

A Finite Element Analysis to Estimate the Temperature of Ceramic Coated Piston

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ABSTRACT: A piston works in variably complicated conditions, and is subjected to not only the gas pressure due to the combustion, but also due to thermal loads. Its behaviour is affected by the temperature variations causing for thermal stresses and thermal fatigue in working. The heat transfer reduces the performance of the engine which causes the reduction in efficiency. Also, piston experiences the high stresses in it. By applying a low thermal conductivity material on the piston crown, the heat transfer from combustion to piston crown reduces. In the present work, the thermal boundary conditions are obtained to calculate the temperature distribution in piston. The analysis is carried out to identify the maximum and minimum temperature location in piston. The modelling of piston is carried out in CATIA software whereas ANSYS workbench is used for the Finite Element Analysis.

KEYWORDS: Piston, Coating, FEM, Heat Transfer, Temperature Field, ANSYS

I. INTRODUCTION

A piston is a component of reciprocating engines, pumps and gas compressors. It is located in a cylinder and is made gas-tight by piston rings. Engine pistons are one of the most complex components among all automotive or other industry field components. The engine can be called the heart of an automobile and the piston may be considered the most important part of an engine. The pistons of the automobile are mostly made of cast iron, steel and aluminium alloy through the casting and forging. The main reason for applying these methods is to produce the components integrally and to reach high productivity with the lowest cost and optimized shape. The piston design is complicated because the engine is to work in variably complicated conditions. The piston is subjected to the varying pressure and temperature by the gases and inertia forces due to the acceleration/retardation in a cycle. Pistons are subjected to forces generated by hot burned gases on fuel combustion and in high temperature combustion chamber. These two causes result in thermal and mechanical stresses. Mechanical stresses appear due to gas force and thermal stresses due to high temperature of combustion; therefore, a piston must be capable of transmitting the kinetic energy of high gas pressure and temperature.

C.S. Wang et al. discussed a heat transfer model that used quasi-steady heat flux relations to calculate the heat transfer from combustion gases through cylinder wall to the coolant in an internal combustion engine to calculate the components temperature distribution [2]. T. Morel et al. showed the temperature and heat flow distribution analytically of an S.I. engine. An advanced engine simulation code was used to solve to engine performance and thermal boundary conditions in WOT condition [3]. Douglas M. Baker et al. discussed about a methodology for a coupled thermodynamic and heat transfer analysis for diesel engine with 1-D and 2-D heat flow finite element models to find the piston and liner temperatures and heat transfer rate [4]. Hidehiko Kajiwara et al. discussed the analytical approach for prediction of piston temperature with provides a piston cooling gallery using CFD tools [5].

Piston temperature distribution is important to find out the thermal stresses and its deformations during the design of a piston. The typical temperature distribution is given in Figure 1 [1].

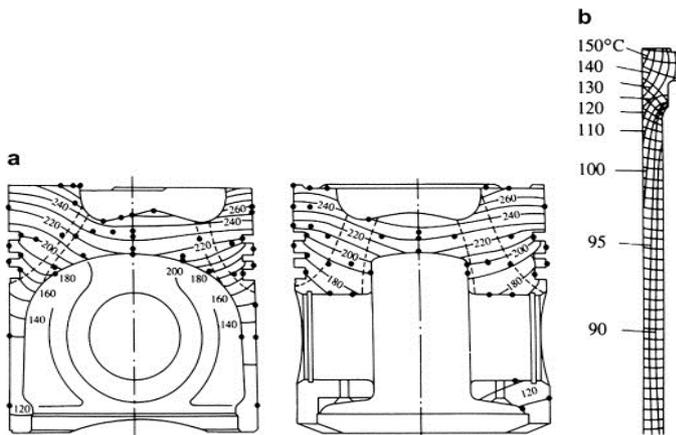


Figure 1: Temperature distribution a) Piston b) Liner

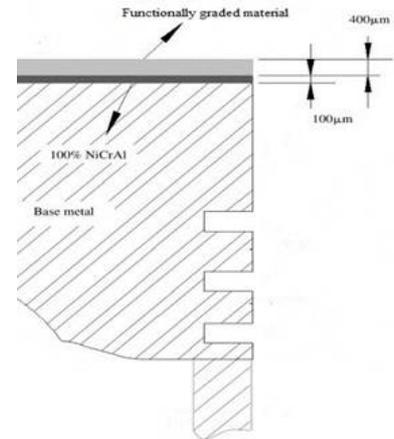


Figure 2: Schematic of piston with bond Coat and ceramic coating

II. FUNCTIONALLY GRADED COATING

Functionally graded coating are coating system used to increase performances of high temperature components in diesel engines. These coatings consist of a transition from the metallic bond layer to cermet and from cermet to the ceramic layer as shown in Figure 2. Functionally Graded Coatings are typically ceramic composites based on zirconia, alumina, and titanium. The high hardness, wear resistance and good chemical stability of TBCs make them very desirable in cutting tool applications. Functionally Graded Coating provides good resistance against the corrosive, high temperature environment of aircraft engines as well. That enhances the power output and better efficiency. Low basic fuel consumption and high heat release rate. The temperature of exhaust gases are with coating. Winkler M.F., et al described the thermal barrier coating effects on diesel engine performance and components lifetime [7].

III. PISTON DESIGN

The piston is a cylindrical object which reciprocates within a cylinder. It is either moved by the fluid or it moves the fluid which enters the cylinder. The main function of the piston of an internal combustion engine is to receive the impulse from the expanding gas and to transmit the energy to the crankshaft through the connecting rod. The piston head thickness is calculated from Grashoff's formula with take the maximum gas pressure is 10 times the mean pressure.

Table 1: Engine specifications

Bore	80 mm
Stroke	110 mm
Connecting Rod	234 mm
Compression Ratio	16.5
Rated Power	3.7 kW @ 1500 RPM
SFC	245 g / kW h

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For present work, to design a piston for an engine, the specifications of an engine are given in Table 1 for single cylinder 4 stroke water cooled engine. A 3D model of piston is generated using CATIA designing software. The dimensions of piston are calculated from the design fundamentals, Piston dimensions are detailed in the Table 2 [8].

Table 2: Piston dimensions

Piston Parameter	Value [mm]
Piston diameter	79
Top ring land	11
Crown thickness	10
Other ring land	2.5
Radial thickness of groove	3
Piston pin diameter	30
Compression height	60
Total height of piston	105

IV. STEADY STATE HEAT TRANSFER

Heat transfer analysis of engine is carried out using convection heat transfer, to calculate the heat transfer coefficient and ambience temperature on piston boundaries. The heat in engine is generated on combustion of fuel. Heat is transferred by all three modes. Heat is transferred by conduction through the cylinder head, cylinder walls, and piston; through the piston rings to the cylinder wall; through the engine block and manifolds. Heat is transferred by forced convection between the in-cylinder gases and the cylinder head, valves, cylinder walls, and piston [9]. In steady-flow forced-convection heat-transfer problems, heat flow through a wall as indicated in Figure 3 the following equations relate the heat flux,

$$\text{Gas side: } q = q_{CV} = h_m(T_{gm} - T_{wg}) \quad \dots(1)$$

$$\text{Wall side: } q = q_{CN} = k (T_{wg} - T_{wc})/t_w \quad \dots(2)$$

$$\text{Coolant side: } q = q_{CV} = h_c(T_{wc} - T_{cm}) \quad \dots(3)$$

Gas temperature is a function of crank angle in an engine and varies with crank angle. So, for steady state thermal analysis we can use the following relationship to obtain mean gas temperature at mean gas pressure [9],

$$T_{gm} = \frac{p_m V M}{m R_u} \quad \dots(4)$$

The average heat transfer coefficient at the gas side is calculated with assumption Nusselt, Reynolds and Prandtl number relationship for turbulent flow in pipes and over flat plates [9]:

$$Nu = a Re^m Pr^n \quad \dots(5)$$

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In present work, the mean heat transfer coefficient is calculated from empirical relationship of Nusselt's equation [11] at mean pressure and bulk gas temperature,

$$h_m = 5.41 \times 10^{-4} P^{2/3} T_g^{1/3} (1 + 1.24 C_m) \quad \dots(6)$$

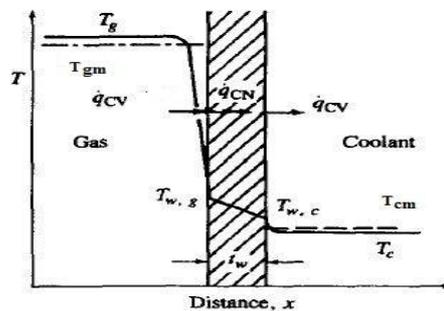


Figure 3: Heat flow path from gas to coolant

The conditions at coolant side [10], wall thickness, wall thermal conductivity, molar mass and density of combustion gases is given in Table 3. The calculated values for inside cylinder gas properties from Equations 4 to 6 are below in Table 4.

Table 3: Physical properties of material

Wall thermal conductivity, k	46 W/mK
Wall thickness, t _w	6 mm
Water temperature, T _{cm}	80 °C
Water heat transfer coefficient, h _c	1400 W/m ² K
Molar mass of combustion gas, M	29 kg/KMole
Combustion gas density	1.127 kg/m ³

Table 4: Steady state cylinder gas properties

Parameter	Value
Bulk gas temperature, T _{gm}	1162 K
Gas heat transfer coefficient, h _m	293 W/m ² K
Cylinder wall temperature, T _{wg}	245 °C

V. THERMAL BOUNDARY CONDITIONS

In this work, finite element thermal analysis is carried out to calculate the piston temperature with the help of third kind boundary condition as below [14]:

$$-k \frac{\partial T}{\partial n} = h(T - T_f) \quad \dots(7)$$

Where, T is the surface temperature, n is the exterior normal vector for the object boundary, h is the convection heat transfer coefficient, k is the thermal conductivity of object and T_f is the ambience temperature at the boundary of the object.

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In this section, the boundary conditions are calculated of piston surfaces from literature with numerical means of surfaces from A to H as figure 5,

At piston crown face, A: Ambience Temperature is bulk gas temperature and gas side heat transfer coefficient.

Ring land surface, B: Since there is a small gap between piston crown and the liner, the captured gas temperature is the mean temperature of the crevice surfaces [12]. Therefore, the heat is conducted through the gas with the convective heat transfer coefficient:

$$h = \frac{k}{\delta} \quad \dots (8)$$

Where δ is crevice clearance, 0.5 mm for the present work, for $k = 0.047$ W/ m K

It gives, $h = 94$ W/ m² K, and the ambience temperature at this face is taken as the wall temperature.

Ring groove face, C: the rings are placed to make a tight seal for gases. The heat transfer modelling in this region is obtained through ring resistance approach. The oil film resistance R_2 is neglected in this face. The heat transfer in rings is shown in Figure 4:

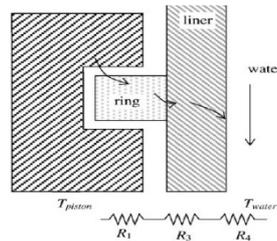


Figure 4: Thermal circuit of heat transfer resistances in the region of the rings

Where, 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

The resistances are:

$$R_1 = \frac{\ln(r_2 / r_1)}{2\pi L_1 k_{ring}}, \text{ conductive resistance of the ring}$$

$$R_3 = \frac{\ln(r_4 / r_3)}{2\pi L_3 k_{liner}}, \text{ conductive resistance of the liner}$$

$$R_4 = \frac{1}{h_{water} A_s}, \text{ convective resistance between the liner and the cooling water}$$

Where, r_1 , r_2 , r_3 and r_4 are inner radius of ring, outer radius of ring, bore radius and inner radius of water-jacket, respectively. L_1 , L_2 and L_3 are the widths of the heat transfer paths, respectively. A_s is the effective area in contact with the coolant.

A heat transfer path is considered (Figure 4) and the values of R_1 , R_3 and R_4 are calculated. The effective heat transfer coefficient is obtained from,

$$h_{eff} = \frac{1}{R_{tot} A_{eff}} \quad \dots (9)$$

Where, A_{eff} is the piston surface in contact with the ring and R_{tot} is the total resistance.

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Other ring land D and E: the heat transfer coefficient at this face is taken as the one third of the gas heat transfer coefficient and the ambience temperature is the 69.5 % and 66.5% of the first ring land temperature for D and E respectively [13].

Skirt F: The heat transfer at this face through convection with low coefficient [14].

Piston underside heat transfer G and H: the piston underside is divided into two regions:

Region G and H, the crown underside is cooled by splash cooling type. The ambience temperature is taken in this region the oil temperature [13]. The value of convective heat transfer coefficient is calculated from the following equations,

$$h_H = 900 \left(\frac{RPM}{4600} \right)^{0.35} \quad h_G = 240 \left(\frac{RPM}{4600} \right)^{0.35} \quad \dots(10)$$

The surface boundary conditions, heat transfer coefficient and gas temperature ambience to the piston surface for given Figure 5 is given in Table 5 below:

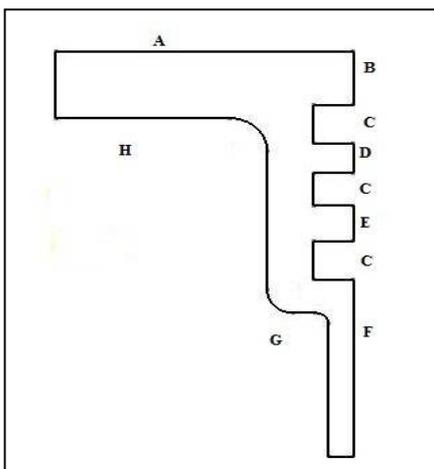


Table 5: Piston thermal boundary conditions

Thermal boundary	Ambience temperature [⁰ C]	Heat transfer coefficient[W/m ² K]
Piston crown, A	890	293
Crevice surface, B	245	94
Rings, C	80	485
Ring land, D	170	98
Ring land, E	162	98
Skirt, F	80	65
Underskirt, G	120	162
Under crown, H	120	608

Figure 5: Surfaces of the heat exchange

VI. FINITE ELEMENT MESH MODEL

The finite element analysis to the piston is to establish the reasonable and accurate finite element model first, thus carrying out analysis by marking cell grids to obtain the accurate results finally. There are a number of steps of FE simulation procedure of engine piston as follows [15]:

- 1. Geometry sub-model:** This sub-model includes 3-D dimensions Geometry of the engine piston with rings (mm) dimensions, as show in Figure 6
- 2. Material sub-model:** This sub-model includes the material properties of the engine piston as shown in Table 6
- 3. Meshing generation:** Three dimensions coupling element of 3-D heat transfer (Conduction) and 3-D-stress analysis are used for modeling of heat transfer and stress analysis.
- 4. Parameter study:** Temperature (variation) of piston is studied through the simulation.

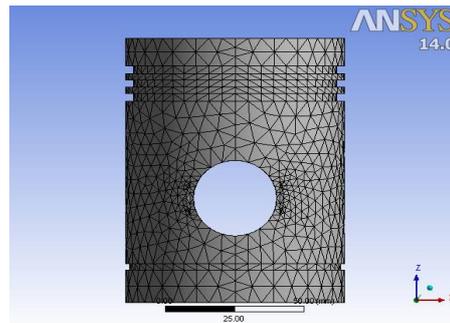


Figure 6: Finite element mesh model of piston

Table 6: Material properties of piston and Thermal barrier materials [6, 12]

Materials	Young's Modulus (GPa)	Density (kg/m ³)	Poisson's Ratio	Thermal Conductivity (W/m °C)	Specific Heat (J/kg ⁰ C)	Thermal Expansion (× 10 ⁻⁶ 1/K)
AlSi Alloy	71	2770	0.33	155	875	23
NiCrAl (Bond Coat)	86	7870	0.30	16.1	764	17
Mullite (2Al ₂ O ₃ .2SiO ₂)	30	2800	0.25	3.3	950	5.3
YPSZ	11.25	5650	0.25	1.4	620	10.9

VII. COMPUTATION AND RESULT ANALYSIS OF THE TEMPERATURE FIELD

Based on the established geometrical modal and finite element modal as well as the established boundary conditions and with the static thermal analysis module of the finite element analysis software, the temperature distribution of uncoated and coated piston as shown in figure 7 .

The piston temperature changes between 161.9⁰C to 263.89⁰C with the maximum temperature at the piston top and minimum temperature at the lower part of the piston skirt. At the piston ring land, temperatures are distributed uniformly along the piston in the radial direction. The piston temperature changes uniformly from the piston top to the bottom, without any sharp change phenomenon.

The maximum temperature in mullite coated piston is found on its crown. The maximum value is 323.21⁰C and minimum is 157.01⁰C on skirt. On crevice surface the temperature is 239.8⁰C and ring temperature is 239.8⁰C. The under crown temperature is 242.53⁰C.

The piston temperature profile of piston with YPSZ coating is below in Figure 5.5, the maximum temperature is 313.62⁰C and minimum on skirt is 157.46⁰C.

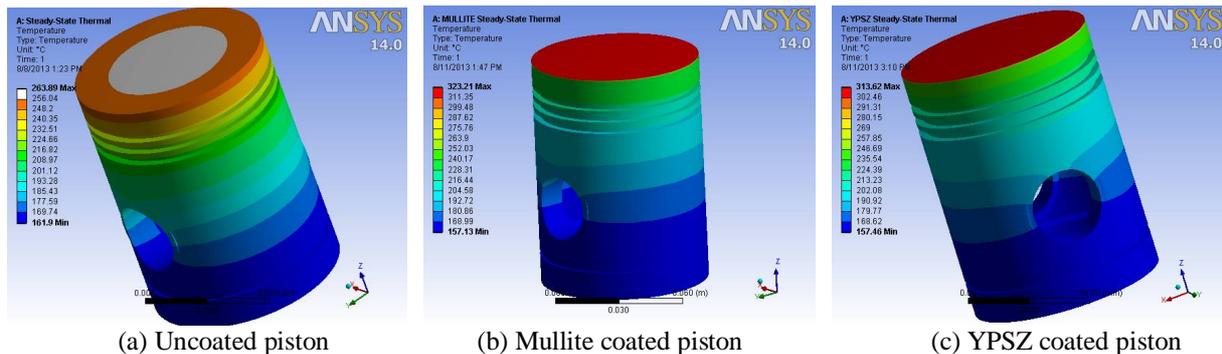


Figure 7: Temperature field of piston surfaces

VIII. CONCLUSION

The maximum temperature is obtained for conventional piston is 263.89 °C, for mullite coated piston is 323.21 °C and for YPSZ coated piston is 313.62 °C. The heat flux on piston crown for conventional piston is 78244 W/m² and for mullite coated piston is 69717 W/m².

Therefore, it is conclude that the surface temperature is higher for mullite and YPSZ coated piston is higher about 22 % and 19 % respectively. The heat flux is reduced with mullite coated piston by 10.89%. It is because the heat insulation of a material is proportional to the thermal diffusivity. The heat transfer to the material decreases as the thermal diffusivity coefficient decreases. In reduction the heat transfer through piston crown, the performance of engine increases.

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