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# Thermal barrier Analysis in Diesel

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***Abstract:*** *The specific outputs of some diesel engine applications have produced thermal loadings in excess of the strength of typical aluminium piston alloys. Functionally graded coatings are used to increase performances of high temperature components in diesel engines. Thermal barrier coating are being evaluated to return the components durability to acceptable levels as well as providing a means of lowering heat rejection. This paper discusses the use of a finite element model to analyze these thermal barrier coating systems, including the impact of material properties, coating thickness, residual stress and boundary conditions.*

*These coatings consist of a transition from the metallic bond layer to cermet and from cermet to the ceramic layer. Thermal analyses were employed to deposit metallic, cermet and ceramic powders such as NiCrAl, NiCrAl+MgZrO3 and MgZrO3 on the substrate. The numerical results of AlSi and steel pistons are compared with each other. It was shown that the maximum surface temperature of the functional graded coating AlSi alloy and steel pistons was increased by 28% and 17%, respectively. In this study, thermal behavior of functional graded coatings on AlSi and steel piston materials was investigated by means of using a commercial code, namely ANSYS*

***Key Words***: *Zirconia, Mullite, Alumina, Thermal efficiency, Electron Beam Physical Vapour Deposition*

**List of Symbols**

| Symbol | Description | Unit |
|---|---|---|
| **Nomenclature** | | |
| H | Heat transfer coefficient | W/m2/K |
| ρ | density | Kg/m3 |
| A | Area | $mm^2$ |
| $P_m$ | Indicated Mean Effective Pressure, | $N/mm^2$ |
| D | Diameter of bore | m |
| P | Thermal expansion | $° C^{-1}$ |
| N | Speed | rpm |
| N | Number of strokes | Strokes/min |
| Cp | Specific heat capacity | J/Kg/K |
| Tc | Temperature at center of the piston | ° C |
| Te | Temperature at edge of the piston | ° C |
| K | Thermal conductivity | W/m/K |
| **Abbreviation** | | |
| HCV | Higher calorific value | KJ/Kg |
| BP | Brake power | KW |
| TBC | Thermal barrier coating | |
| EBPVD | Electron beam physical vapor deposition | |

## I. Introduction

The demand for energy is increasing day by day. The world is depending mostly on fossil fuels to face this energy needs. The increase in standard of living demands better mode of transport, hence a large number of automobile companies has been introduced. Automobiles provide better transport but the combustion of fuel in automobile engine creates harmful effluents, which has an adverse effect on water and air.Combustion generated pollution is by far the largest man made contribution to atmospheric pollution. The principal pollutants emitted by the automobile engines are CO, $NO_X$, HC and particulates. The modern day automobiles is a result of several technological improvements that have happened over the years and would continue to do so to meet the performance demands of Exhaust-Gas Emissions, Fuel Consumption, Power Output, Convenience and Safety.In order to reduce emissions and increasing engine performance, modern car engines carefully designed to control the amount of fuel they burn. An effective way for reducing automotive emission and increase engine's performance is accomplished by coating automobile piston head with low thermal conductivity material such as ceramic. This process is known as Thermal Barrier Coating (TBC).

ANSYS is general-purpose finite element analysis (FEA) software package. Finite Element Analysis is a numerical method of deconstructing a complex system into very small pieces (of user-designated size) called elements. The software implements equations that govern the behaviour of these elements and solves them all; creating a comprehensive explanation of how the system acts as a whole. These results then can be presented in tabulated or graphical forms. This type of analysis is typically used for the design and optimization of a system far too complex to analyze by hand. Systems that may fit into this category are too complex due to their geometry, scale, or governing equations.ANSYS is the standard FEA teaching tool within the Mechanical Engineering Department at many colleges. ANSYS is also used in Civil and Electrical Engineering, as well as the Physics and Chemistry departments. ANSYS provides a cost-effective way to explore the performance of products or processes in a virtual environment. This type of product development is termed virtual prototyping.

With virtual prototyping techniques, users can iterate various scenarios to optimize the product long before the manufacturing is started. This enables a reduction in the level of risk, and in the cost of ineffective designs. The multifaceted nature of ANSYS also provides a means to ensure that users are able to see the effect of a design on the whole behavior of the product, be it electromagnetic, thermal, mechanical etc.ANSYS is capable of both steady state and transient analysis of any solid with thermal boundary conditions. Steady-state thermal analyses calculate the effects of steady thermal loads on a system or component. Users often perform a steady-state analysis before doing a transient thermal analysis, to help establish initial conditions. A steady-state analysis also can be the last step of a transient thermal analysis; performed after all transient effects have diminished.

A steady-state thermal analysis may be either linear, with constant material properties; or nonlinear, with material properties that depend on temperature. The thermal properties of most material vary with temperature. This temperature dependency being appreciable, the analysis becomes nonlinear. Radiation boundary conditions also make the analysis nonlinear. Transient calculations are time dependent and ANSYS can both solve distributions as well as create video for time incremental displays of models. The ANSYS/Multiphysics, ANSYS/Mechanical, ANSYS/FLOTRAN, and ANSYS/Thermal products support steady-state thermal analysis. A steady-state thermal analysis calculates the effects of steady thermal loads on a system or component. Engineer/analysts often perform a steady-state analysis before doing a transient thermal analysis, to help establish initial conditions. A steady-state analysis also can be the last step of a transient thermal analysis, performed after all transient effects have diminished. You can use steady-state thermal analysis to determine temperatures, thermal gradients, heat flow rates, and heat fluxes in an object that are caused by thermal loads that do not vary over time. A steady-state thermal analysis may be either linear, with constant material properties; or nonlinear, with material properties that depend on temperature. The thermal properties of most material do vary with temperature, so the analysis usually is nonlinear. Including radiation effects also makes the analysis nonlinear.

## II. Literature Review

Ekrem Buyukkaya and Muhammed Cerit investigated the effects of ceramic coating over diesel engine piston using 3D finite element method; they found that maximum surface temperature of the coated piston with material which has low thermal conductivity is improved approximately 48% for the AlSi alloy and 35% for the steel.[1]. EkremBuyukkaya, Department of Mechanical Engineering, Esentepe Campus, Turkey.. Thermal analysis of functionally graded coating AlSi alloy and steel pistons... Thermal analyses were employed to deposit metallic, cermet and ceramic powders such as NiCrAl, NiCrAl+MgZrO3 and MgZrO3 on the substrate. The numerical results of AlSi and steel pistons are compared with each other. It was shown that the maximum surface temperature of the functional graded coating AlSi alloy and steel pistons was increased by 28% and 17%, respectively. [2]. Imdat Taymazinvestigated the effect of thermal barrier coatings on diesel engine performance his results indicate a reduction in fuel consumption and an improvement in the efficiency of the diesel engine.[3]. P. M. Pierz investigated the thermal barrier coating development for diesel engine aluminum piston he found that the resulting predicted temperatures and stresses on the piston, together with material strength information, the primary cause of coating failure is proposed to be low cycle fatigue resulting from localized yielding when the coating is hot and in compression.[4]. O. Altun ,Mechanical Engineering Department , Turkey., Investigated in Problems for determining the thermal conductivity of TBCs by laser-flash method., Laser-flash method is the most widely used experimental technique to determine the thermal conductivity of APS TBCs at high temperatures. The research contributes to better understanding and recognition the importance of sample preparation in laser-flash method.[5]

S. C. Mishra., Laser and Plasma Technology Department, Mumbai, India. Investigated in Microstructure, Adhesion, and Erosion Wear of Plasma Sprayed Alumina–Titanium Composite Coatings.. Adhesion strength value of the coating varies with operating power. The trend of erosion of the coatings seems to follow the mechanism predicted for brittle materials. Coating deposited at 18kW power level shows a higher erosion rate than that of the sample deposited at 11kW power level [6]. H.W. Grunling and W. Mannsmann, ABB Kraftwerrke AG, KallstadterStz 1, 6800 Mannheim 31, Germany., investigated in Plasma sprayed thermal barrier coatings for industrial gas turbines: morphology, processing and properties. The properties of thermal barrier coating systems depend strongly on the structure and phase composition of the coating layers and the morphology of and the adhesion at the ceramic-metal interface. They have to be controlled by the process itself, the process parameters and the characteristics of the applied materials. [7]. A. J. Slifka, National Institute of Standards and Technology, Boulder. Thermal-Conductivity Apparatus for Steady-State, Comparative Measurement of Ceramic Coatings, and an apparatus has been developed to measure the thermal conductivity of ceramic coatings. Since the method uses an infrared microscope for temperature measurement, coatings as thin as 20 _m can, in principle, be measured using this technique. This steady-state, comparative measurement method uses the known thermal conductivity of the substrate material as the reference material for heat-flow measurement.[8]. Dongming Zhu Ohio Aerospace Institute, Cleveland, Ohio. Effect of Layer-Graded Bond Coats on Edge Stress Concentration and Oxidation Behavior of Thermal Barrier Coatings.. A low thermal expansion and layer-graded bond coat system, that consists of plasma-sprayed FeCoNiCrAI and FeCrA1Y coatings and a high velocity oxy fuel (HVOF) sprayed FeCrAIY coating, was developed for minimizing the thermal stresses and providing excellent oxidation resistance.[9]. S. Alphine’, M. Derrien, Thermal Barrier Coatings: the Thermal Conductivity challenge. In this paper, the importance of the challenge associated with the control of the thermal conduct why of thermal barrier coatings for turbine engines hot stages is being reviewed. It is firstly illustrated by the description of a practical aeronautic coated and uncoated turbine blade design exercise. The various contributions to TBC thermal conductivity are then reviewed. [10].

## III. Thermal Barrier Coating

Thermal barrier coatings are highly advanced material systems applied to metallic surfaces, such as gas turbine aero-engine and diesel engine parts, operating at elevated temperatures. These coatings serve to insulate metallic components from large and prolonged heat loads by utilizing thermally insulating materials which can sustain an appreciable temperature difference between the load bearing alloys and the coating surface. In doing so, these coatings can allow for higher operating temperatures while limiting the thermal exposure of structural components, extending part life by reducing oxidation and thermal fatigue. In fact, in conjunction with active film cooling, Thermal barrier coatings permit flame temperatures higher than the melting point of the metal airfoil in some turbine applications.Modern Thermal barrier coatings are required to not only limit heat transfer through the coating but to also protect engine components from oxidation and hot corrosion. No single coating composition appears able to satisfy these multifunctional requirements. As a result, a “coating system” has evolved. Research in the last 20 years has led to a preferred coating system consisting of three separate layers such as metal substrate, bond coat and ceramic coating to achieve long term effectiveness in the high temperature, oxidative and corrosive use environment for which they are intended to function.

The application of Thermal barrier coatings on the diesel engine piston head reduces the heat loss to the engine cooling-jacket through the surfaces exposed to the heat transfer such as cylinder head, liner, piston crown and piston rings. It is important to calculate the piston temperature distribution in order to control the thermal stresses and deformations within acceptable levels. The temperature distribution enables the designer to optimize the thermal aspects of the piston design at lower cost, before the first prototype is constructed. As much as 60% of the total engine mechanical power lost is generated by piston ring assembly. Most of the internal combustion (IC) engine pistons are made of aluminum alloy which has a thermal expansion coefficient 80% higher than the cylinder bore material made of cast iron. This leads to some differences between running and the design clearances. Therefore, analysis of the piston thermal behavior is extremely crucial in designing more efficient engines. The thermal analysis of piston is important from different point of views. First, the highest temperature of any point on piston should not exceed 66% of the melting point temperature of the alloy. This limiting temperature for the current engine piston alloy is about 370°C. This temperature level can be increased in ceramic coating diesel engines.

Thermal barrier coatings consist of three layers. They are the metal substrate, metallic bond coat and ceramic topcoat. The metal substrate and metallic bond coat are metal layers and the topcoat is the ceramic layer. The metal substrate is typically a high temperature aluminium alloy that is either in single crystal or polycrystalline form. The metallic bond coat is an alloy typically with the composition of Nickel, Cobalt, Chromium, Aluminium. The bond coat creates a bond between the ceramic coat and substrate. The third coat is the ceramic topcoat, Zirconia ($ZrO_3$), Mullite($3Al_2O_3$-$2SiO_2$), Alumina ($Al_2O_3$) which is desirable for having very low conductivity while remaining stable at nominal operating temperatures typically seen in applications. This layer creates the largest thermal gradient of the thermal barrier coating. In industry, thermal barrier coatings are produced in a number of ways.

- Electron Beam Physical Vapor Deposition (EBPVD)
- Air Plasma Spray (APS)
- Electrostatic Spray Assisted Vapour Deposition (ESAVD)
- Direct Vapor Deposition

Diesel engine piston made of Aluminium Alloy is taken for this study and ceramic material having low thermal conductivity is preferred as the coating material on the piston head or crown.

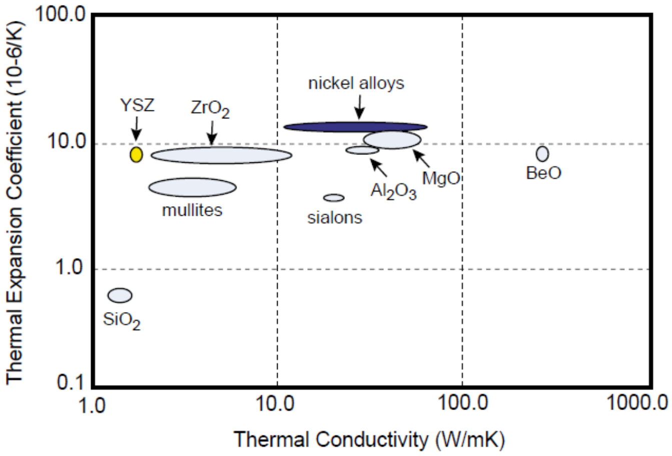

Fig.1. Materials for thermal barrier coating

The ceramic material choosen for this study should have low thermal conductivity and thermal expansion as shown in the above graph. The selected materials are as follows,

- Zirconia ($ZrO_2$)
- Mullite ($3Al_2O_3$-$2SiO_2$)
- Alumina ($Al_2O_3$)

## IV. Electron Beam Physical Vapor Deposition

EB-PVD is an evaporation process for applying ceramic thermal barrier coatings to gas turbine engine parts .It has been the favored deposition process technique for TBCs because of the increased durability of coating that is produced when compared to other deposition processes. EB-PVD TB exhibits a columnar microstructure that provides outstanding resistance against thermal shocks and mechanical strains. Figure presents a diagram of the coating chamber where the EB-PVD process takes place.The EB-PVD process takes place in a vacuum chamber consisting of a vacuum-pumping system, horizontal manipulator, a water-cooled crucible containing a ceramic ingot to be evaporated, an electron-beam gun, and the work piece being coated. The electron beam gun produces electrons, which directly impinge on the top surface on the ceramic coating, located in the crucible, and bring the surface to a temperature high enough that vapor steam is produced. The vapor steam produces a vapor cloud, which condenses on the substrate and thus forms a coating. The substrate is held in the middle of vapor cloud by a horizontal manipulator that allows for height variation in the chamber. During the coating process, oxygen or other gases may be bled into the vapor cloud in order to promote a stoichiometric reaction of ceramic material. An .over source.heater or an electron beam gun may be used for substrate heating, which keeps the substrate at a desired temperature.

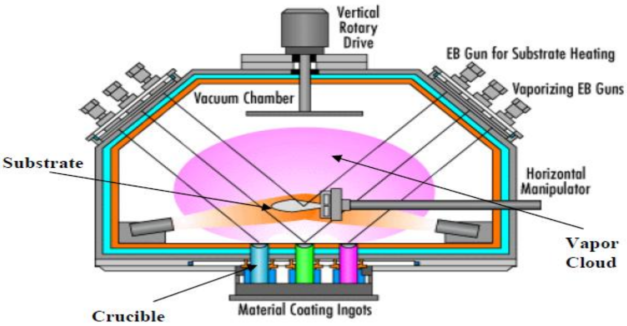

Figure 2. EB-PVD Coating Chamber

In our six stroke engine we are placing thermal barrier component in between the cylinder block and cylinder liner. The heat is transferred from the combustion chamber to the cylinder block through the cylinder liner and thermal barrier. The heat flow rate through the thermal barrier is low. Materials of thermal barrier are discussed in the forthcoming chapters.

## V. Simulation

In this project work, ANSYS workbench 10 software has been used to investigate the temperature distribution in the ceramic coated Aluminium alloy piston and to compare the maximum surface temperature of the uncoated Aluminium alloy piston with ceramic coated Aluminium alloy piston, ceramic materials such as Zirconia stabilized with magnesium oxide, Mullite and Alumina were used for this study

In the numerical simulation performed, a diesel engine piston, made of Al alloy is analyzed. 3-D finite element thermal analyses are carried out on both uncoated and ceramic coated pistons. In the model, surface-to-surface contact elements are defined between piston ring and ring grove. Piston thermal boundary conditions consist of the ring land and skirt thermal boundary condition, underside thermal boundary condition, combustion side thermal boundary condition. Convective heat transfer coefficients and ambience temperatures were specified as the thermal boundary conditions.

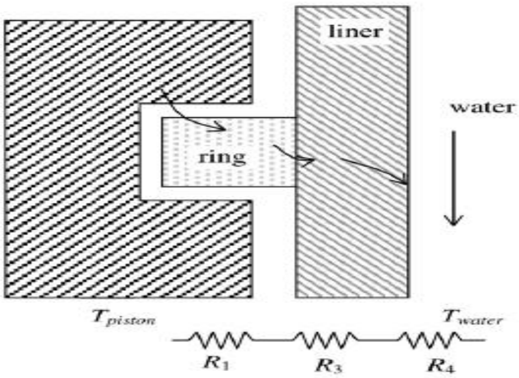

Fig 3. Thermal circuit of heat transfer resistances in the region of the rings.

$R_1$: Conductive resistance of the ring,
$R_2$: Conductive resistance of the oil film is negligible,
$R_3$: Conductive resistance of the liner,
$R_4$: Convective resistance between the liner and the cooling water.

Thermal circuit of heat transfer resistances in the ring land is to be set with the following assumptions.

1) The effect of piston motion on the heat transfer is neglected.
2) The rings and skirt are fully engulfed in oil and there are no cavitations.
3) The rings do not twist.
4) The heat transfer mode in the oil film is neglected.

Table .1.Thermal properties of parts

| Material | Thermal conductivityW/m$^0$C |
|---|---|
| Piston (Al-Si) | 155 |
| Oil Ring | 33 |
| Compression Ring | 52 |
| Liner | 55 |

The resistances are:
Conductive resistance of the ring, $R_1=(\ln(r_1/r_2)/2\pi L_1K_{ring})$ = 0.085048 $m^2k/kw$
Conductive resistance of the film, $R_2=(\ln(r_3/r_2)/2\pi L_2K_{oil})$ = $8x10^{-5}$ $m^2k/kw$
Conductive resistance of the liner, $R_3=(\ln(r_4/r_3)/2\pi L_3K_{block})$ = 0.06417 $m^2k/kw$
Conductive resistance between the liner and cooling water, $R_4$ = $1/ (h_{water}A_s)$ =0.171 $m^2k/kw$
Total resistance $R_{tot}$=0.32 $m^2k/kw$
The effective heat transfer is obtained from, $h_{eff}=1/R_{tot}xA_{eff}$ = 617.68 $w/m^2k$
The value of convective heat transfer coefficient of crown underside is, $h_{un1}=900(N/4600)^{0.35}$ =672.415 $w/m^2k$
The value of convective heat transfer coefficient of piston skirt underside, $hun2=240(N/4600)^{0.35}$ =179.31 $w/m^2k$
The Crevice heat transfer coefficient, h=k/S =230 $w/m^2k$

Table 2.Coating Materials

| Properties | Aluminium-Silicon Alloy | Zirconia stabilized with Magnesium oxide ($ZrMgO_3$) | Mullite ($3Al_2O_3$•$2SiO_2$) | Alumina ($Al_2O_3$) |
|---|---|---|---|---|
| Density kg/m³ | 2.68 x10³ | 5.6 x10³ | 2.8 x10³ | 3.69 x10³ |
| Thermal expansion (20 ºC) ºC⁻¹ | $19.4x10^{-6}$ | $10x10^{-6}$ | $5.4x10^{-6}$ | $7.3x10^{-6}$ |
| Specific heat capacity J/(kg*K) | 850 | 400 | 950 | 880 |
| Thermal conductivity W/(m*K) | 154 | 2.5 | 6 | 18 |

Initial Conditions
Piston top surface temperature : 400$^0$C
Piston skirt temperature : 110$^0$C
Boundary Conditions
The Crevice convective heat transfer coefficient, h = 230 $w/m^2k$
The piston crown or head underside convective heat transfer coefficient,$h_{un1}$ = 672.415 $w/m^2k$
The piston skirt underside convective heat transfer coefficient, $h_{un2}$ = 179.31 $w/m^2k$

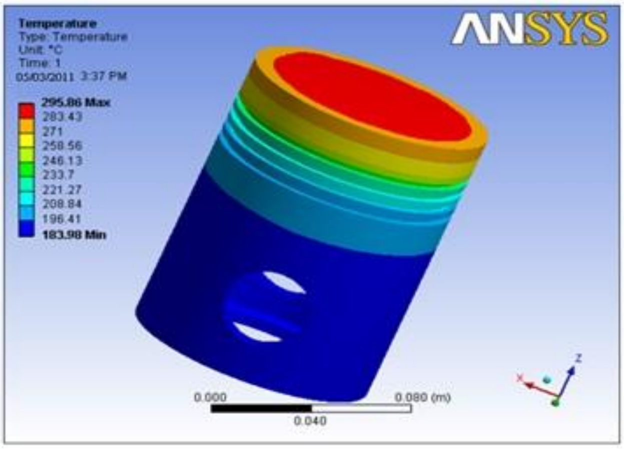

Fig .4 Uncoated Aluminium alloy piston

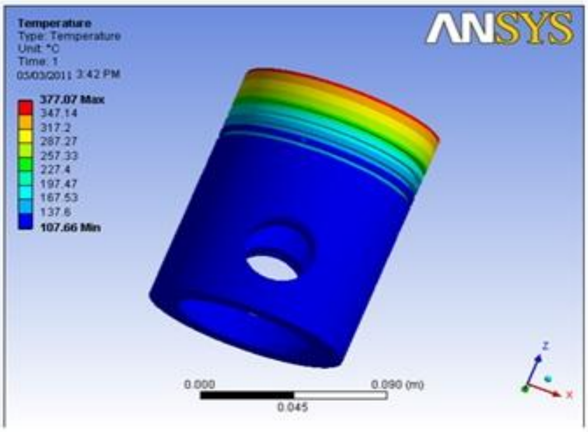

Fig 5.Ceramic material Zirconia coated piston

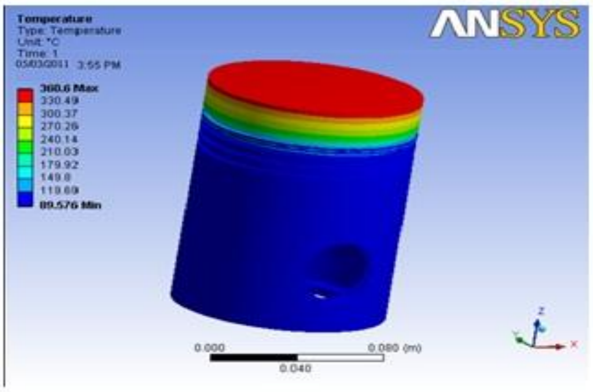

Fig .6 Ceramic materialMullite coated piston

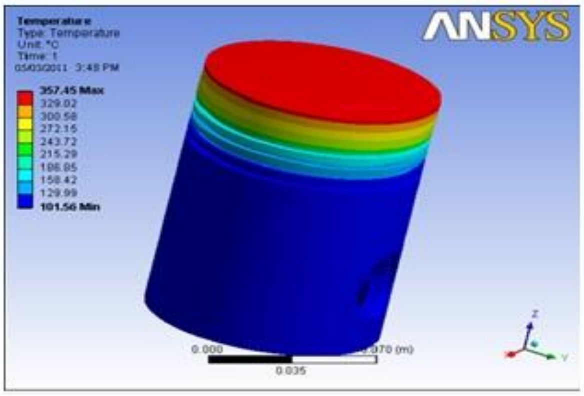

Fig 7. Ceramic material Alumina coated piston

## VI. Results and Discussion

Finite element analysis were performed to evaluate temperature gradients of the uncoated Aluminium alloy piston and ceramic materials such as partially stabilised zirconia with magnesium oxide ($ZrMgO_3$), Mullite and Alumina ($Al_2O_3$) coated Aluminium alloy piston. The temperature distributions of an uncoated aluminium alloy piston are shown in the figure 4. The maximum surface temperature on the piston crown of the Aluminium alloy piston is determined as 295.86$^0$C.The temperature distributions of the ceramic materials such as partially stabilised zirconia with magnesium oxide ($ZrMgO_3$), Mullite and Alumina ($Al_2O_3$) coated Aluminium alloy piston is shown in the figure 5, figure 6, figure7, respectively.The maximum surface temperature on the piston crown for Ziconia coated Aluminium alloy piston is determined as 377.07$^0$C, For Mullite Coating it is 360.6$^0$C and for Alumina coating it is 357.45$^0$C.

Fig.8 represents the temperature distribution comparison curve of uncoated Aluminium alloy piston with zirconia, Mullite and Alumina coated piston. It is clear that the maximum surface temperature of Zirconia coated piston (377.07$^0$C) is more than the conventional Aluminium alloy piston (295.86$^0$C).and the maximum surface temperature of Mullite coated piston (360.6$^0$C) is more than the conventional Aluminium alloy piston (295.86$^0$C) and the maximum surface temperature of Alumina coated piston (377.07$^0$C) is more than the conventional Aluminium alloy piston (295.86$^0$C).From the graphical representation the ceramic material partially stabilized Zirconia gives more performance to the diesel engine taken for this study.

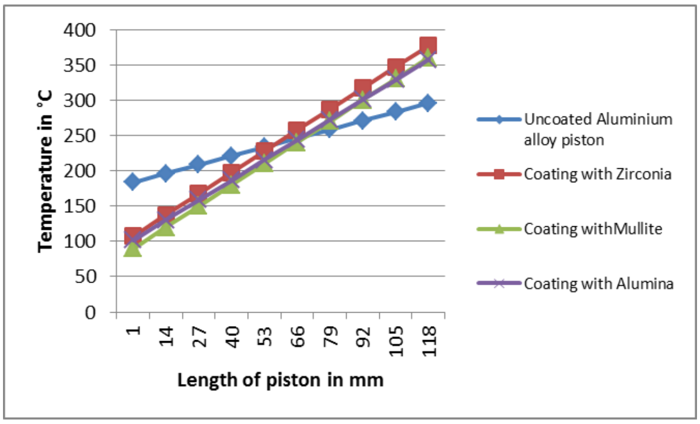

Fig. 8.Comparisons of coated Aluminium alloy piston with uncoated Aluminium alloy piston

## VII. Conclusion

A comparative evaluation was made between the temperature distributions of the uncoated aluminium alloy piston and the ceramic coated piston. The maximum surface temperature of the ceramic coated piston is improved approximately 28% for Zirconia stabilised with magnesium oxide ($ZrMgO_3$) coating, 22% for Mullite coating ($3Al_2O_3$-$2SiO_2$) and 21% for Alumina ($Al_2O_3$) than the uncoated piston by means of ceramic coating. According to the software simulations conducted in this project, it has been concluded that the using of ceramic coating for Aluminium alloy piston increases the temperature of the combustion chamber of the engine and the thermal strength of the base metal.Finally the combustion chamber temperature increases the thermal efficiency of the engine also increases.

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