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Material Coating Optimization and Thermal Analysis of a Four Stroke Piston by Using Analytical and FEM

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ABSTRACT:

The constantly increasing fuel prizes one of the main development directions in the vehicle industry is to increase the combustion efficiency. My goal is to decrease the specific fuel consumption but to keep the same performance. This paper deals with the steady state thermal analysis is of diesel engine piston coated with ceramic coating. Temperature distribution on the piston's top surface and substrate surface is investigated by using finite element based software called Ansys and compare with analytical approach with Matlab. Yttria-stabilized Zirconia is used as ceramic coating applied on Al–Si piston crown. The 2 thickness of ceramic top coating is about 0.1mm and for NiCr Al bond coat it is taken to be 0.2mm to 1.6mm of material Al_2O_3. Temperature distribution is investigated. The distributions of temperature and deformation for the coated and uncoated piston crown are compared. The most efficient existing method consists in application of thermal insulation coatings on the work surfaces of the piston, in particular, the formation of an oxidized layer on the piston crown. In order find out how efficient the suggested method is, we have carried out theoretical calculations and comparative Analysis on oxidized pistons is studied. The major part of the energy released on combustion transferred to its environment by thermal radiation instead of power train.

In order to decrease the thermal waste in future vehicles we need to use other materials such as ceramic. This has great attributes of today's commonly used aluminum alloys, but in addition bad heat transfer ability.

1. INTRODUCTION:

1.1 PISTON:

A piston is a component of reciprocating engines, reciprocating pumps, gas compressors and pneumatic cylinders, among other similar mechanisms. It is the moving component that is contained by a cylinder and is made gas-tight by piston rings. In an engine, its purpose is to transfer force from expanding gas in the cylinder to the crankshaft via a piston rod and/or connecting rod. In a pump, the function is reversed and force is transferred from the crankshaft to the piston for the purpose of compressing or ejecting the fluid in the cylinder. In some engines, the piston also acts as a valve by covering and uncovering ports in the cylinder wall. The petrol enters inside the cylinder and the piston moves upwards and the spark plug produces spark and the petrol is set on fire and it produces an energy that pushes the piston downwards.

1.2 HISTORY

OTTO CYCLE

Nikolaus August Otto as a young man was a traveling salesman for a grocery concern.

In his travels he encountered the internal combustion engine built in Paris by Belgian expatriate Jean Joseph Etienne Lenoir. In 1860, Lenoir successfully created a double-acting engine that ran on illuminating gas at 4% efficiency. The 18 liter Lenoir Engine produced only 2 horsepower. The Lenoir engine ran on illuminating gas made from coal, which had been developed in Paris by Philip Lebon. In testing a replica of the Lenoir engine in 1861 Otto became aware of the effects of compression on the fuel charge. In 1862, Otto attempted to produce an engine to improve on the poor efficiency and reliability of the Lenoir engine. He tried to create an engine that would compress the fuel mixture prior to ignition, but failed as that engine would run no more than a few minutes prior to its destruction. Many other engineers were trying to solve the problem, with no success.

1.3 THERMODYNAMIC ANALYSIS:

The thermodynamic analysis of the actual four-stroke or two-stroke cycles is not a simple task. However, the analysis can be simplified significantly if air standard assumptions are utilized. The resulting cycle, which closely resembles the actual operating conditions, is the Otto cycle. During the normal operation of the engine as the fuel mixture is being compressed an electric arc is created to ignite the fuel. At low rpm this occurs close to TDC (Top Dead Centre). As engine rpm rises the spark point is moved earlier in the cycle so that the fuel charge can be ignited while it is still being compressed. We can see this advantage reflected in the various Otto engines designs. The atmospheric (non-compression) engine operated at 12% efficiency. The compressed charge engine had an operating efficiency of 30%.

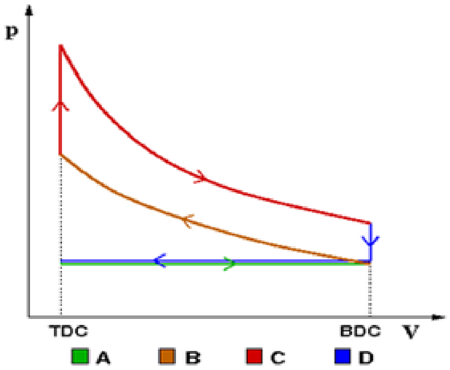

Fig 1.1 : Four-stroke Otto cycle P-V diagram

The idealized four-stroke Otto cycle P-V diagram: The intake (A) stroke is performed by an isobaric expansion, followed by the compression (B) stroke , performed by an adiabatic compression. Through the combustion of fuel an isochoric process is produced, followed by an adiabatic expansion, characterizing the power (c) stroke. The cycle is closed by an isochoric process and an isobaric compression, characterizing the exhaust (D) stroke.

1.4 DESIGN AND ENGINEERING PRINCIPLES POWER OUTPUT LIMITATIONS

The maximum amount of power generated by an engine is determined by the maximum amount of air ingested. The amount of power generated by a piston engine is related to its size (cylinder volume), whether it is a two-stroke engine or four-stroke design, volumetric efficiency, losses, air-to-fuel ratio, the calorific value of the fuel, oxygen content of the air and speed (RPM). The speed is ultimately limited by material strength and lubrication. Valves, pistons and connecting rods suffer severe acceleration forces. At high engine speed, physical breakage and piston ring flutter can occur, resulting in power loss or even engine destruction. Piston ring flutter occurs when the rings oscillate vertically within the piston grooves they reside in. Ring flutter compromises the seal between the ring and the cylinder wall, which causes a loss of cylinder pressure and power. If an engine spins too quickly, valve springs cannot act quickly enough to close the valves.

This is commonly referred to as 'valve float', and it can result in piston to valve contact, severely damaging the engine. At high speeds the lubrication of piston cylinder wall interface tends to break down. This limits the piston speed for industrial engines to about 10 m/s.

INTAKE/EXHAUST PORT FLOW:

The output power of an engine is dependent on the ability of intake (air–fuel mixture) and exhaust matter to move quickly through valve ports, typically located in the cylinder head. To increase an engine's output power, irregularities in the intake and exhaust paths, such as casting flaws, can be removed, and, with the aid of an air flow bench, the radii of valve port turns and valve seat configuration can be modified to reduce resistance. This process is called porting, and it can be done by hand or with a CNC machine.

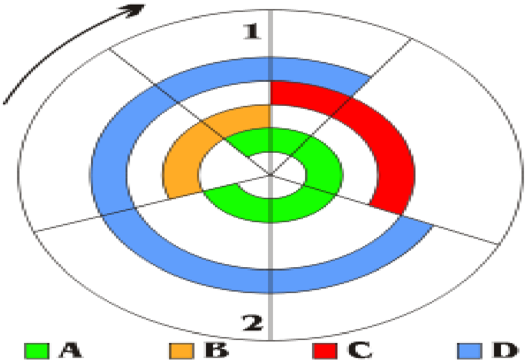

Fig 1.2 : Four-stroke cycle

The four-stroke cycle
1=TDC
2=BDC
A:Intake
B:Compression
C:Power
D: Exhaust

2.0 TYPES OF COATINGS:

- Metals
- Hot-dip galvanizing
- Metal spraying
- Electrochemical deposition
- Sherardizing
- Polymers
- Aerogels

2.1 Ceramics:

Ceramic materials:

- Zirconium dioxide – ZrO_2
- Alumina – Al_2O_3
- Chromia – Cr_2O_3

2.2 Alumina – Al_2O_3:

Aluminum oxide, often referred as alumina (Al_2O_3), is one of the most commonly applied ceramic materials in the coating industry. Among its properties of interest are its high hardness, chemical inertness, wear resistance and a melting point at 2072 °C. Its service temperature can be up to1650 °C. It can be alloyed with TiO_2 to increase its toughness, however simultaneously hardness is reduced. These properties allow its use in many applications. Alumina is utilized in heavy-duty forming tools, resistor cores in electronic industry, tiles for wear protection and ballistics, thread guides in textile engineering and even in protection tubes in thermal processes.

2.3 APPLICATIONS OF COMPOSITE MATERIALS:

1 – Overall Thermal Barrier protection
2 – Reduction in overall operating temperatures
3 – Increases component life by reducing friction and heat
4 – Perfect for High horsepower applications such as turbo's & superchargers
5 – Protection against galling and other damage on metal to metal contact
6 – Increases in performance
7 – Protection from stressful environments such as racing
8 – Protects Piston rings from Radial tension Loss
9 – Protection against hot spots by increasing flame propagation
10 – Helps to scavenge heat from the motor more quickly

2.4 Thermal Barrier Coating Material:

Thermal barrier coating defined as low thermal conductivity material coating which improves the piston's performance by decreasing the non-inflamed hydrocarbons and heat loses. Due to the low thermal conductivity of TBC, thermal barrier coating increases the temperature of the piston and makes the piston to operate or with stand at higher temperature.TBC does not need cooling as soon as metals due to their higher thermal durability. This project consist steady state thermal analysis of piston coated with 0.4 mm thick NiCrAl. NiCrAl can withstand at the temperature about1000 °C. NiCrAl is used in most cases due to its high performance at high temperature areas like gas turbines and diesel engines. The NiCrAl coating provides the more corrosion resistance than ZrO_2 coating . The materials properties are considered to be linearly elastic and isotropic. The Aluminum Alloy is taken as piston material. The bond coat of 0.1mm thickness is used between the top surface and the substrate surface to provide bonding and to reduce the stresses between them. Thermal properties of substrate, and top coat.

2.5 Mathematical Approach:

The temperature T(x, y, z, t) satisfies the periodic differential equation known as heat equation when it is used as a function of coordinate system parameters and time as,

$$k_x\frac{\partial^2 T}{\partial x^2} + k_y\frac{\partial^2 T}{\partial y^2} + k_z\frac{\partial^2 T}{\partial z^2} + Q = \rho c_p\frac{\partial T}{\partial t}$$

In which Q is define as` the source or sink rate of heat in a domain (W/m3), Cp is the volumetric specific heat (J/m3 C) and k is the thermal conductivity (W/m C). The essential boundary condition and natural boundary conditions at the boundary are define as

$$T(x, y, z, t) = T_1(x, y, z, t)$$

$$k_n\frac{\partial T}{\partial n} + q_p + h(T - T_\infty) + \sigma\varepsilon\left(T^4 - T_\infty^4\right)=0$$

In which kn is thermal conductivity normal to the surface, qp (x, y,z,t) is a prescribed flux(W/m2), his the heat transfer coefficient for convection(W/m2 C), σ is Stefan–Boltzmann constant(W/m2 C4), ε is the emissivity and ∞ T is the ambient temperature for convection and/or radiation. For a heat transfer analysis, initial condition must be specified other than the boundary conditions

$$T(x,\ y,\ z,\ 0) = T_{in}(x,\ y,\ z)$$

can be reduce by using the different techniques into the following form

$$CT + KT = F$$

Where K is the effective conductivity and F is the effective load, which becomes zero for steady state analysis. On the solving the system the temperature distribution in the domain is determined.

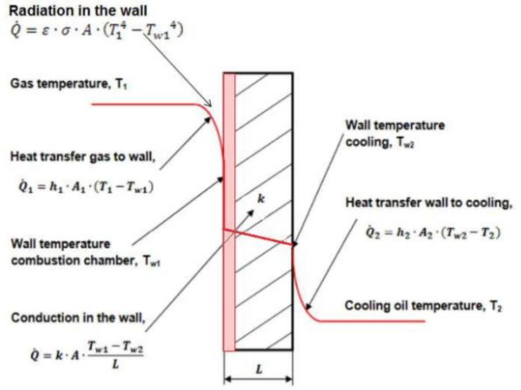

Fig 2.1 : Schematic heat transfer in the piston with insulation

Thermal Resistance Network Consider steady, one-dimensional heat flow through two plane walls in series which are exposed to convection on both sides, see Fig. 2.1 . Under steady state condition: rate of heat convection into the wall = rate of heat conduction through wall 1= rate of heat conduction through wall 2 = rate of heat convection from the wall

$$Q^\bullet = h_1 A\left(T_{\infty,1} - T_1\right) = k_1 A\frac{T_1 - T_2}{L_1} = k_2 A\frac{T_2 - T_3}{L_2} = h_2 A\left(T_2 - T_{\infty,2}\right)$$

$$Q^\bullet = \frac{T_{\infty,1} - T_1}{1/h_1 A} = \frac{T_1 - T_2}{L/k_1 A} = \frac{T_2 - T_3}{L/k_2 A} = \frac{T_2 - T_{\infty,2}}{1/h_2 A}$$

$$Q^\bullet = \frac{T_{\infty,1} - T_1}{R_{conv,1}} = \frac{T_1 - T_2}{R_{wall,1}} = \frac{T_2 - T_3}{R_{wall,2}} = \frac{T_3 - T_{\infty,2}}{R_{conv,2}}$$

$$Q^\bullet = \frac{T_{\infty,1} - T_{\infty,2}}{R_{total}}$$

$$R_{total} = R_{conv,1} + R_{wall,1} + R_{wall,2} + R_{conv,2}$$

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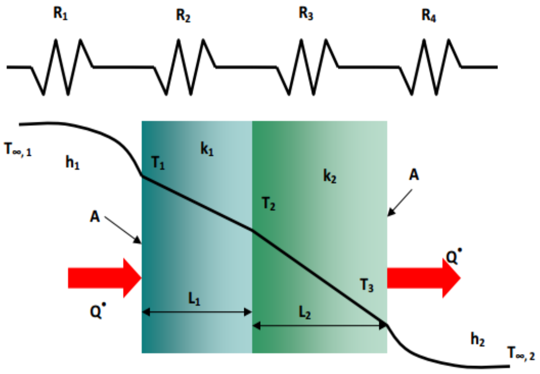
Note that A is constant area for a plane wall. Also note that the thermal resistances are in series and equivalent resistance is determined by simply adding thermal resistances.



The rate of heat transfer between two surfaces is equal to the temperature difference divided by the total thermal resistance between two surfaces.

It can be written:

$$\Delta T = \dot{Q} R$$

The thermal resistance concept is widely used in practice; however, its use is limited to systems through which the rate of heat transfer remains constant. It other words, to systems involving steady heat transfer with no heat generation.

3.0 RESULTS:

Specification of Piston are given below:

Engine type : MWM TBRHS 518-V16 direct injection, water cooled diesel engine.
Bore : 90.00 mm
Stroke : 120.00 mm
Compression ratio : 19:1
Power (at 1500 rpm) : 30 k/W
Power Capacity : 5 H.P
- Speed : 1440 R.P.M
- Atmospheric Pressure : 1.01325 bar
- Working Pressure : 20 bar

Material for Piston: Al–Si (Aluminum Alloy).
Bond coat : NiCrAl
Coating on Piston Top: Alumina – Al2O3

Table 3.1 : Properties of Materials

S.No.	Property	AL-Si	NiCrAl	AL2O3
1	Bulk Modulus	67GPa	170 GPa	210GPa
2	Density	2.0g/cm3	7.870 g/cm3	3.95g/cm3
3	Young's Modulus	69GPa	156 GPA	413 GPA
	Poissons ratio	0.2	0.27	0.33
4	Elongation at Break	9 – 25%	17%	NA
5	Electrical Conductivity	40-58% IACS	NA	NA
6	Fatigue Strength	55-97 Mpa	NA	NA
7	Hardness	25-95 MPA	382MPA	55-220 MPA
8	Shear Modulus	34GPa	58GPA	88-165GPA
9	Shear Strength	70-207MPa	NA	NA
10	Specific Heat Capacity	910 J/kg C	764 J/kg C	995 J/kg C
11	Ultimate Strength	310MPa	1350MPA	665MPA
12	Yield tensile strength	276 MPa	NA	488MPA
13	Thermal Conductivity	155 W/m-K	16.1 W/m-K	12.0 W/m-K
	Thermal coefficient	2.1E-5	1.20E-05	1.09E-08

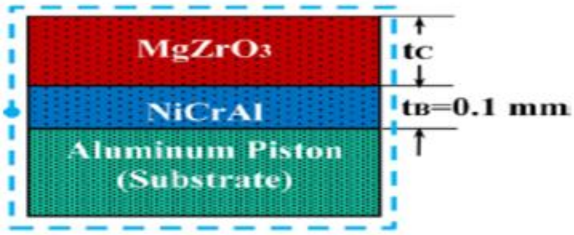


Fig 3.1 : COATING PARAMETERS OF PISTON

Coating Thickness:

tc : 0.2, 0.4, 0.6.... 1.6 mm

COATING PARAMETERS OF PISTON

PROCEDURE FOR PISTON DESIGN

Design of piston has been initiated by taking dimension of piston as

Diameter of bore = 90.0mm

Length of Piston = 120mm

Taking properties from TABLE I following piston parameters have been derived.

☐ ☐ Thickness of piston head Th)

☐ ☐ Heat flows through the piston head (H)

☐ ☐ Radial thickness of the ring (t1)

☐ ☐ Axial thickness of the ring (t2)

☐ ☐ Width of the top land (b1)

☐ ☐ Width of other ring lands (b2)

According to Grashoff's formula

$T_h = \sqrt{3PD2/16\sigma}$ in mm

Where

P = maximum pressure due to fuel in N/mm²

D = cylinder bore / outside dia of the piston in mm.

σ t = maximum allowable stress for the material of the piston.

Here the material is a particular grade of Al-Si alloy whose permissible stress is 50 Mpa-90Mpa. For calculation of thickness of piston head, the diameter of the piston is to be specified as 138mm.

The heat flow through the piston head is deliberated as

H = 12.56* Th* k * (tc – te)

Where

k = thermal conductivity of material which is 174.15W/mk

for Al-Si alloy

tc = temperature at center of piston head in °C.

te = temperature at edges of piston head in °C

Radial Thickness of Ring (t1)

$t_1 = D\sqrt{(3Pw/\sigma t)}$

Where D = cylinder bore in mm

Pw = pressure exerted by fuel on cylinder wall in N/mm².

Its value ranges from 0.025N/mm² to 0.042N/mm².

For Al-Si material here σt is considered as 90Mpa i.e. for maximum stress we are calculating design considerations.

Axial Thickness of Ring (t_2)

The thickness of the rings can be calculated as

$t_2 = 0.7t_1$ to t_1

Let assume $t_2 = t_1$

Width of the top land (b_1)

The width of the top land varies from

b1 = tH to 1.2*tH

i.e. b1=32.544

Width of other lands (b2)

Width of other ring lands varies from

b2 = 0.75t2 to t2

i.e. b2=2.7105mm

Maximum Thickness of Barrel (t3)

t3 = 0.03*D + b + 4.5 mm

Where b = Radial depth of piston ring groove

Here as per the calculated values these values are summarized as shown in Table 2.

Table 3.2 : Summarized values of piston

S.No.	SERIAL NUMBER DESIGN PARAMETERS	SIZE IN MM
1	Length of the Piston (L) 150	150
2	Cylinder Bore dia OR Outside diameter of piston (D)	138
3	Thickness of piston Head(Th)	32.544
4	Radial thickness of ring (t1)	2.78
5	Axial thickness of ring (t2)	1.946
6	Width of top land (b1)	39.0598
7	Width of other ring lands (b2)	1.4595

Model of piston using specification as per output from Matlab is model in CATIAV5:

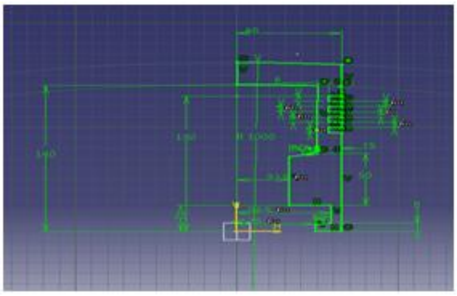


Fig 3.2. Profile of Cross Section of Piston modelled in CATIA V5 as per given data in Output Matlab

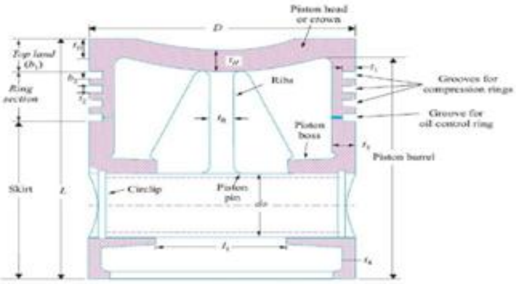


Fig 3.3 : Cross-section view with Representation with labels

Solid model of Impeller with four blades is model is given below and it if forward blade design as per specification given above reference.

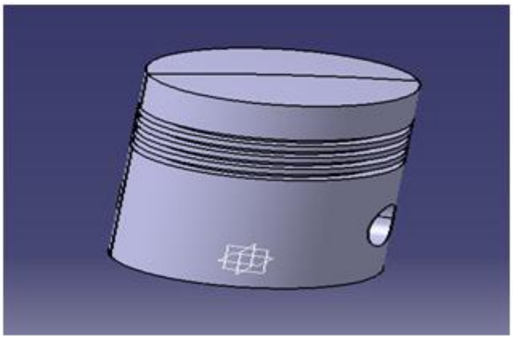


Fig 3.4 : Coating model of Piston:

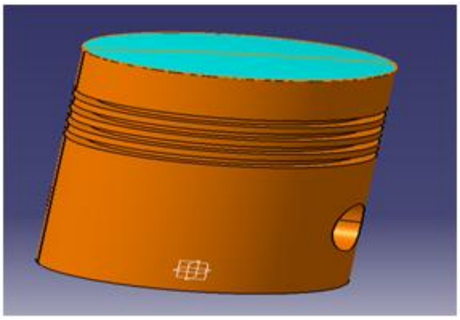


Fig 3.5 Thickness of ceramic top coating is about 0.4mm and for Al_2O_3 bond coat is taken to be 0.1mm NiCrAl

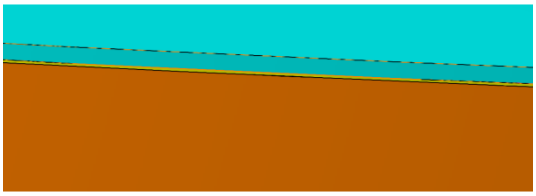


Fig 3.6 Thickness of ceramic top coating is about 0.4mm and for Al_2O_3 bond coat it is taken to be 0.1 NiCrAl

CASE 1: PISTON WITHOUT COATING

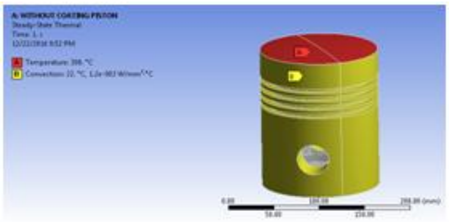


Fig 3.7 : LOAD AND BOUNDARY CONDITIONS FOR PISTON WITHOUT COATING

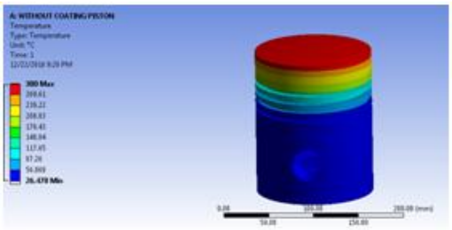


Fig 3.8 : HEAT FLOW THROUGH PISTON IS SHOWN FOR WITHOUT COATING

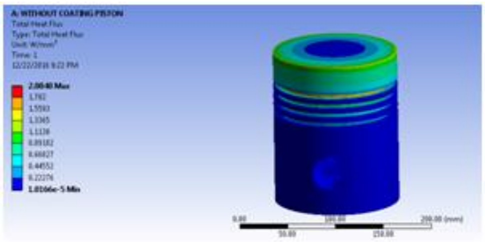


Fig 3.9 : HEAT FLUX FOR PISTON WITHOUT COATING

CASE 2: PISTON WITH COATING THICKNESS T=0.2 MM (Al_2O_3)

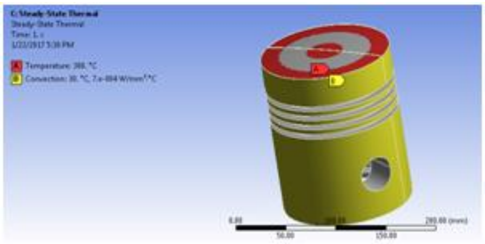


Fig 3.10 : LOAD AND BOUNDARY CONDITIONS FOR PISTON WITH COATING

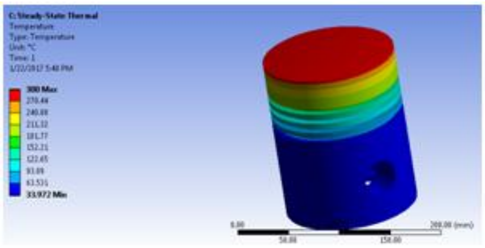


Fig 3.11 :HEAT FLOW THROUGH PISTON IS SHOWING WITH COATING TEMP VARIES FROM 33 TO 300 DEG

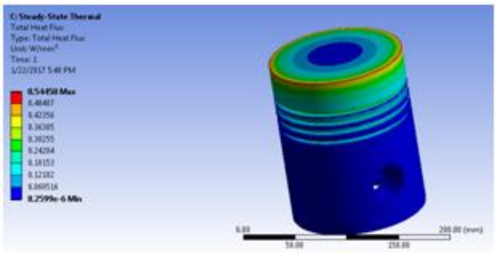


Fig 3.12 : HEAT FLUX FOR PISTON WITH COATING AND VARIES FROM 8.25E-6 TO 0.544 W/MM^2

CASE 3: PISTON WITH COATING THICKNESS T=0.4MM (AL2O3)

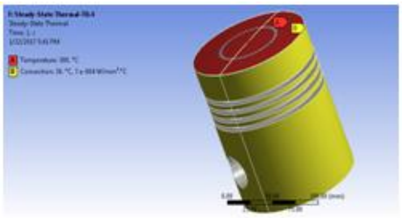


Fig 3.13 : LOAD AND BOUNDARY CONDITIONS FOR PISTON WITH COATING

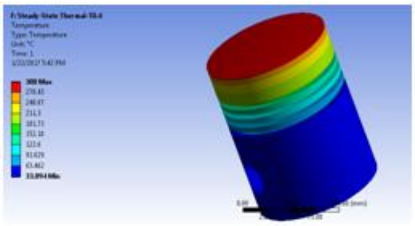


Fig 3.14 : HEAT FLOW THROUGH PISTON IS SHOWING WITH COATING TEMP VARIES FROM 33.89 TO 300 DEG

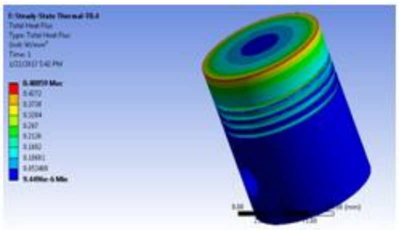


Fig 3.15 : HEAT FLUX FOR PISTON WITH COATING AND VARIES FROM 9.44E-6 TO 0.481 W/MM^2

CASE 4: PISTON WITH COATING THICKNESS T=0.8MM (AL2O3)

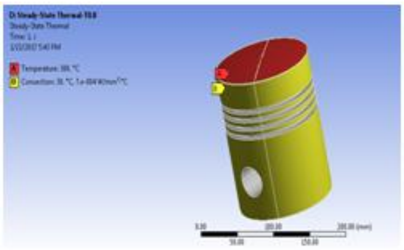


Fig 3.16 : LOAD AND BOUNDARY CONDITIONS FOR PISTON WITH COATING

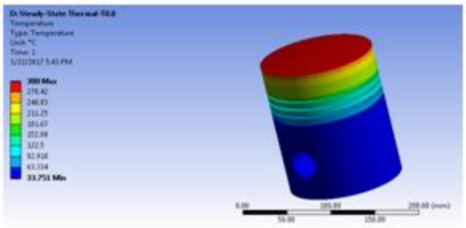


Fig 3.17 : HEAT FLOW THROUGH PISTON IS SHOWING WITH COATING TEMP VARIES FROM 33.75 TO 300 DEG

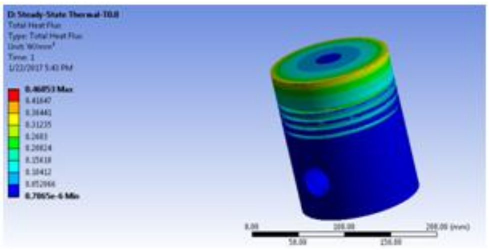


Fig 3.18 : HEAT FLUX FOR PISTON WITH COATING AND VARIES FROM 8.78E-6 TO 0.468 W/MM^2

Table 3.3 : Result table for heat flow and heat flux as per thickness

S.NO.	CASE STUDIES	HEAT FLOW(°C)	HEAT FLUX (W/MM2)
1	CASE 1 (PWOC)	26.47	2.01
2	T-0.2 (PWC)	33.97	0.544
3	T-0.4 (PWC)	33.89	0.481
4	T-0.8 (PWC)	33.71	0.468
5	T-1.2 (PWC)	33.62	0.471
6	T-1.6(PWC)	33.5	0.447

PWOC: Piston without Coating;
PWC: Piston with Coating

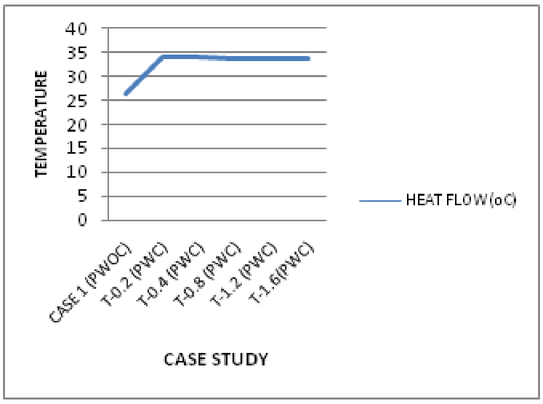


Fig 3.19 : Case Study Vs Heat Flow (°C)

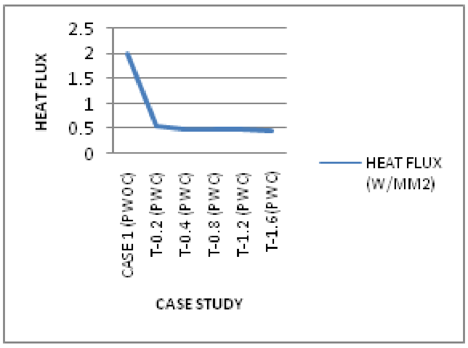


Fig 3.20 : Case Study Vs Heat Flux (W/Mm^2)

CONCLUSION:

The investigated heat insulating coating on the piston top reduces the heat flow from the working gas in the combustion chamber of the diesel engine in the surface of the piston. As a result a reduction of the maximum temperature of piston crown of 2-6°C, and of the piston skirt of 0–6°C is estimated. However, this does not result in significant changes in mechanical deformation of the piston skirt. It can be seen from the thermal analysis of piston of reciprocating Diesel engine that the stresses produced during the operations are less as compared to the design stress. The distribution of the temperature can be determined by this study. Average piston temperature beneath piston ring is about 1300C. Also we have described the general programme of piston in MATLAB so we can design any piston by entering the different parameters. So This study is also useful to reduce the time to design of piston.

The numerical simulations clearly show that temperature and thermal stress distribution are a function of coating thickness. For all the coating thicknesses, the highest temperature appeared at the top crown. The temperature at the surface of the coated region is significantly higher than that of the uncoated piston surface. Increase in the maximum temperature at the crown, compared with the uncoated piston, is 32.7%, 55.8%, 72.5% and 84.8% for 0.4 mm, 0.8 mm, 1.2 mm and 1.6 mm thick coating, respectively. It is clear that a higher combustion chamber temperature is provided by means of TBC. As a result, thermal efficiency of the engine increases. Moreover, reduction of the piston (substrate) surface temperature has a positive effect on engine performance. It is quite obvious that the maximum thermal heat flow is a function of coating thickness. Form result table it conclude that heat flux reduce and temperature flow is reduce. from images it is comes conclusion that heat flow reduce by forming layer.

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