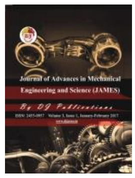
Journal of Advances in Mechanical Engineering and Science, Vol. 3(1) 2017, pp. 1-13



REVIEW ARTICLE

Efficiency of Nano Ceramic Coated and Turbocharged Internal Combustion Engine- A Review

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Received- 2 December 2016, Revised- 12 January 2017, Accepted- 19 February 2017, Published- 25 February 2017

ABSTRACT

Thermal Barrier Coating (TBC) often denotes the ceramic/Nano ceramic insulation layered to the surface of the engine or any other parts to enhance the thermal insulation characteristics by increasing efficiency and minimizing the need of cooling system. Above all, load and speed of the engine is optimized with respect to output power, volumetric efficiency and exhaust control. Insulation of combustion chamber with ceramic enhances its efficiency and it is also significant in terms of pollution control and fatigue lifespan. On account of these, this article reviews a list of papers that contribute in studies, where the influence of nano ceramic coating and the use of turbocharging mechanism in optimization of engine performance are described.

Keywords: Thermal barrier coating, Ceramic insulation, Volumetric efficiency, Exhaust control, Fatigue lifespan.

1. INTRODUCTION

Efforts in improving internal combustion engine efficiency have been progressing through constructional alterations. There is a rapid growth in ceramic coating applications throughout this sector. Designing of engines with minimum heat rejection exhibits gradual growth due to unusual rise of fuel cost and decline in its generation with possibly higher quality and emission factors. Improvement in engine efficiency lies in faster conversion rate of fuel to mechanical energy. Increase in temperature and pressure enhances engine performance, which could be enabled by Nano ceramic coating of the combustion chamber. Coating of the internal combustion engine with Nano ceramic component minimizes heat passing from in-cylinder to the cooling device. These cooling systems from IC engines could be replaced by the Nano ceramic structures due to its advancement in technology. These turned to be advantageous in terms of engine power enhancement, apart from decreasing its mass and it is cost effective as well. Normally, the metal surface of pistons is coated with TBC and its influence is getting more because of fuel source scarcity and emission risk factors. [1] Basically extreme operating temperature is adequate for the enhancement of thermal performance in turbine engine. The exposure of metals at high temperature, limits its lifespan and so there arises the need for a compressor as a cooling agent. In this case, TBC is required in order to solve all these issues, which improves the thermal performance by enhancing the inlet temperature and minimizing the cooling air quantity. [2] TBC consists of four layers viz, base, bonding layer, thermally grown oxides and then upper coating. The upper and the bonding material are ceramic and metallic coat to provide insulation and adhesion respectively. Piston and cylinder coating in an IC engine itself provides around 3% increase of thermal efficiency. Coating of engine parts not only protects the engine but also acts like an anti-oxidative layer. Using of ceramic coated combustion engine results in low heat rejection which in turn leads to increase in temperature thus aiding in reduction of ignition delay. So, its operation can be conducted at minimized combustion ratios, where mechanical performance and fuel economy

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Double blind peer review under responsibility of DJ Publications
https://dx.doi.org/10.18831/james.in/2017011001

could be enhanced. Besides these, recent studies have found out that, owing to the utilization of Nano ceramic coating in IC engines, CO exhaust has been considerably reduced, which increases the thermal and turbocharger efficiency. Generally ceramic coatings are preferred for turbocharged internal combustion engine due to its exhibition of increased volumetric efficiency and exhaust emissions, which is not available in non-turbocharged engine. Use of turbocharger could enhance the performance rate by 20%. In single cylinder diesel engine, the addition of turbocharger might not be advantageous, but for multi cylinder types, its use is highly considered and many of the researches conducted were based on these principles. Not all the materials can be listed as thermal barrier coating substance, unless they satisfy the below mentioned attributes [3].

- Should possess high melting point
- Should not undergo any phase change between room and operation temperature
- Should have low chemical activity and thermal conductivity
- Highly adhesive
- Higher thermal durability

[4] TBC improves combustion and reduces harmful emissions apart from exhibiting effective wear parameters. To minimize heat rejection, zirconia is coated over the piston surfaces and engine valves with an intention to tackle pollution by enhancing engine efficiency.

2. INFLUENCE OF NANO CERAMIC COATING ON IC ENGINE

In certain concepts as in [5], diesel engine piston has been coated using ceramic. ANSYS code determines the transfer of temperature, where zirconia was employed as ceramic layer. In this analysis, the ceramic layer had holes, and thus the temperature distribution depends on holes in it. As this hole radius increases, the surface temperature also tends to increase, whereas the base temperature is inversely proportional to increase in hole radius. [6, 7] Thermal barrier coatings are beneficial in reference with thermal performance, engine durability and internal friction. It also lowers erosion, noise and air pollution. While many papers suggest that such thermal coatings are helpful in eliminating exhausts, there are articles with negative impacts. The impacts of ceramic coatings over environmental emissions can be listed as,

- Ceramic coating reduces solid particulate fraction significantly up to 50%. It is proven in the experiments conducted utilizing heavy duty and bus engines.
- There is slight reduction in case of nitrogen oxides, where carbon monoxide and visible smoke reduce considerably.
- Due to the influence of coating, organic particulate fraction and Hydro Carbons (HC) slightly increases.

[8] Investigating the impacts of ceramic coating of IC engine at its full load, the test results reveal that carbon monoxide emission was reduced by 45%. In the experiments scheduled, the engine pistons were coated with 0.5mm and 1mm thickness. At 1.5mm layer, emission was found to be low with minimum engine rate, whereas usage of 0.5mm ceramic coating improved thermal performance by 10% when compared with the metal piston in the absence of coating. The results were not fair with the increase in the thickness of the coating. In such a way, unburned hydrocarbons and nitrogen oxide emissions were also minimized when coated piston was employed. [9] When some of the papers focused on emission characteristics, there are studies that relates with frictional and wear factors. Deposition of hydrogenated diamond-like carbon insulators was deployed to be wear resistant. Certain merits of using ceramic coating are as follows,

- Temperature and wear resistant
- Richly available
- High hardness degree and compression strength
- Improved chemical stableness
- Low density and heat conduction coefficient

[10] Comparisons were made with respect to plasma and flame spraying of coating. The results show that lying of coatings using plasma spray is better in providing thermal fatigue resistance. In plasma spraying, refractory oxides of oxy-hydrogen and oxy acetylene methods are widely adopted. Usually, prior to insulation, the surface is treated with nickel-chromium to prevent oxidation and to act as a binding substrate. Results from silicon nitride coating represent that it is effective in terms of engine noise and life time. [11] reports that efficiency of common diesel engine would be around 40%.

Most of the fuel energy wastage is due to exhaust heat and that ranges by 60%. Around 60% energy generated during combustion is lost due to cooling. So it is a must to reserve energy by protecting the hot parts by thermal insulation. By doing so, heat transfer gets reduced leading to the utilization of maximum amount of generated energy. While applying a couple of layer coating by plasma spraying, an increase in diesel engine performance was noted [12]. One of the layers is made up of MCrAlY, where M stands for Nickel and the other is of zirconia based 8% Yttria. A significant progress of engine power and performance was noted with decrease in emission and fuel usage. Additionally fatigue life span of cylinder head and piston was improved owing to surface temperature minimization by 100℃.

3. APPLICATIONS IN IC ENGINES

Low heat rejection engine is the IC engine, where its surface of the combustion chamber is coated with TBC substances in order to minimize coolant heat loss. It is essential to overview the coating thickness and mechanism to improve its efficiency [13].

3.1. Features of Nano ceramic

Nano ceramic comes under the broad term ceramic in where it consists of at least one material in nano scale. [14] Nano ceramics differ from ceramics in their brittleness and rigidity where they stand unique in characteristics like super plasticity, wear, corrosion resistance, machinability and insulating ability. These features enable Nano ceramics as the most efficient component in providing chemical inertness, thermal shock and oxidation resistance as well.

3.2. Ceramic types

Nano ceramics can be oxides of aluminium, beryllium and magnesium, zirconia, silicon and tungsten carbide and silicon nitride. Apart from these, some of the Nano ceramics that are given commercial importance are silica, titania, ceria, iron and mixed oxides. Table 1 describes some of their ceramic characteristics, where ℃ relates to melting temperature, (g/cm^3) denotes density, (MPa and GPa) refers to strength and elasticity module respectively, ($MPa\ m^{1/2}$ and kg/mm^2) to fracture roughness and hardness accordingly.

Table 1.Characteristics of ceramic materials

Ceramic	SiO_2	Al_2O_3	ZrO_2	SiC	Si_3N_4
℃	500	2050	2700	3000	1900
g/cm^3	2,2	3,96	5,6	3,2	3,24
MPa	48	250-300	113-130	310	410
GPa	7,2	36-40	17-25	40-44	30-70
$MPa/m^{1/2}$	0,5	4,5	6-9	3,4	5
Kg/mm^2	650	1300	1200	2800	1300

Some of the thermal barrier coating materials are given by,

- Yttria-stabilized zirconia is one among the widely used ceramic materials since it is corrosion resistive [15-17]. It is effective in correspondence with brittleness, chemical stability at extreme temperatures and fracture toughness.
- Mullite (combination of silica and alumina) is low dense, thermally stable, low thermal conductive and chemically inert. Mullite can be opted for diesel engines with decreased surface temperature and silicon carbide substrate [18].
- Alumina can be combined with yttria-stabilized zirconia to enhance oxidation resistance, hardness and bonding.
- To improve the span of thermal cycling and shock tolerability, cerium dioxide has been used along with yttria-stabilized zirconia.
- Lanthanum zirconate exhibits lower thermal conductivity and sintering capability [19-21]. Lanthanum aluminate can be preferred for structural and thermo-chemical strength.
- Zirconia when used with silica leads to higher chemical stability. Zirconates are employed in obtaining maximum energy conversion effectiveness [22].

3.3. Coating types

Ceramic coatings can be thin (0-5mm) or thick layered (>5mm). Thin layers are suitable for diesel engines, gas turbines and pistons. Coatings can be made by thermal spray or laser coating or flame spray or chemical ceramic coating or by arc spark alloying or ion enrichment mechanism.

3.3.1. Flame spray insulation

In flame type, a binding material is kept in between the test material and the coating. Flame spray can be of two types, namely, wire flame spray and powder flame spray coating. [23, 24] In powder flame spray type, cold coating is applied, where the thickness varies from 0.5 mm to 2.5 mm depending upon the requirement. It employs either ceramics or metal and ceramic alloys as insulation. Wire flame spraying includes wire shaped metal that can be sprayed over the test surfaces. The melting point of this wired metal is lower than the flame temperature, where it is melted by means of oxygen and gas fuel flame (acetylene, propane, hydrogen). [25] This technique is advantageous and disadvantageous in certain prospective, i.e. its cost effectiveness and spray rate are the merits, whereas the lower intensity of insulation and adherence quality are its noted demerits.

[26] Cold coating that includes nanostructured particles prevents tensile residual stress apart from oxidation and corrosion protection.

3.3.2. Dense gas (plasma) spray insulation

In dense plasma spray coating, electrons and protons are equally numbered. With reference to heat transferring ability, this approach is preferred. [27, 28] Metals and alloys with increased melting point can be used due to its higher operating temperature. Both the thermal and cold coatings attribute corrosion resistance behaviour. Meanwhile the application of inert gas in this method helps in reduction of oxidation defect. [29] Ceramic itself prevents oxidation when compared to other materials. It also degrades thermal shock oxidation in high temperature field.

4. IMPACT OF NANO CERAMIC COATING

[30] Nano ceramic insulation protects engine from high cyclic temperature/forces and other impairments. Traditionally thick chambered combustion walls followed by cooling system have been constructed to prevent excess heat and then on substitution, low thermal conductivity substances are utilized. [31] Since notable improvements in engine performances could not be seen in spite of all these, ceramic coatings came into practice due to its high efficiency and decreased fuel intake. Engines can be turbocharged or non-turbocharged. Ceramic insulation might not be suitable to engine without turbocharger owing to its volumetric inefficiency. But this goes well with turbocharged internal combustion engines. It provides higher efficiency and discharge mechanism. This occurs in turbochargers due to the increase of air mass flow speed with respect to exhaust emission increase. [32] Zirconium oxide ceramic is preferred to other ceramic materials even though others were also used commonly. Almost all the papers reveal that there could be up to 40% increase of nitrogen oxide exhaust due to the usage of ceramic insulation. This can be brought into control by alteration of injection timing or reduction of advance angle so that such exhaust can be reduced by 28%. [33] Even coating thickness influences the performances of the engine. Comparison of piston crown insulation with alumina and zirconia are carried out comprising of several thicknesses. The results are drawn such that, load increase results in increase of thermal performance which in turn lead to lower fuel intake. Furthermore, carbon monoxide, hydrocarbons and visible smoke were reduced with slight increase in nitrogen oxide exhaust. [34] The influence of ceramic coating tends to rise as many researches have come up utilizing these as insulating material due to their significant benefits. In this aspect, partially stabilized zirconia has been used by means of plasma spraying type. It has been found out that the brake thermal efficiency was improved by 6% in coated engine and also it shows reduction in heat flux and thermal stress.

4.1. Engine efficiency

[35] Based on the comparison conducted using several nanostructured ceramic coating, carbon stabilized and yttria stabilized zirconia was proven to be better in providing increased thermal cycling lifespan. [36] TBC becomes significant since the heat engine parts are thermally insulated, thereby in-cylinder transfer of heat and surface temperature get reduced. It has been found out that the Nano structured ceramic materials coated in the engine components result in loss of friction and wear. The article deals with thin TBC in single cylinder engine, in which certain engine components are partially coated whereas the others are fully coated. It is concluded that the ceramic coatings of cylinder liner reduced fuel intake considerably and the insulation of cylinder head reduced heat rejection. [37] Cylinder liner coating of the combustion engine improved its performance. The requirement in considering the

macroscopic and microscopic effect for optimization of cylinder layer has been illustrated by honing mechanism. The ceramic, silicon carbide has been used in the process, which showed corrosion and abrasion resistant properties [38]. [39] Fuel economy could be maintained not only through proper coating strategy but also by reducing power to weight ratio via low mass structure. More or less one fifth of engine loss is constituted by means of friction and around 50% of the parasitic loss is due to frictional loss. So this must be lowered to enhance fuel consumption and reduce environmental exhausts. Output power could be enhanced by surface texturing that is pivotal where a hard coating increases adhesion, which also reduces wear and scuffing. Wear loss helps in improving fuel economy along with prevention of oil leakage so that lubricant loss and exhaust can be kept in control. [40] Optimizing the piston of the IC engine is essential as it takes high percentage of the mechanical friction. Thermal coatings layered on the cylinder liner reduced the risk of increased friction.

4.2. Fuel consumption and emissions

Air pollution is mostly due to auto emission, where it gets elevated because of increased development of automobiles and shortage of throughput system. Carbon monoxide emission is considered to have the most poisoning effect. [41] The basic emission catalytic converter would be the answer for this question. Metals and metal oxide catalytic converter would reduce air contamination, which could be opted for IC engine as well. Application of several type of coating material would have different effect upon lowering exhausts. In general around 20% reduction of unburned fuel emission was pointed out due to the addition of ceramic catalyst. Certain metal on silica and alumina contribute for the oxidation of HC and CO. [42] A novel method featuring Nano zirconia along with micro silicon carbide was carried out with the intention to suit diesel and bio diesel fuelled IC engine. With the overall improvement in thermal performance, in-cylinder stress and heat emission speed, it also demonstrated to be efficient in reduction of greenhouse gases. Yet nitrogen oxide exhaust optimization remained to be an unsolved problem in this method too. [43, 44] Incorporating Nano ceramic alumina by plasma spraying in the surface of the combustion chamber increases engine power and fuel economy. Its role is marked in minimization of emission as well without taking nitrogen oxide into account. The test unit was diesel engine with single cylinder and four-stroke. [45] The incorporation of catalytic coating to lower emission is emphasized. IR and Raman spectroscopy and scanning electron microscopy results convey that 99% of carbon oxide conversion rate is achievable by using ceramic catalyst (Palladium/ Silica/ Aluminium/ silicon). Several other combinations produced different conversion rate. [46] In concern with fuel effectiveness and harmful exhausts, diamond like carbon layer was coated over the IC engine parts in order to lower friction and extend lifetime. Based on comparisons, it shows that usage of dialkyl dithiophosphate and glycerol mono oleate have not produced desired results corresponding to generation of reaction layer. [47] Engine parts are subjected to corrosion that they tend to degrade. So, even in case of diesel engines on aero networks, protective coatings are significant. Nanostructured thermal spraying is exposed to deal with corrosion engine components.

4.3. Durability

To attain durability of insulation, coatings have to be optimized. [48] Ceramic layers and hard amorphous carbon are integrated to produce scuffing resistance and durability. It is efficient in managing scuffing problem besides being reliable and provides robustness to the piston rings. [49] Ceramic coatings of scandia and yttria stabilized zirconia are employed to resist corrosion and to exhibit chemical stableness. The results reveal that the phase change of zirconia forms cracks so that the thermal barrier coating gets degraded. [50] Traditional coating mechanism including diamond like carbon insulation ends in shortcomings in relation with dimensional stability and durability. In this regard, Nano grains of crystalline coating have developed, that solved all such limitations. [51, 52] A fourfold and fivefold rise in sliding wear and abrasive wear resistance was proven accordingly due to the addition of nano-alumina and titania composite in combination with ferric oxide as solid lubricant. Here the nanomaterials are structured alike lubricant coatings, which also demonstrated advantages in relation with cleavability and low friction. It is regarded suitable while concerning with the fields under high lubricity at room and extreme temperatures. The article aimed to minimize friction simultaneously with high wear resistance using Nano alumina/titania coating as ceramic titania is stable and inexpensive.

5. THERMAL PERFORMANCE AND HEAT BALANCE OF TURBOCHARGER

Heat transfer generally includes energy flows that are not at all taken into consideration in assessing turbocharger efficiency in certain cases. Some of the existing methods in measuring heat transfer convey fluid temperature change at low turbine pressure ratio. 1D transfer model is capable in simulating heat fluxes to high accuracy. It is noted that the heat transfer coefficients do not influence the test turbochargers used. [53] The role of turbocharger in satisfying the requirements of exhaust and fuel intake optimization is effective. In this regard, automotive turbochargers operate at high range and unsteady gas flow, but steady flow rates are usually common. All these complexities are overcome by the proposed strategy via whole estimation process. [54] Turbocharging is applied to enhance efficiency and lower total displacement of the IC engines. The research carried out in this article includes optimization of engine-turbocharger matching and estimation of steady turbine efficiency. It has also analyzed the unsteady characteristics of small engine and simulated using GT-Power mechanism. These unsteady functions were induced by rotating valve in the test rig circuit. [55] A lumped capacitance model has been used to relate the heat transfer loss of a turbocharger. On the basis of analysis with and without the presence of turbocharger, it has been found out that using turbocharger, heat transfer function has been enhanced at maximum load and in the premises of engine rate. [56] Analysis was made corresponding to gas stand and on-engine turbocharger. A correlation of the heat transfer characteristics was obtained from experiments to analyze heat transfer between gases and turbine where the turbine outlet temperature error was minimized. The housing thermal inertial conditions are formulated. The results demonstrated that the maximum transient heat passage was influenced by the inlet degree of the turbine. When the gas temperature is increased or decreased, the maximum heat passage tends to remain high or low respectively.

[57] Computer codes and look up maps were used in predicting the function of engine and turbocharger. Various heat transfer mechanisms are measured along with flow correlation analysis. These benefits are dependent on estimating the outlet temperatures of fluids, where the oil and coolant temperatures are significant in determining ideal cooling structure. [58] Using algorithms in accordance with the lump capacitances the heat passed via turbocharger is calculated. Compressor maps were crested with respect to the rate and temperature of the emissions from the inlet and change in performance level has been assessed. Then, compressor correlation was determined using multiple regressions on the basis of the factors that influence the heat transfer system. [59] As the functioning of small turbocharger affects heat transfer criteria, the measure of energy loss due to heat transfer or the loss of hot turbine has to be analyzed. On account of these, radiation and convective strategies have been developed to predict the external heat flows. It also represents the important operative points in where such heat transfer in turbocharger could not be avoided in any case.

[60] developed a proton exchange membrane fuel cell that makes use of turbocharger for the purpose of reusing the waste energy. A 1D isothermal 2-phase and isenthalpic system have been modelled for fuel cell and turbocharger respectively. System performance, power construction and exergy analysis were done in order to determine an ideal energy source and to assess the feasibility. It is found out that there is improvement in efficiency after the introduction of turbocharger in the system. It is concluded that the addition of turbocharger after the hydrogen tank would favour system performance and exergy efficiency. [61] investigates the thermal balance of spark ignition engine with turbocharger when operated using natural gas. Due to the rise of load and coolant temperature, there is decline in coolant energy rate and increase in exhaust energy. Furthermore, thermal performance of gaseous fuel and turbocharger increased by around 5%. Exergetic effectiveness was also enhanced by 3.6% because of the usage of turbocharger. The entire experimental procedure was based on first and second law of

thermodynamics. [62] Heat transfer effect was evaluated with an intention to improve compressor efficiency. This method seems to be advantageous in terms of database economy, requirement of fewer geometrical and physical attributes and there is no need of a local test bench for achieving compressor maps. [63, 64] Turbochargers enhance performance and lower specific exhausts in vehicles and power generators. Oxidation resistance and mechanical characteristics were analyzed when using nickel based titanium aluminade alloys at 850-950℃. The results conclude that nickel based alloy coatings are suitable for turbochargers at ≥950℃. The referred papers validate that turbocharged engine perform better than the system without it. [65] The simulation of turbocharged engine depends upon the compressor adiabaticity. At the same time, the performance of the compressor is also influenced by the turbine heat transfer. So far as, in concern with the referred papers, they convey that turbochargers enhance system performance both in terms of its efficiency and emission control.

6. FURTHER PERSPECTIVES

Certain direct injection engines that make use of petroleum based HC possess lubricating characteristics. It is a known fact that the demand for ecofriendly fuels is high, but the so called cleaner fuels like ether and alcohol based products do not tend to have lubricant features and so some sort of alternative has to be included to meet the scope. [66] Even in this aspect, high pressured pump with corrosion and abrasion resistance and contact surface with lubricity would be the substitute. Based on the function of Nano ceramic materials that are discussed so far, it can be concluded that Nano ceramic coated system is capable to fit into these considerations. Both oxide and non-oxide solid lubricants are common in applications, where these are dispersed into ceramic composites that result in lubricant coatings. Nano ceramic coatings are manifested to be better than that of ceramic coatings with respect to wear and erosion/corrosion resistance. Most of the thermal spray coatings are utilized for the preparation of titanium dioxide due to their hardness, compatibility and other mechanical properties. [67] Yttria stabilized zirconia coated turbocharger was described in which thermal resistance is directly proportional to amount of coating substance. Slurry typed coating was done where the ceramic coating material was added with nickel to prevent it from spallation. The usage of automatic film applicator helps in reduction of production cost of TBC. The results are desirable with efficient quality.

7. CONCLUSION AND FUTURE SCOPE

Ceramic materials provide thermal protection to turbine engines. Thermal barrier coating enhances operating temperatures and reliability of engines and effectiveness of fuel. Almost all the papers reviewed unfold that due to the innovation of internal combustion engine coating mechanism, increase in nitrogen oxide emission is marked, which convey that a proper strategy must be put forth so that its emission could also be limited along with other merits like increased engine and fuel efficiency and exhaust control. Again, in rare cases, these coating expire prematurely which then would be the cause to expose its base material to hot gases. Thus the failure system has to be dealt appropriately in such a way that further development in coating process resolves all these demerits. Even though the advantages of using Nano ceramics in combustion engines are listless, only a handful of researches have been carried out so far and there is a need for rapid experiments in the sector of Nano ceramic coating.

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