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Analysis of Piston with Thermal Barrier Coating Using Finite Elements

Harish Ravat[1], Pushpak Sheth[2]

[1]Department of Mechanical Engineering, Assistant Professor, Government Engineering College, Godhra
[2]Department of Mechanical Engineering, Assistant Professor, L .D. College of Engineering, Ahmedabad.

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ABSTRACT

The piston serves the purpose of converting the gas pressure generated by the combustion gases into reciprocating motion, hence facilitating the transfer of kinetic energy. Throughout this procedure, the piston crown experiences a continual array of thermal and structural stresses, including but not limited to gas pressure load, side thrust, connecting rod load, and inertia load. The consequence of overheating is the seizing of the piston, as well as the development of cracks on the top land, which eventually has a negative impact on the efficiency of the engine. In order to mitigate heat absorption and enhance insulation capabilities, it is important to implement measures. The application of thermal barrier coating is performed on the upper surface of the land. The piston is modelled using SolidWorks software. In this study, an analysis is conducted on a piston composed of aluminium alloy, comparing its performance with and without the application of thermal barrier coating materials such as Magnesium zirconate, Lanthanum doped zirconate, and Yttria stabilised zirconia. A comparative analysis is conducted on the behaviour of the piston using steady-state thermal analysis in ANSYS, with a focus on structural aspects, in order to assess its performance relative to a traditional piston.

Keywords: *Thermal Barrier Coating, Structural Analysis, Steady State Thermal Analysis*

I. INTRODUCTION

The piston of an internal combustion engine is the reciprocating component responsible for transmitting the force created by the combustion of the air-fuel combination. The phenomenon takes place by the application of significant force to the piston, which is generated by the expansion of combustion gases. In a traditional internal combustion engine, a properly proportioned combination of air and fuel is introduced into the cylinder as the piston moves towards the bottom dead centre during the intake stroke. During the compression stage, the air-fuel mixture undergoes compression to significantly elevated levels of temperature and pressure. Towards the end of the stroke, the charge is ignited, leading to the combustion of the charge. This combustion process causes the expansion of combustion gases, which in turn exerts force on the piston, propelling it downwards at a considerable velocity. The piston subsequently transfers this energy to the piston pin, connecting rod, and crankshaft. The piston is subject to many thermal forces, inertia force, combustion gas pressure, connecting rod load, and side thrust, which mostly exert their effects on the top land or crown of the piston.

During this operation, the majority of the thermal energy generated is absorbed by the piston. In order to mitigate the risk of piston failure,

including fractures on the crown and piston seizure resulting from overheating, the implementation of a thermal barrier coating on the surface of the piston is employed. The thermal barrier coating functions as an insulating layer that serves as a barrier to impede the transmission of heat into the piston. The materials utilised for coating have a low thermal conductivity and a high coefficient of thermal expansion, enabling them to maintain their structural integrity and phase stability even at extreme temperatures. The study demonstrates that a significant proportion of heat, namely 30%, is dissipated through the engine cooling system. A potential effective remedy for this issue might involve the implementation of an engine thermal barrier layer. Thermal barrier coatings possess insulating qualities that contribute to the enhancement of fuel economy. This is achieved by mitigating the effects of elevated temperatures in the surrounding area, resulting from the combustion of fuel. Consequently, the improved thermal management leads to increased engine efficiency. The use of thermal barrier coatings has been shown to effectively mitigate hydrocarbon emissions by reducing the production of smoke and carbon monoxide. Another study has demonstrated that there is a positive correlation between temperature and the thermal efficiency of an engine. The implementation of this measure will lead to a decrease in heat dissipation from the piston due to the combustion of unburned gases.
According to reports, the application of thermal barrier coating is said to alter the pre-existing conditions for fuel combustion, leading to a reduction in ignition delay time and a decrease in fuel consumption.

II. REALATED WORK

OBJECTIVE: The objective of this project is to increase the insulating property of piston by coating various types of TBC material on piston crown namely La1.7Dy0.3Zr2O7, MgZrO3 and Yttria stabilized zirconia (YSZ) and perform comparative study by varying thickness of coating. By performing static structural analysis and Steady state thermal analysis in ANSYS most effective thermal barrier coating material is identified.

PROBLEM IDENTIFICATION:

• In the internal combustion engine, piston subjected to fatigue load, gas pressure load and side thrust.

· Engine cooling system carries away 30 percentage of heat which is direct loss.

·Overheating of piston result ultimately piston seizure

·Un-burnt fuel mixture cause reduction in engine efficiency

LITERATURE REVIEW

[1] Thermal barrier coating on IC Engine Piston to enhance better utilization of heat produced inside the combustion chamber ultimately improving engine’s efficiency
Year of publication: 2017
Author: Mohsin Attar, Prof.Mr. Ajay Bhongade
Observation: This research is aimed to improve efficiency of engine with utilizing Yttria stabilized zirconia as thermal barrier coating material. This research considered 150 cc engine piston and compared with yttria stabilized zirconia coating with various thickness on top land of piston. This research suggested that using YSZ coating of 0.6mm reduces heat flux and temperature on crown of piston.

[2] Analysis on a thermal barrier coated (TBC) piston in a single cylinder diesel engine powered by Jatropha biodiesel–diesel blends
Author: Harish Venu, Prabhu Appavu
Year of publication: 2019
Observation: This research work aimed to improve diesel efficiency operated with Jatropha bio diesel blends using Yttria stabilized zirconia coating (YSZ). Yttria stabilized zirconia of 200 micro meter thick layer is coated by plasma spray technique at temperature 8300℃ on piston operated on JB20(20% jatropha biodiesel and 80% diesel fuel). This research indicates in improving combustion characteristics and lowering Hydro carbon, carbon dioxide emissions.

[3] Design and static thermal analysis of piston using thermal barrier coating materials using fem
Author: Mr. Vatti Sairam Krishna, Mr.K. Muralidhar
Year of publication: 2021
Observation:
In this research thermal analysis is conducted on piston of 150cc engine of materials Al402, Ti64AlV coated with Thermal barrier coating materials, Mgzro3 ,Ni-Cr-Al of 0.4mm and suggested that Al-Sic piston coated Ni-Cr-Al Is efficient and suited for high temperature application.

[4]Design and Thermal Analysis of Ceramic Coated Diesel Engine Piston (Mgzro3 &Nicral)
Author:M.Mathanbabu,P.Mohanraj,S.Navaneetha, Krishnan ,T.Naveen Kumar ,S.Vijay
Year of publication: 2019

Observation: In this research Mahindra Scorpio Group M11B15-Piston is considered and piston material as Alsic and steel is assumed. Thermal analysis is conducted for uncoated piston and piston coated with thermal barrier coating materials MgZrO3 and NiCrAl as bond coat. This research compared results of analysis and suggested that piston coated with MgZrO3 has better insulating property.

[5] Static and Thermal Analysis of Aluminium Alloy Piston with Ceramic Coating

Author: G.Venkata Srinivasa Rao, CH.Venkateswara Rao, T.N.Charyulu, Sk.Nakki Jani, N.Ch.Sai Prathap

Year of publication:2019

Observation: In this research paper piston is designed in catia v5 and the model is then imported to ansys and in ansys geometric model is converted into FEA model and apply boundary conditions to find the stress, temperature distribution and heat flux and piston is coated with two thermal barrier coatings those are ALSIC(aluminium silicon) and NICRAL(nickel chromium aluminium).They concluded that based on their analysis aluminium silicon carbide has more temperature resistance and less amount of heat flux as compared with aluminium alloys.

[6] Design and thermal analysis of ceramic coated aluminium alloy piston

Author: T. G. Thiyagarajan, A. Velladurai

Year of publication: 2017

Observation: In this paper they mainly focus on determining the temperature distribution of a ceramic coated piston. In this research they used various materials to coat piston like mullite, yttrium stabilized zirconia(Y-PSZ), and Magnesium Stabilized Zirconia (Mg-PSZ) are used as ceramic coatings. Based on the analysis the uncoated piston has less performance has compared with the coated one. And they found that magnesium stabilized zirconia has similar properties of Yttrium stabilized zirconia which is best suitable for TBC material.

[7] Investigation on effect of Yttria Stabilized Zirconia coated piston crown on performance and emission characteristics of a diesel engine

Author: G. Sivakumar, S. Senthil Kumar

Year of publication: 2014

Observation: In this paper experimental investigation made on three-cylinder diesel engine with piston coated with Yittria stabilized zirconia and performance and emissive characteristics are studied. Based on study TBC material coated engine has improved Brake specific fuel consumption and hydrocarbon emission reduced up to 35.27% and carbon monoxide reduction up to 2.7%.

[8]Thermo-Mechanical Analysis of a Piston with Thermal Barrier Coatings (Tbc)

Author: Abhinav Lal, Mr. Morrish kumar

Year of publication: 2017

Observation: In this paper FEA analysis and thermal analysis is conducted on piston of Al-sic and Titanium material and coated with MgZrO3 and Yittria partially stabilized zirconia. This research suggest that Al-sic coated with MgZrO3 of 0.5 mm thickness retained its Temperature near to titanium piston.

[9]ThermalBehaviorand Optimization of Piston Coating Material (Al-Si) Used in Petrol Engine

Author: M. Sivanesan and C. Vinothkumar

Year of publication:2016

Observation: In this paper piston is with various amount of thickness from 0.2 to 1.6mm without considering bond
carbidecoating layers. In this research paper they are mainly focusing on thermal stress distribution of piston at real engine during combustion. They conduct thermal and structural analysis by coating with different materials like aluminium oxide, zirconium oxide and mullite. Finally, they concluded that aluminium oxide has higher efficiency as compared with other materials

3. PROPOSED WORK

DESIGN:

In this work we have considered royal Enfield 500cc engine which dimensions as bore B=84mm and stroke l=90mm, maximum power=27.184 bhp at 5250 rpm,maximum torque=41.3 Nm at 4000 rpm

DIMENSIONS OF ROYAL ENFIELD 500cc Engine Piston

Thickness of piston head	10.378 mm
Radial thickness of piston ring	2.59 mm
Axial thickness of piston ring	2.08 mm
No of piston rings	4
Width of top land	11.415 mm
Width of ring land	1.664 mm
Radial depth of piston ring groove	2.99 mm
Thickness of piston barrel at top end	10.01 mm
Piston pin diameter	25.2 mm
Diameter of piston boss	43.434 mm
Length of Skirt	50.4 mm
Total length of piston	75.126 mm
Thickness of piston barrel at open end	2.505 mm

Table : 1

MODELLING IN SOLID WORKS: In this project we have considered Royal Enfield 500cc engine piston of material Aluminium alloy and designed using Solid Works. Ceramic material of 0.3mm and 0.5mm thick layers are modeled.

Piston without Thermal barrier coating:

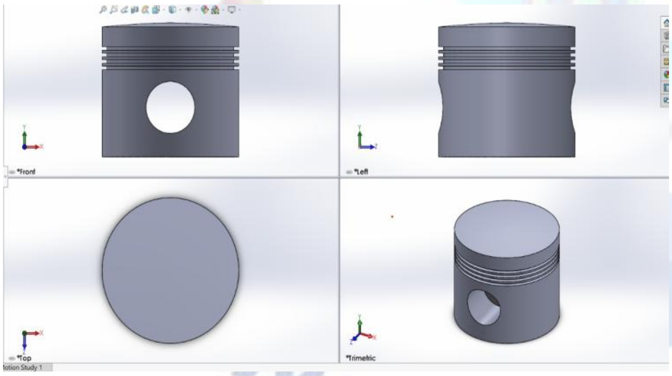
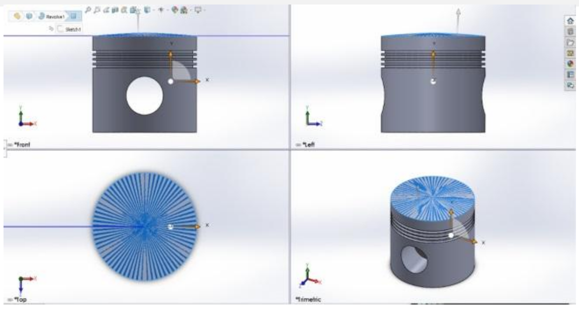


Figure: 1



Piston with Thermal barrier coating:

Figure:2

MATERIAL INFORMATION

Based on the properties and studying the literature review we are choosing three materials those are Magnesium zirconate (MgZrO3),lanthanum doped zirconate($La_{1.7}Dy_{0.3}Zr_2O_7$, Yttria Stabilized Zirconia(YSZ) and their compositions are tabulated below.

1.Aluminium alloy(Al6061)

Derived from	Young's modulus and Poisson's ratio
Young's modulus	70000MPa
Poisson's ratio	0.33
Bulk modulus	68627MPa
Shear modulus	26316MPa
Isotropic secant coefficient of thermal expansion	23.6 1/℃
Tensile ultimate strength	310MPa
Tensile yield strength	276MPa
Thermal	
Isotropic thermal conductivity	0.167 W/mm℃
Specific heat constant pressure	896mJ/kg℃
Density	2.7×10^{-6}kg/mm^3

Table: 2

2. Magnesium zirconate (MgZrO3)

structural	
Derived from	Young's modulus and Poisson's ratio
Young's modulus	46000MPa
Poisson's ratio	0.2
Bulk modulus	25556MPa
Shear modulus	19167MPa
Isotropic secant coefficient of thermal expansion	2.7×10^{-05} 1 /℃
Tensile ultimate strength	180MPa

Tensile yield strength	51MPa
Thermal	
Isotropic thermal conductivity	0.0008 W/mm°C
Specific heat constant pressure	1.04× 10^6mJ/kg°C
Density	5.6 × 10^{-6}kg/mm³

Table: 3

3.Lanthanum doped zirconate ($La_{1.7}Dy_{0.3}Zr_2O_7$)

structural	
Derived from	Young's modulus and Poisson's ratio
Young's modulus	1.75 × 10^5MPa
Poisson's ratio	0.28
Bulk modulus	1.3258×10^5MPa
Shear modulus	68359MPa
Isotropic secant coefficient of thermal expansion	1.035 ×10^{-05} 1 /°C
Thermal	
Isotropic thermal conductivity	0.000468 W/mm°C
Specific heat constant pressure	1.356 × 10^6mJ/kg°C
Density	5.6 × 10^{-6}kg/mm³

Table: 4

4.Yttria Stabilized Zirconia(YSZ)

structural	
Derived from	Young's modulus and Poisson's ratio
Young's modulus	2.1 × 10^5MPa
Poisson's ratio	0.3
Bulk modulus	1.75 ×10^5MPa
Shear modulus	80769MPa
Isotropic secant coefficient of thermal expansion	6.69 ×10^{-05} 1 /°C
Tensile ultimate strength	690MPa
Tensile yield strength	550MPa
Thermal	
Isotropic thermal conductivity	0.0022 W/mm°C
Density	6.02×-06 kg/mm³

Table: 5

ANALYSIS: The designed piston model from Solid works is imported to ANSYS work bench and steady state thermal analysis, static structural analysis carried out as,designed piston is imported in ansys and the materials are assigned for the piston and also for the coating on the piston crown. Meshing is done for the piston and tetrahedron elements are formed in meshing. Loads applied on the piston crown such as temperature and co efficient of convection film. Then the solver is made to run so that the solution can be obtained. Total heat flux and temperature is obtained. Static structural analysis carried out as,Upto meshing same procedure is followed. At static condition the loads were applied.Pressure at piston crown and the surfaces are considered to be non frictional contact. Analysis is carried to observe total deformation, stress and strain.

BOUNDARY CONDITIONS FOR PISTON:

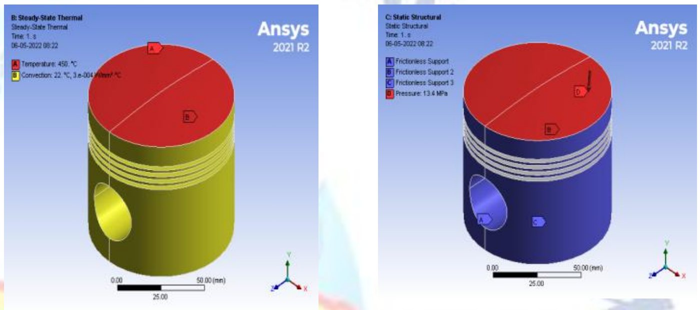
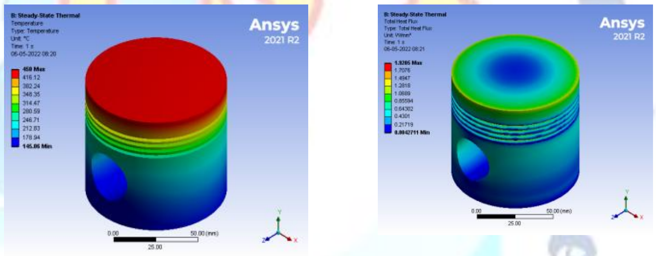


Fig: 3(a) **Fig: 3(b)**

STEADY STATE THERMAL ANALYSIS:

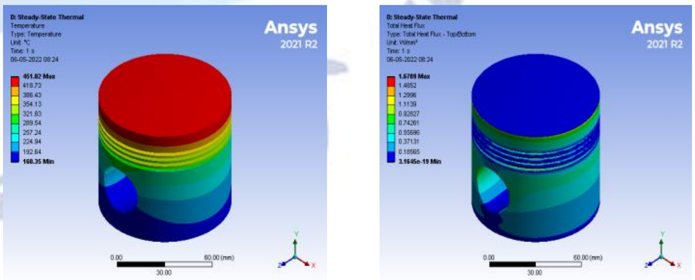
Material: Al6061 + without coating



(a) **(b)**

Fig: 4(a) Temperature Distribution, (b) Total Heat Flux

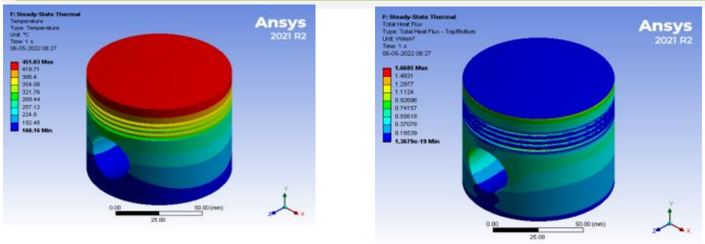
Material: Al6061 + with MgZrO3 of 0.5 mm thickness coating



(a) **(b)**

Fig: 5 (a) Temperature Distribution, (b) Total Heat Flux

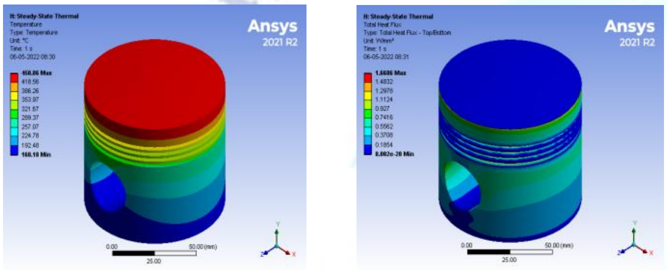
Material: Al6061 + with MgZrO3 of 0.3 mm thickness coating



(a) (b)

Fig: 6 (a) Temperature Distribution, (b) Total Heat Flux

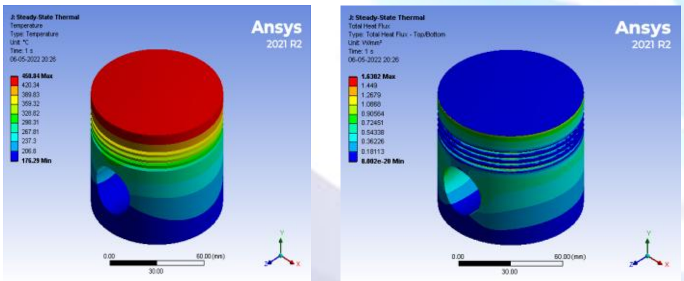
Material: Al6061 + with La1.7Dy0.3Zr2O7 coating of 0.5 mm thickness



(a) (b)

Fig: 7 (a) Temperature Distribution, (b) Total Heat Flux

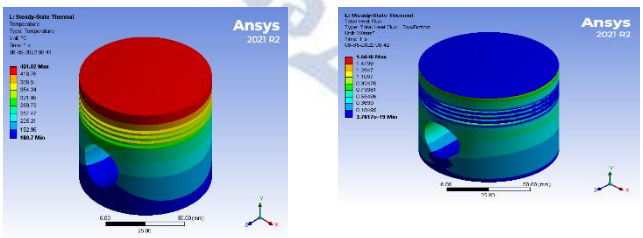
Material: Al6061 + with La1.7Dy0.3Zr2O7 coating of 0.3mm thickness



(a) (b)

Fig: 8 (a)Temperature Distribution, (b) Total Heat Flux

Material: Al6061 + with YSZcoating of 0.5 mm thickness

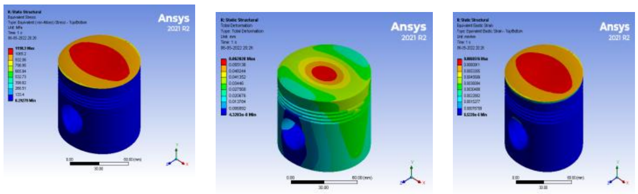


(a) (b)

Fig: 9(a) Temperature Distribution, (b) Total Heat Flux

(c)

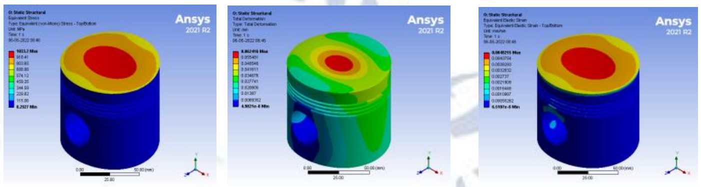
Material: Al6061 + with La1.7Dy0.3Zr2O7 coating of 0.3 mm thickness:



(a) (b) (c)

Fig: 10 (a) Equivalent Stress (b) Total Deformation (c) Equivalent Elastic Strain

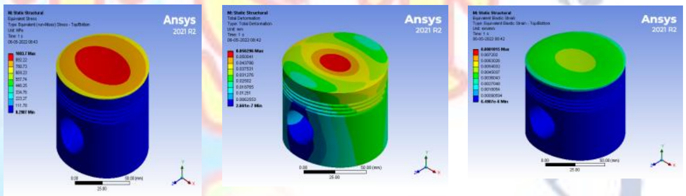
Material: Al6061 + with YSZcoating of 0.3 mm thickness



(a) (b) (c)

Fig: 11(a) Equivalent Stress (b) Total Deformation (c) Equivalent Elastic Strain

Material: Al6061 + with YSZcoating of 0.5 mm thickness



(a) (b) (c)

Fig: 12(a) Equivalent Stress (b) Total Deformation (c) Equivalent Elastic Strain

4. RESULTS

From the analysis of 0.3 mm and 0.5 mm thickness of Thermal barrier coating, results of Total heat flux, Temperature distribution and von-Misses stress and equivalent strain are obtained and values are listed below

Piston with 0.5 mm coating thickness

Material	Temperature℃		Heat flux W/mm²	
Al6061+TBC	Max	Min	Max	Min
Uncoated	450	145	1.920	0.00427
Mgzro3	450	160.5	1.6709	3.1645e-19
Ldz	450	160.18	1.6686	8.002e-20
Ysz	450	160.7	1.6646	3.1677e-19

Table: 6

Material	Total deformation mm		Equivalent elastic strain		Von-Mises stress MPa	
Al6061+TBC	max	min	max	min	max	min
Uncoated	0.072	3.195e-7	0.001705	9.2133e-6	119.28	0.26528
MgZrO3	0.064353	3.0196e-8	0.015207	6.551e-6	699	0.2909
LDZ	0.055378	2.87e-7	0.010532	6.519e-6	1174.9	0.2195
YSZ	0.056296	2.661e-7	0.0081015	6.498e-19	1003.6	0.2907

Table: 7

Piston with 0.3 mm coating thickness:

Material	Temperature °C		Heat flux W/mm²	
Al6061+TBC	Max	Min	Max	Min
Mgzro3	450	160.15	1.6685	1.367e-19
Ldz	450	176.29	1.6302	8.002e-20
Ysz	450	144.78	1.8546	6.571e-18

Table: 8

Material	Total deformation mm		Equivalent elastic strain		Von-Mises stress MPa	
Al6061+TBC	Max	Min	Max	Min	Max	Min
Mgzro3	0.068105	7.547e-7	0.015254	6.594e-6	701.27	0.29989
LDZ	0.06202	4.320e-8	0.0068516	6.522e-6	1198.2	0.29279
YSZ	0.062416	4.9281e-8	0.0049215	6.510e-6	1033.2	0.2927

Table: 9

5. CONCLUSION

Hence the results from analysis of Aluminum alloy piston coated with 0.5mm thickness of Yttria stabilized zirconia and Lanthanum doped zirconate has less heat flux compared with magnesium zirconate and heat flux decreases with increase in thickness of Thermal barrier coating. With decrease in heat flux results better utilization of heat therefore engine efficiency increases.From observing the Analysis results piston coated with TBC material is more efficient than uncoated piston.

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