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Thermal barrier coating on IC Engine Piston to enhance better utilization of heat produced inside the combustion chamber ultimately improving engine's efficiency

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Abstract -*Conventionally, the small portion of the total energy produced in internal combustion engine is converted to useful work. More than half of this energy is expelled from the system through frictional losses, cooling the engine components, exhaust, etc. The most effective way of increasing the percentage of useful work is to reduce the energy loss. One way of reducing the energy loss or increasing the efficiency of the engine is by using thermal barrier coatings (TBC) on the various elements of the combustion chamber like valves, piston, cylinder surfaces, and rings. This work presents the design and analysis of an IC engine piston coated with thermal barrier material (yttiria stabilized zirconia) so as to understand the performance of piston and study its heat resistant behavior in comparison with a non coated thermal barrier piston.*

Keywords: **Thermal barrier coating (TBC),Yttiria stabilized zirconia (YSZ).**

1. INTRODUCTION

Internal Combustion(IC) engine is a main part of Automobile design, whose efficiency and performance depends on the amount of heat produced due to combustion of the fuel in the engine. An IC Engine is that kind of prime mover that converts chemical energy to mechanical energy. The fuel on burning changes into gas which impinges on the piston and pushes it to cause reciprocating motion. The reciprocating motion of the piston is then converted into rotary motion of the crankshaft with the help of connecting rod. The purpose of IC engine is to transfer force from expanding gas in the cylinder to the crankshaft via a piston rod. Piston is subjected to the cyclic gas pressure and the inertial forces, causing fatigue damage, side wear, head cracks etc. Thus, it must possess good strength to resist gas pressure, minimum weight to reduce inertia, reciprocate with minimum noise, sufficient bearing area to prevent wear, disperse the heat generated during combustion and good resistance to distortion under heavy forces and heavy temperature. In most of existing piston some amount of heat is transferred through piston surface, which results in decrease in engine efficiency. This can be reduced to some extent by coating the piston with proper material. Thermal Barrier Coatings, as the name suggests are coatings which provide a barrier to the flow of heat. Thermal Barrier Coatings (TBC) performs the important function of insulating components such as gas turbine and aero engine parts operating at elevated temperatures.TBC are layer systems deposited on thermally highly loaded metallic components.

2. PISTON TERMINOLOGY:-

FIG-1: Piston terminology.

3. LITERATURE REVIEW:

The work on performance of TBC on various piston materials, as seen in the literature, is shown in table 1. They have shown simulated results using finite elements method based software as ANSYS, in majority. It can be seen that almost all studies are done on diesel engine and many of them done on piston material as aluminum alloys. The main material in composition of TBC are seen to be NiCrAl [1,2,3,5,9,11] and YSZ(Yttria stabilized zirconia) [1,5,7,8,10] followed by others which are mullite, alumina, zirconium etc. The major performance measures studied by various authors are temperature distribution, deformation, thermal stresses, fuel and brake thermal efficiency. The temperature distribution in piston is crucial parameter influencing the thermal stresses and deformation. The thermal insulation thus obtained is supposed to lead, to an improvement in the engine's heat efficiency and a reduction in fuel consumption. The thickness of coating applied ranges from 0.1to 0.8 mm.

Table-1. Literature review study

Ref no	TBC material	Piston material	Engine	Coating Thickness (mm)	Performance measuremenn
1	NiCrAl and ceramic based yttria partially stabilized zirconia	AC8A aluminum alloy CNG DI piston crown and normal CamPro piston crown.	CNG DI		Heat flux
2	Aluminum oxide (Al2O3) + Molybdenum (Mo) + Titanium oxide (TiO2) (40%+30%+30%), over a 150μm thickness of NiCrAl bond coat	Torodial piston	Ethanol blend diesel	0.3	Fuel and brake thermal efficiency
3	NiCrAl and MgZrO	AlSi and steel	5BHP kirloskar Diesel		
4	YSZ, Zirconia, Mullite, NiCrAl, MgZrO3	Aluminum alloy	TATA INDICA V2 diesel	1	Deformation
5	Zirconium	Aluminum alloy	diesel	0.1	Thermal efficiency
6	Yttrium Stabilized Zirconia (Y-PSZ) and Magnesium Stabilized Zirconia (Mg-PSZ)	Aluminum alloy	diesel	0.2 to 0.8	Temperature distribution and thermal stresses
7	Yttrium Stabilized Zirconia		TVS STAR CITY engine	0.4	Fuel and brake thermal efficiency
8	MgZrO3 + NiCrAl	AlSi alloy and cast alloy steel		0.35 + 0.15	Deformation with flat head and curved head piston
9	Zirconia stabilized with magnesium oxide, Mullite and Alumina	aluminum alloy			Temperature distribution
10	NiCrAl + $CaZrO_3$	Structural steel	Diesel engine	0.1 to 0.5	Temperature distribution

MODELING AND ANALYSIS:

In this work, a piston of two wheeler 150cc Honda Unicorn Engine is considered with specifications as: Engine type air cooled 4-stroke, Bore × Stroke (mm) = 57×58.6, Displacement = 149.5CC. Maximum Power = 13.8bhp at 8500rpm, Maximum Torque = 13.4Nm at 6000rpm, Compression Ratio = 9.35/1.Theoretical designing of piston was done using standard design procedure. The piston specifications are shown table 2.

DESIGNING OF PISTON:

Consider a 150cc engine

Engine type air cooled 4-stroke

Bore × Stroke (mm) = 57×58.6

Displacement = 149.5CC

Maximum Power = 13.8bhp at 8500rpm

Maximum Torque = 13.4Nm at 6000rpm

Compression Ratio = 9.35/1

Force and Pressure acting on piston:

Mechanical Efficiency, $\eta = \frac{B.P}{I.P}$

$I.P = \frac{B.P}{\eta}$

$B.P = \frac{2\pi NT}{60}$

$= \frac{2 \times \pi \times 6000 \times 13.4}{60}$

B.P = 8.420 KW

$I.P = \frac{8.420}{0.8}$

= 10.52 KW

$I.P = P \times A \times L \times \frac{N}{2}$

Where, P = Pressure acting on piston

A = Area of piston

L = Stroke length

N = No. of revolutions

$$10.52 \times 10^3 = P \times \frac{\pi}{4}(0.057)^2 \times 0.0586 \times \frac{6000}{2 \times 60}$$

$$P = 14.06 \times 10^5 \ N/m^2$$

Max pressure = 10 × P

= 10 × 14.06 × 10^5

= 14.06 MPa

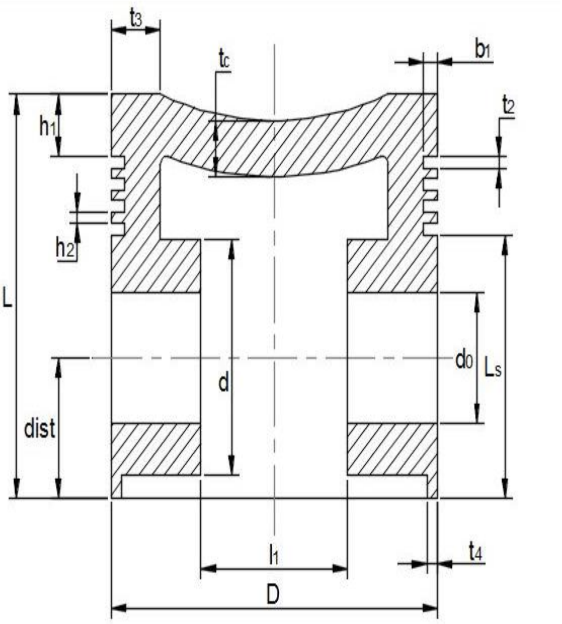
Force on piston

$$F = \frac{\pi}{4} D^2 \times P_{max}$$

$$= \frac{\pi}{4} \times 57^2 \times 14.06$$

= 35882.37 N

Design parameters of Piston:



L = Total length of piston

D=Bore diameter

t_c = Thickness of piston head

t_2 = Axial thickness of piston ring

h_1 = Width of top land

h_2 = Width of ring land

b_1 = Radial depth of piston ring groove

t_3 = Maximum thickness of piston barrel at top end

t_4 = Thickness of piston barrel at open end

d_0 = Outer diameter of piston pin

d = Diameter of piston boss

l_1 = Length of piston pin in the connecting rod bushing

L_s = Length of skirt

Assuming piston material as Aluminum Alloy Steel

σ_t = (160 to 100) N/mm²

Take, σ_t = 160 N/mm²

Acc to Grashoff's formula

Thickness of piston head

$$t_c = D\sqrt{\frac{3 \times P_{max}}{16 \times \sigma_t}}$$

$$= 57\sqrt{\frac{3 \times 14.06}{16 \times 160}}$$

= 7.31 mm

Design of piston ring:

Radial thickness of piston ring,

$$t_1 = D\sqrt{\frac{3 \times P_w}{\sigma_p}}$$

Where, P_w = Allowable radial pressure on cylinder wall

σ_p = Permissible tensile strength

Assume, P_w = 0.025 MPa

σ_p = 110 N/mm²

$$t_1 = 57\sqrt{\frac{3 \times 0.035}{110}}$$

= 1.76 mm

Take, t_1 = 2 mm

Axial Thickness

t_2 = (0.7 to 1) t_1

Take, $t_2 = 0.8\, t_1$

= 0.8 × 2

= 1.6 mm

No of piston rings

$$t_2 = \frac{D}{10 \times n}$$

$$1.6 = \frac{57}{10 \times n}$$

n = 3.56

Take n = 4

Width of top land

$$h_1 = (1 \text{ to } 1.2)\, t_c$$
$$= 1.1\, t_c$$
$$= 1.1 \times 7.31$$
$$= 8.04 \text{ mm}$$

Width of ring land

$$h_2 = (0.75 \text{ to } 1)\, t_2$$
$$= 0.8\, t_2$$
$$= 0.8 \times 1.6$$
$$= 1.28 \text{ mm}$$

Radial depth of piston ring groove

$$b_1 = 0.4 + t_1$$
$$= 0.4 + 2$$
$$= 2.4 \text{ mm}$$

Maximum thickness of piston barrel at top end

$$t_3 = 0.03D + b + 4.5$$
$$= 0.03 \times 57 + 2.4 + 4.5$$
$$= 8.61 \text{ mm}$$

Thickness of piston barrel at open end

$$t_4 = (0.25 \text{ to } 0.35)\, t_1$$
$$= 0.25\, t_1$$
$$= 0.25 \times 7.31$$
$$= 1.827 \text{ mm}$$

Piston pin dia.

$$d_i = 0.03D$$
$$= 0.3 \times 57$$
$$= 17.1 \text{ mm}$$

Outer diameter of piston pin

$$F = P_b \times d_0 \times l_1$$

Where, P_b = bearing pressure in bush at small end of connecting rod

Assume, P_b = 30Mpa

$l_1 = (2 \text{ to } 2.5)\, d_0$

Take, $l_1 = 2.5\, d_0$

$$F = P_b \times d_0 \times 2.5 d_0$$

$$d_o = \sqrt{\frac{F}{2.5 \times P_b}}$$

$$d_o = \sqrt{\frac{35882.37}{2.5 \times 30}}$$

$$d_o = 21.87 \text{ mm}$$

Diameter of piston boss

$$d = 1.4 \times d_o$$
$$= 1.4 \times 21.87$$
$$= 30.62 \text{ mm}$$

Length of piston pin in the connecting rod bushing

$$l_1 = 45\% \text{ of the piston diameter}$$
$$= 0.45 \times 57$$
$$= 25.65 \text{ mm}$$

Length of skirt

$$L_s = (0.6 \text{ to } 1.1)\, D$$
$$= 0.6 \times 57$$
$$= 34.2 \text{ mm}$$

The center of the piston pin should be 0.02 D to 0.04D above the centre of the skirt.

Total length of piston

$$L = \text{Top land} + \text{ring section} + \text{skirt length}$$
$$= h_1 + 4t_2 + 3h_2 + L_s$$
$$= 8.04 + 4 \times 1.6 + 3 \times 1.28 + 34.2$$
$$= 52.48 \text{ mm}$$

Table-2: Piston parameters

Thickness of piston head	7.31 mm
Radial thickness of piston ring	2 mm
Axial thickness of piston ring	1.6 mm
No of piston rings	4
Width of top land	8.04 mm
Width of ring land	1.28 mm
Radial depth of piston ring groove	2.4 mm
Thickness of piston barrel at top end	8.61 mm
Thickness of piston barrel at open end	1.827 mm
Piston pin dia.	17.1 mm
Diameter of piston boss	30.62 mm
Length of Skirt	34.2 mm
Total length of piston	52.48 mm

The piston specifications are shown in table 2.Considering the above design parameters the piston was then accordingly designed on SOLIDWORKS 2015

Based on literature review the 3 best suited materials seen was;YSZ (Yttria stabilized zirconia), zirconates and alumina.

The properties of these materials is shown in table 3.

Table-3: Shortlisted materials.

Materials	Coefficient of Thermal Expansion (1/k)	Melting Temperature (k)	Modulus of Elasticity (GPa)	Thermal conductivity (W/m k)
Zirconates	15.3×10^{-6}	2973	21	2.17
YSZ(Yttiria stabilized zirconia)	10.7×10^{-6}	2973	40	2.12
Alumina	9.6×10^{-6}	2323	30	5.8

ANALYSIS:

Considering the above properties of materials as well as studying the literature review, it was found out that the best suited material to carry out the project work is YSZ (Yttria stabilized zirconia).The designed piston is then analysed using ANSYS 15.1 with and without TBC coating (coating of YSZ material).Varied thickness of coating material is applied on the piston crown. The piston is subjected to operating condition of 600ºC temp on top surface of piston crown, convection along remaining surface with film coefficient of 0.0002w/mm²ºC and ambient temperatue of 29ºC.

RESULTS OBTAINED FROM ANALYSIS IS SHOWN IN FOLLOWING FIGURES

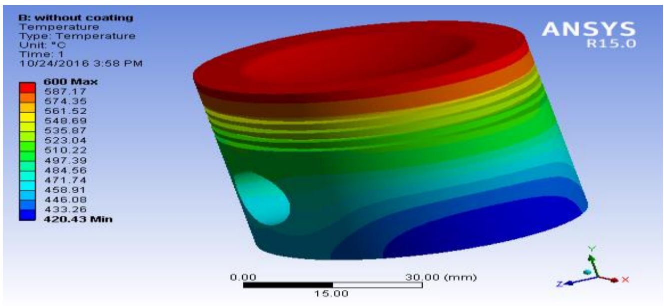


FIG 2: Temperature distribution of uncoated piston

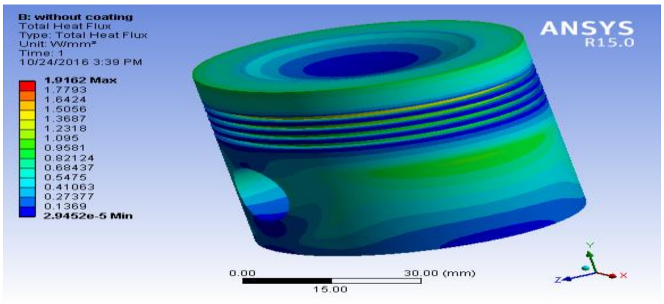


FIG 3: Heat flux distribution of uncoated piston

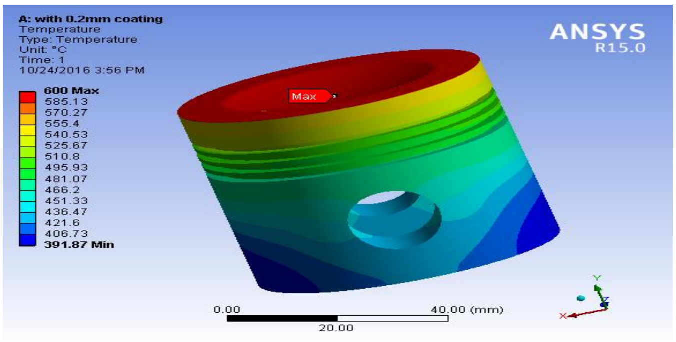


FIG 4: Temperature distribution of 0.2mm YSZ coated piston

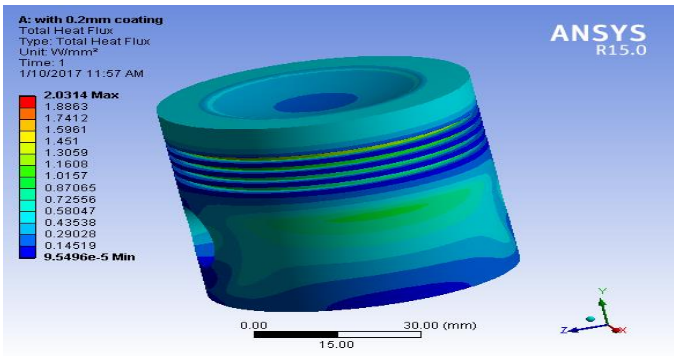


FIG 5: Heat flux distribution of 0.2mm YSZ coated piston

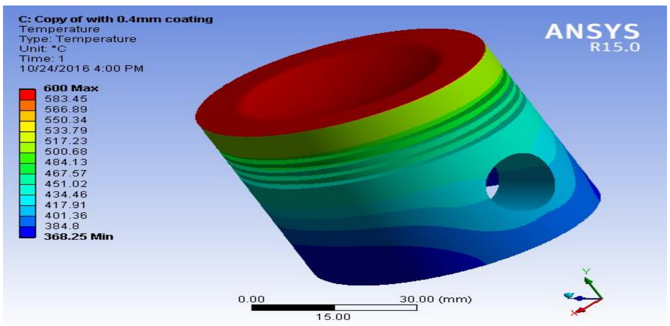


FIG 6: Temperature distribution of 0.4mm YSZ coated piston

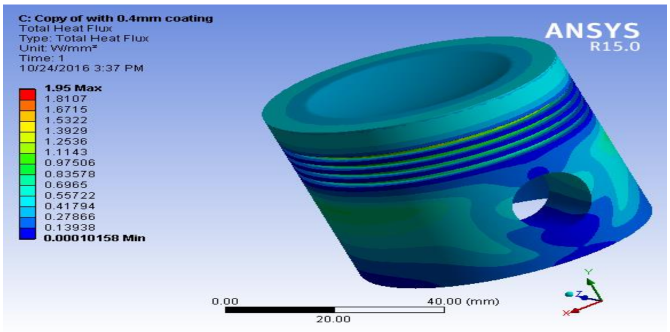


FIG 7: Heat flux distribution of 0.4mm YSZ coated piston

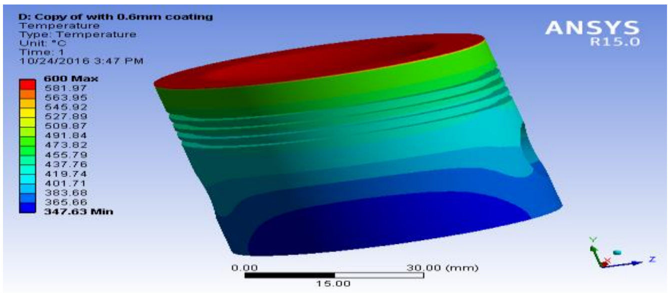


FIG 8: Temperature distribution of 0.6 mm YSZ coated piston

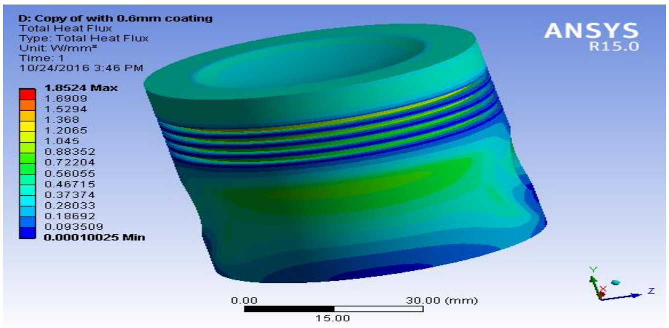


FIG 9: Heat flux distribution of 0.6mm YSZ coated piston

TABLE 4: Analytical results

Piston Geometry	Heat flux at top land (W/mm^2)	Temperature at top land (ºC)
Uncoated piston	0.95	600
Piston 0.2mm coating	0.74	560
Piston 0.4mm coating	0.65	500
Piston 0.6mm	0.467	473

THEORETICAL CALCULATION:

From Fourier's law of heat conduction,

$$Q = -K \times A \times \frac{dt}{dx}$$

Q = Heat flow through a body per unit time in watts.

A = Surface area of heat flow (perpendicular to the direction of heat flow) in m^2.

dt = Temperature difference of the faces of block (Homogeneous solid) of thickness 'dx' through which heat flows in k.

dx = thickness of body in the direction of flow in m.

k = thermal conductivity of TBC YSZ = 2.12

$$Q = 2.12 \times \frac{\pi}{4} \times d^2 \times \frac{dt}{dx}$$

1) For thickness of 0.2 mm TBC coating

$$Q = 2.12 \times \frac{\pi}{4} \times 57^2 \times \frac{(600 - 560)}{0.2}$$

Q = 1081.946 W

Net flux, q = Q/A = 0.424 W/mm^2

2) For thickness of 0.4 mm TBC coating

$$Q = 2.12 \times \frac{\pi}{4} \times 57^2 \times \frac{(600 - 500)}{0.4}$$

Q = 1352.432 W

Net flux, q = Q/A = 0.53 W/mm^2

3) For thickness of 0.6 mm TBC coating

$$Q = 2.12 \times \frac{\pi}{4} \times 57^2 \times \frac{(600 - 473)}{0.6}$$

Q = 1145.06 W

Net flux, q = Q/A = 0.448 W/mm^2

TABLE 5: RESULTS COMPARISON

Piston Geometry	Heat flux at top land Theoretically	Heat flux at top land Analytically
Piston with 0.2mm coating thickness	0.424 W/mm^2	0.72 W/mm^2
Piston with 0.4mm Coating thickness	0.53 W/mm^2	0.65 W/mm^2
Piston with 0.6mm Coating thickness	0.448 W/mm^2	0.467 W/mm^2

CONCLUSION:

The results obtained for temperature and heat flux distribution of uncoated and coated piston shows that piston having YSZ coating on piston crown has less temperature and heat flux at top land.. It can be seen that piston with 0.6 mm YSZ coating shows least heat flux and temperature at top land,which means as the thickness increases the temperature and heat flux at the top land decreases.This indicates that the piston coated with thermal barrier materials shows a lot of heat resistant ability which can lead to better utilization of heat produced in the combustion chamber as heat dissipation will be lesser which ultimately can improve the engine efficiency as compared to a non coated piston

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