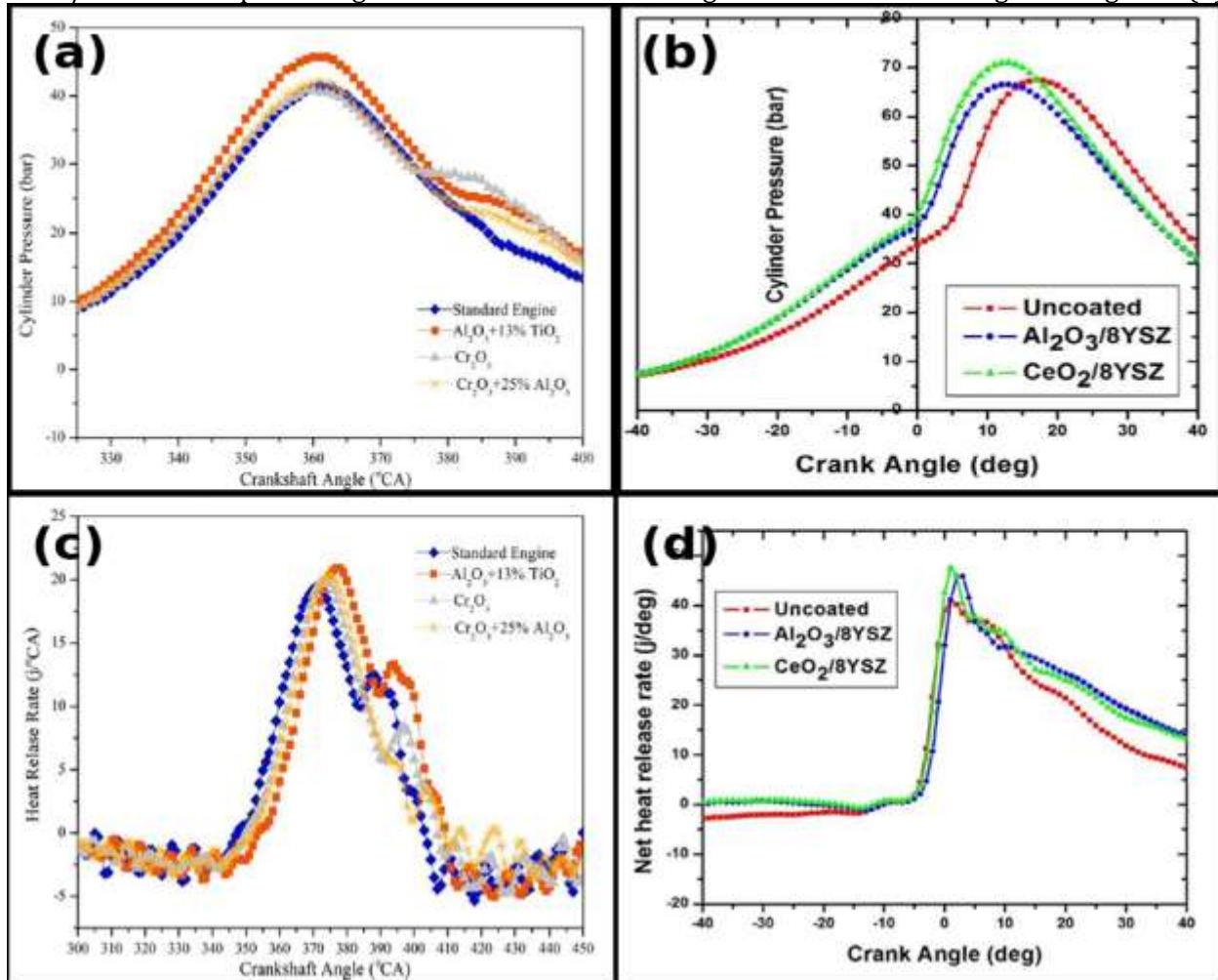


Figure 7 (a) and (b) Variation Cylinder Pressure with Crank Angle 7 (c) and (d) Heat Release Rate with Crank Angle [9] [25]

9.2 Brake Specific Fuel Consumption

It is evaluate that brake specific fuel consumption declined with increases of engine speed due to reduction of ignition delay. However continue increases of engine speed reaches at high then starts increases the fuel consumption and decreases of momentum due to incomplete of fuel combustion, decreases of volumetric efficiency, short combustion time and less fuel injection interval. In compression of non coated engine, it is observed that BSFC decreases corresponding 1.07% for the Cr_2O_3 coating, 2.34% for $\text{Cr}_2\text{O}_3 + 25\% \text{Al}_2\text{O}_3$ and 11.82% for $\text{Al}_2\text{O}_3 + 13\% \text{TiO}_2$. with the increased engine speed shown in Figure 8(a). BSFC decreases due to creation of homogenous mixture with help of high turbulence of the air swept during fuel injection in combustion chamber. With better fuel combustion increases the temperature of gases and wall which converts heat into more useful mechanical work at same amount of fuel consumption compare to non coated engine [9]. The reduced value of brake specific fuel consumption has shown in Figure 7 (b) causes of the higher combustion chamber temperature in cylinder, the fuel temperature increases, resulting in reduced fuel viscosity. This promotes improved atomization and faster evaporation of the injected fuel, thereby reducing the physical ignition delay. Consequently, more efficient combustion occurs [25].

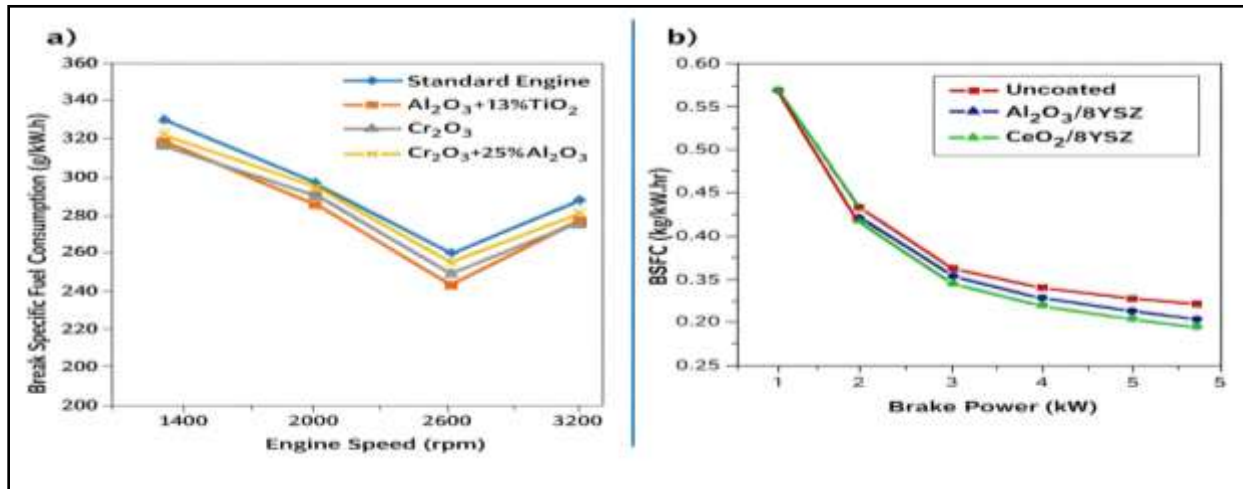


Figure 8 (a) BSFC with Engine RPM [9] (b) BSFC with Brake Power [25]

9.3 Brake Thermal Efficiency

It is found that increases brake thermal efficiency with reduction of brake specific fuel consumption, increases of brake power, high heat release rate due to homogenous mixture of and increased combustion efficiency. It is elaborate that with $\text{Al}_2\text{O}_3 + 13\% \text{TiO}_2$ coated diesel engine piston shows that maximum torque value is 13.1 Nm at 2600 rpm and maximum power measured 3.59 kW at 3200 rpm shown in Figure 9 (a) and (b) [9]. The all parameters are causes to increase the brake thermal efficiency causes of resistance in heat loss and convert it into mechanical work. The thermal barrier coating of both materials coated material $\text{Al}_2\text{O}_3 / 8\text{YSZ}$ and $\text{CeO}_2 / 8\text{YSZ}$ have higher brake thermal efficiency 8% and 11.37 than non coated engine shown in Figure 8 (c) at maximum load working conditions causes of reduction of heat into cooling system and conversion into more available work on shaft [25].

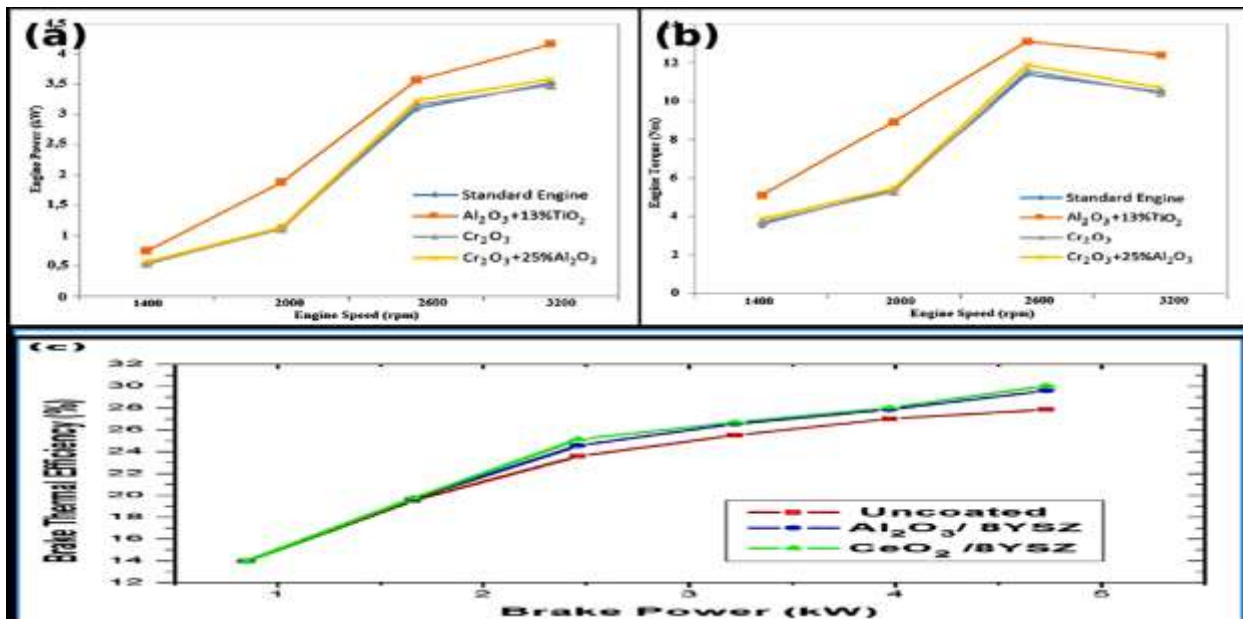


Figure 9 (a) Engine Power with RPM (b) Engine Torque with Engine Speed (c) Brake Thermal Efficiency with Brake Power [9] [25]

9.4 Emissions

As shown in Figure 10 (a) (b) and (c), the application of $\text{Al}_2\text{O}_3 / 8\text{YSZ}$ and $\text{CeO}_2 / 8\text{YSZ}$ coated pistons resulted in a significant reduction in exhaust emissions compared to the uncoated piston. The

hydrocarbon (HC) emissions decreased in the range of 12.5%–14.54%, carbon monoxide (CO) emissions were reduced by 18.96%–25.86%, and smoke opacity decreased by 26.92%–28.88% for both coating systems. These reductions are primarily attributed to the increase in in-cylinder temperature due to the thermal barrier effect of the coatings, which enhances combustion quality. The elevated temperature promotes improved fuel oxidation, higher combustion efficiency, more stable ignition, and better air–fuel mixing, thereby leading to lower incomplete combustion products. Additionally, the CeO_2 /8YSZ coating exhibited superior thermal stability under high-temperature operating conditions, making it more suitable as a thermal barrier coating (TBC) for engine components and resulting in better emission performance compared to the Al_2O_3 /8YSZ coating. However, an increase in NO_x emissions was observed for the coated engines, as shown in Figure 10 (d). The NO_x emissions increased by up to 13.42% for the Al_2O_3 /8YSZ coating and 23.37% for the CeO_2 /8YSZ coating compared with the uncoated engine. This increase is mainly attributed to the elevated flame temperature in the combustion chamber caused by the enhanced thermal insulation effect of the coatings. According to the Zeldovich mechanism, the formation of thermal NO_x is strongly influenced by high combustion temperature, where reactive radicals such as OH are generated and subsequently react with nitrogen atoms to produce NO. In the coated engine, a larger fraction of the premixed fuel undergoes rapid combustion prior to the attainment of peak in-cylinder pressure, which leads to elevated local flame temperatures and thereby promotes NO_x formation. As a result, NO formation dominates the total NO_x emissions, accounting for more than 90%, while the remaining fraction (approximately 10%) consists of NO_2 , NO_3 , and NO_4 species [25]. G. Vidyasagar Reddy et al found experimental values of emissions with different coating material applied as thermal barrier coating on piston top diesel engine. The coating materials investigated in this study were 7YSZ, 2 Nd-YSZ, Gd YSZ, and a hybrid composition of 2Nd + 2 GdYSZ, which were individually applied to four different pistons using the plasma spray coating process. A top coat thickness of 250 μm and a bond coat thickness of 50 μm composed of NiCrAlY were maintained for all coated pistons. Experimental investigations found on a single cylinder, four stroke, water cooled diesel engine operated at speed of 1500 rpm with zero loads to full load. The results show a notable reduction in exhaust emissions for all coated pistons compared to noncoated piston. Specifically, hydrocarbon (HC) emissions decreased by 12.6%–22.5%, carbon monoxide (CO) emissions by 5.9%–16.1%, and smoke opacity by 4.6%–17.7% for the different coating systems. However, an increase in NO_x emissions was also observed for the coated pistons, with a maximum increase of 17.1% compared to the uncoated piston engine [42].

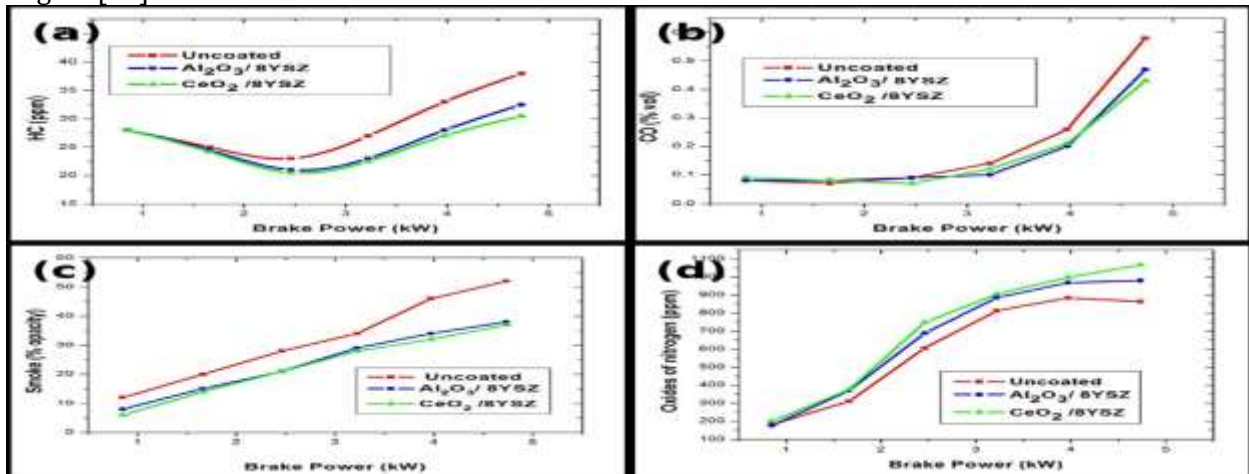


Figure 10 (a) Engine HC Emission with Power (b) Engine CO Emission with Power (c) Engine Smoke Emission with Power (d) Engine NO_x Emission with Power [25]

10 CONCLUSION

In this review study, thermal barrier coatings (TBCs) applied to various diesel engine components using different ceramic coating compositions are systematically examined. The literature primarily investigates experimental findings related to the thermal stability, durability, and tribological

behavior of the piston–liner interface with TBC application. Additionally, comprehensive analyses of the combustion process in thermal barrier–coated diesel engines are reviewed, including their effects on brake thermal efficiency, engine torque, and brake-specific fuel consumption. The effect of TBC on exhaust gas emissions like as hydrocarbons, carbon monoxide, smoke opacity, and nitrogen oxides is also critically analyzed and compared with corresponding results obtained from non-coated diesel engines. The following findings are drawn from the above review study:

- The TBC coating applied to the engine components only piston crown in most literature, but it is not sufficient for reduction of heat loss in engine cooling consequently, several researchers have extended TBC on cylinder liner, valves and cylinder head which increase cylinder gas pressure, wall temperature, heat energy release rate and increase exhaust gas temperature. It was observed that the substrate surface must be thoroughly cleaned and degreased using ultrasonic cleaning, followed by sequential grit blasting to increase surface roughness and enhance coating adhesion.
- It is concluded that ceramic coating material parameters such as thermal conductivity, specific heat capacity, and porosity are the key factors governing the selection of suitable ceramics for thermal barrier coatings. Consequently, most researchers have widely adopted 8YSZ as the topcoat material with NiCrAlY as the bond coat, applied using the atmospheric plasma spray process. Furthermore, to enhance the thermal stability, phase stability, and durability of zirconia-based coatings, various reinforcements and dopants such as Al_2O_3 whiskers, CeO_2 , and rare-earth oxides including Nd_2O_3 , Gd_2O_3 , and Yb_2O_3 have been incorporated into the zirconia base materials. The FE-SEM examination confirmed that the splat structure, micro-cracks, porosity, and surface texture were improved after the addition of reinforcing compounds. The XRD analysis revealed enhanced phase stability of the coating, while EDS elemental analysis with color mapping verified the elemental distribution and additionally confirmed the coating thickness. The morphology of coating surface identified with which find the splats structure, after atmospheric plasma spray coating process.
- Surface hardness was evaluated using the Rockwell hardness test and was found to be 60.6 HR15N at an applied load of 15 kgf, which is higher than the substrate. An increase in coating thickness resulted in higher surface hardness, whereas porosity and surface roughness decreased after applied TBC. The results of thermal cyclic test of sample found better of CeO_2 /8YSZ than Al_2O_3 /YSZ and conventional YSZ because of CeO_2 doping has less stress between interface of upper coat and bond coat cause of decreases the mismatches of CTE in coating layers.
- Additionally, with the application of thermal barrier coatings on the cylinder liner, the researchers have evaluated the tribological, the YSZ coated liners consistently dropped COF from 0.3222 to 0.0778 (76%) and 0.0768 to 0.0637 (17%) under dry and wet sliding conditions respectively with 60N normal load application. Similarly, reduced wear rate from 61.810×10^{-6} to 38.656×10^{-6} mm^3/Nm (38%) and 18.845×10^{-8} to 2.467×10^{-8} mm^3/Nm (87%), under dry and wet sliding conditions respectively with 60 N normal applied load. The results showed that the TBC material act as lubricant which reduces COF and wear rates due to low shear YSZ surface and tribofilm formation minimized asperity interactions.
- The CFD based TBC model of the engine combustion chamber successfully validated the combustion process by showing an increase cylinder gas pressure and temperature which good matched with the experimental results obtained for a $\text{La}_2\text{Zr}_2\text{O}_7$ coated piston. The lower thermal conductivity, lower specific heat, and higher porosity of the coating increases heat resistance to the engine walls and increased the heat energy release rate within the combustion chamber. This enhancement led to improved engine performance and reduced exhaust emissions, except for NO_x , which increased due to the elevated combustion temperature.
- Most experimental studies have demonstrated that the thermal barrier coatings using 8YSZ as the top coat with a NiCrAlY bond coat, with thicknesses up to 500 μm , on diesel engine components significantly enhances the heat energy, cylinder gas pressure, and combustion temperature. These improvements result of reduced in BSFC and improved in brake thermal efficiency. Furthermore, coated engines exhibit notable reductions in hydrocarbon HC, carbon monoxide CO, and smoke opacity in exhaust gases compared to uncoated engines. However, higher side of NO_x emissions is consistently reported causes of higher combustion temperatures. In addition to conventional YSZ

coatings, advanced ceramic systems such as $\text{Al}_2\text{O}_3/\text{8YSZ}$, $\text{CeO}_2/\text{8YSZ}$, $\text{Al}_2\text{O}_3 + 13\% \text{TiO}_2$, and $\text{Al}_2\text{O}_3 + 25\% \text{Cr}_2\text{O}_3$ have shown superior performance and emission characteristics compared to both pure YSZ and non-coated diesel engine components. The environmental challenge associated with increased NOx emissions can be effectively controlled by incorporating SiC as a porous medium within the coating system, which helps in controlling peak combustion temperatures.

Future Scope

The future scope of this research activity will take into account the reduction of NOx emissions and utilization of recovery heat from exhaust gas to drive cogeneration system with thermal storage and cooling system.

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