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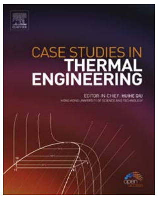

Thermal analysis of holes created on ceramic coating for diesel engine piston

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ABSTRACT

This paper deals with the steady state thermal analysis of diesel engine piston coated with ceramic coating having holes on its surface. Temperature distribution on the piston's top surface and substrate surface is investigated by using finite element based software called Ansys. Yttria-stabilized Zirconia is used as ceramic coating applied on Al–Si piston crown. The 2 thickness of ceramic top coating is about 0.4 mm and for NiCrAl bond coat it is taken to be 0.1 mm. Temperature distribution is investigated by choosing various radiuses of holes created on the ceramic coating surface about 1.5 mm, 2 mm and 2.5 mm. From the results it is observed that the top surface (coated surface) temperature is increasing with increase the radius of the holes. Maximum temperature of coated surface is occurs for highest hole radius of about 2.5 mm. Compared with coating have no hole, a significant increase in the pistons top surface temperature occurs with coating having holes. Although, the substrate temperature is decreasing with increase the radius of the holes.

1. Introduction

The input energy of an internal combustion engine has three parts: energy used by coolant, energy which is utilized for useful work and energy lost through exhaust and only 1/3 of the total energy is converted to work. Thus the efficiency and overall performance of internal combustion engine can be increased by utilizing these heats lose into the useful work. To minimize heat transfer and improve the performance of an internal combustion engine a technology of insulating the piston, cylinder head, combustion chamber, and valve's surfaces with thermal barrier coating materials has been introduced. Engine is a heart of the vehicle and piston is the main component of the engine. For the past few decades TBC is used to improve efficiency and performance of various machine components. TBC provides not only the thermal fatigue protection, but it also reduces heat rejection from the engine. It also protects piston from corrosion attack, thermal stress, high heat emissions and it reduces heat flux into the piston and fuel consumption [1]. TBC applied to high temperature areas or heat transfer surfaces of gas turbine and IC engine to improve its performance. The temperature of other components of an engine also gets affected either increases or decreases if coating is applied on any part of the engine. The heat transfer phenomena in internal combustion engine always have been a topic of research due to some complexity. For the analysis convection is selected as a major mechanism of heat transfer. The heat transfer problem for internal combustion engine is very complicated because of following reasons [2]:

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Nomenclature

SI	spark ignition
IC	internal combustion
TBCs	thermal barrier coatings
NOx	nitrous oxide
CFD	computational fluid dynamics
RPM	rotation per minute
HC	hydro carbon
CO	carbon mono oxide
FGM	functionally graded material
YSZ	yttria stabilized zirconia
$h_{gas}(t)$	instantaneous convective heat transfer coefficient (W/m^2 K)
$V_C(t)$	instantaneous cylinder volume (m^3)
P(t)	instantaneous pressure (bar)
T(t)	instantaneous temperature (K)
S_P	mean piston speed (m/s)
α	calibration constants
b	calibration constants
t	temperature (°C)
Q	source or sink rate of heat in a domain (W/m^3)
c_p	volumetric specific heat (J/m^3 C)
k	thermal conductivity (W/ m C).
k_n	thermal conductivity normal to the surface,
q_p	prescribed flux (W/m^2)
h	heat transfer coefficient for convection (W/m^2 C)
σ	Stefan–Boltzmann constant (W/m^2 C^4)
ε	emissivity
T_∞	ambient temperature for convection and/or radiation
K	effective conductivity
F	effective load
δ	crevice clearance
h_{eff}	effective convective heat transfer coefficient on the piston (W/m^2 K)
T_{piston}	piston temperature (K)
T_{wall}	wall temperature (K)
ρ	gas density (kg/m^3)

- Inside the cylinder the temperature of gases changes continuously.
- To determine the exact value of temperature and heat transfer coefficient is not much easy.
- Piston is the main component responsible for combustion thus it subjected to high temperature and heat transfer coefficient.

A one another reason of using TBC is the continuous increase in fuel prices and reduction in supply of high quality fuel [3]. On the other hand combustion of these fuels leaves HC particles, CO emissions and smoke behind them due to improper combustion at low temperature. TBC allows using low quality fuels by making the piston temperature much higher than uncoated one due to which proper combustion of fuel occurs. Due to proper combustion of fuel the thermal barrier coating reduces HC, CO emissions in the environment. TBC mainly consists three layers of substrate, bond coat and top coat. The substrate is a metal surface which takes maximum load on it. High temperature aluminum alloys are generally used for substrate material. Bond coat is used to provide bonding between substrate and top coat surface. It also helps to reduces stresses occurring during thermal shock [4]. The top coat is material of lower thermal conductivity to withstand at higher temperature. To determine and control the temperature and stress in internal combustion engine temperature distribution for piston have to investigate.

Analysis of temperature distribution helps the designer to estimate the project cost before actual designing begins. Thus, thermal analysis of piston is very important [5].

The governments, industries and various academics started the working in the adiabatic engine technology after the great invention has been done by Kamo and Bryzik [6] in the diesel engine field by the experimental work. They used silicon nitride as coating applied to combustion chamber surfaces and the result of which improvement in piston temperature about the 7% was found. Similarly ceramic coating was applied by Dicky [7] to engine performance. The low heat release rate and longer combustion duration with coated piston compared to the baseline cooled engine has been found. An experimental and theoretical study has been carried out by Hultqvist et al. [8] on Homogeneous Charged Compression Ignition (HCCI) engine piston in which the top of the piston, cylinder head and upper part of the piston was coated with thermal barrier and catalytic coating. From the analysis, it was concluded that as the thickness of coating increasing the ignition delay is decreased. Hejwowski and Weronski [3] used thermal barrier coating to determine the performance of diesel engine piston. From the results of this analysis, it was found that ceramic coating does not produce knock in the engine and protects the piston skirt and cylinder liners from wear. Cerit [4] investigated the temperature and stress distribution of SI engine piston, partially coated with ceramic coating. The investigation has been carried out by using various thickness of ceramic coating. It was found that the temperature of the piston was increasing with coating thickness and normal stress was decreasing. Vedharaj et al. [9] investigated the performance of coated and uncoated piston engine operated with cashew nut shell liquid. Experimental results showed 6% higher brake thermal efficiency with coated piston compared to uncoated piston. Numerical investigation of the zirconia coated piston using finite element method has been carried out by Sathyamoorthi et al. [10]. From the results brake thermal efficiency and indicated thermal efficiency of coated piston was found 5.89% and 11.14% higher respectively compared to conventional piston.

From the literature, it is observed that there was lots of studies has been done on the IC engine piston coated with thermal barrier coating by changing the designing of piston or by changing the coating material but only few studies based on the coating design have been carried out. The main reason of this analysis is to determine the maximum temperature distribution of the piston by using the ceramic coating having holes on its surface which improve the piston temperature for combustion .

2. Methodology

For the above analysis the following steps are taken:

- First of all, the various thermal properties of piston, bond coat and ceramic coating materials were defined in the engineering data section.
- After defining the materials properties finite element modeling of piston was done in the geometry section of the system by giving the bore diameter, bond coat and top coat thickness.
- Then, model analysis of ceramic coated piston has been carried out. In this step, materials are assigned to particular solid i.e. piston, coating, rings. Contact between ring and ring groove, bond coat-substrate and top coat substrate are defined default which is bonded contact. Meshing also created by taking default settings.
- After all, temperature on substrate surface and top surface was investigated by applying convection boundary condition (Fig. 1).

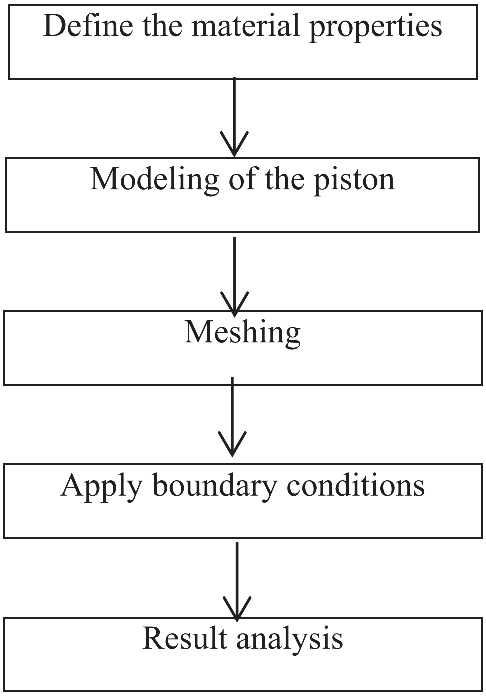


Fig. 1. Methodology used for the analysis.

Table 1
Thermal properties of materials for piston, piston rings, bond coat and ceramic top coat [1,11,13].

Material	Thermal conductivity [w/m °C]	Thermal expansion 10^{-6} [1/°C]	Specific heat [J/kg °C]
Piston (aluminum alloy)	155	21	910
Rings (cast iron)	16	12	460
Bond coat	16.1	12	764
Y-PSZ	1.4	10.9	620

3. 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 hydro carbons 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 withstand at higher temperature. TBC does not need cooling as soon as metals due to their higher thermal durability [5]. This paper consist steady state thermal analysis of piston coated with 0.4 mm thick Yttria stabilized zirconia. Just 6–9% Y-PSZ improves the performance of coating [11]. Y-PSZ can withstand at the temperature about 1000 °C. Y-PSZ is used in most cases due to its high performance at high temperature areas like gas turbines and diesel engines. The Y-PSZ coating provides the more corrosion resistance than ZrO_2 coating [12]. The materials properties are considered to be linearly elastic and isotropic.

The aluminum is taken as piston material. The bond coat of 0.1 mm 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, bond coat, rings and top coat are tabulated in Table 1.

4. 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 [14],

$$k_x\frac{\partial^2 T}{\partial x^2} + k_y\frac{\partial^2 T}{\partial y^2} + k_z\frac{\partial^2 T}{\partial z^2} + Q = \rho c_p\frac{\partial T}{\partial t} \tag{1}$$

In which Q is define as the source or sink rate of heat in a domain (W/m^3), C_p is the volumetric specific heat (J/m^3 C) and k is the thermal conductivity (W/ m C). The essential boundary condition and natural boundary conditions at the boundary are define as [11]

$$T(x, y, z, t) = T_1(x, y, z, t) \tag{2}$$

$$k_n\frac{\partial T}{\partial n} + q_p + h(T - T_\infty) + \sigma\varepsilon\left(T^4 - T_\infty^4\right)=0 \tag{3}$$

In which k_n is thermal conductivity normal to the surface, q_p(x, y, z, t) is a prescribed flux (W/m^2), h is the heat transfer coefficient for convection (W/m^2 C), σ is Stefan–Boltzmann constant (W/m^2 C^4), 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

$$T(x,\ y,\ z,\ 0) = T_{in}(x,\ y,\ z) \tag{4}$$

Eq. (1) can be reduce by using the different techniques into the following form [11]

$$CT + KT = F \tag{5}$$

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 [11,15].

5. Finite element modeling

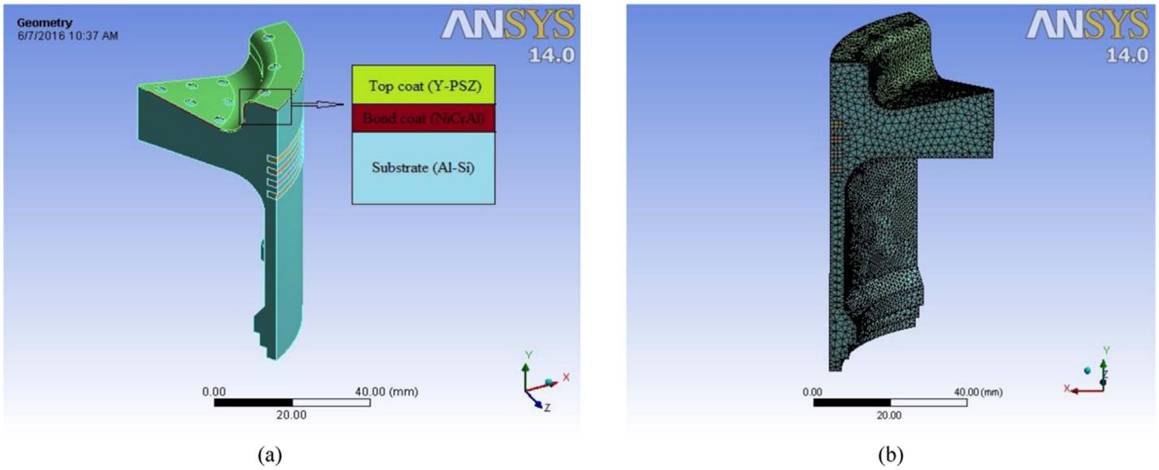
This paper consist the problem of steady state heat transfer in the coated and uncoated piston. The numeric modeling of MWM TBRHS 518-V16 direct injection, water cooled diesel engine piston made up of aluminum has done in ansys workbench. To reduce the number of elements and solving time axially symmetric model is used. The engine is rated at 300 kW at 1500 rev/min for turbocharged configuration and water-cooled. The geometric compression ratio is 19:1 [13]. Ansys provide accurate results of analysis by dividing geometry into smaller elements. The piston is coated with 0.4 mm Y-PSZ coating and 0.1 NiCrAl coating having holes of 1.5 mm, 2 mm, and 2.5 mm radius on its surface as shown in Fig. 2(a). The holes are taken in the optimum range because below 2 mm radius of the hole, it is difficult to observe effects on piston temperature and above 2.5 mm the stresses in the piston increases due to higher temperature. Except the holes radius, all the dimensions of piston remain same for whole analysis. The specifications of test engine are tabulated in Table 2.

First of all material properties of the substrate, rings, bond coat and top ceramic coat of Y-PSZ are defined. The material properties valves are given in Table 1. Then modeling of diesel engine piston with 130 mm bore and 160 mm stroke length is designed. The NiCrAl bond coat and Y-PSZ top coat applied on top surface of the piston as a thin layer. After those holes on bond coat and ceramic top coat was created by taking 1.5 mm, 2 mm and 2.5 mm radius.

The materials to the geometry are assigned at modal section of the system. The geometry has default bonded contact between top coat-bond coats, bond coat-substrate (piston) and piston rings-rings groove. After modeling of piston fine meshing has been created by taking default element type and settings in workbench with 1 mm element size as shown in Fig. 2(b). The model contains approximately 162,179 nodes and 82,867 elements.

6. Steady state thermal analysis

In this analysis properties of materials are considered to be constant with time, thus, steady-state thermal analysis is



(a) (b)

Fig. 2. (a) Modeling of piston has coating with holes, (b) Mesh model of piston.

Table 2
The engine specifications.

Engine type	MWM TBRHS 518-V16 direct injection, water cooled diesel engine
Bore	130 mm
Stroke	160 mm
Compression ratio	19:1
Power (at 1500 rpm)	300 k/W

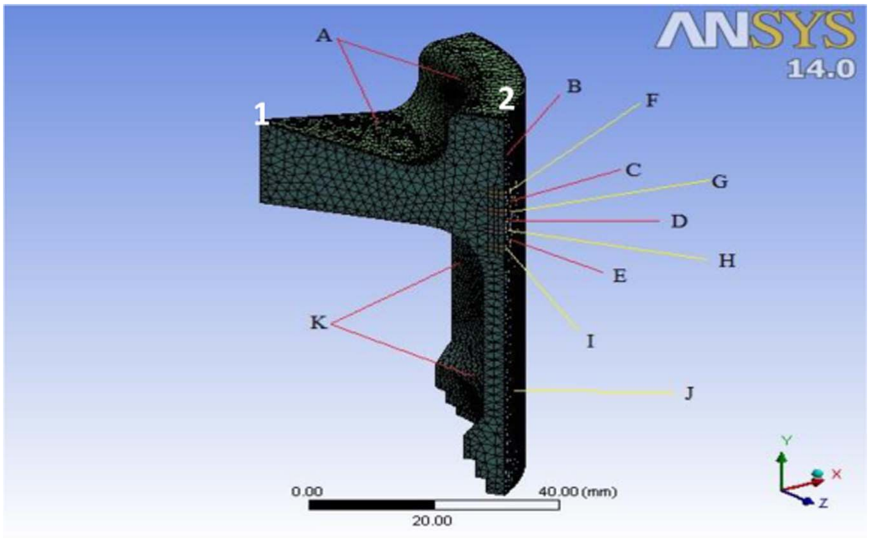


Fig. 3. Thermal boundary regions.

carried out in order to determine the temperature distribution of Al-Si piston has a Y-PSZ coating with holes. The piston of the engine is subjected to some mechanical stresses as well as thermal fatigue during the working cycle. Due to high temperature gradient some thermal stresses are developed in the piston. Steady state thermal analysis is useful to determine the highest temperature within the piston body which causes the piston performance [2].

Convection is taken as a major phenomenon of heat transfer in the piston. Different temperature and heat transfer coefficient are applied to the different areas of piston as shown in Fig. 3. The values of various temperature and film coefficient is determined by following equation of Hohenberg [15]-

$$h_{gas}(t) = \alpha\, V_c(t)^{-0.06} P(t)^{0.8} T\,(t)^{-0.4} (Sp + b)^{0.8} \tag{6}$$

where $h_{gas}(t)$ define as the instantaneous convective coefficient heat transfer (W/m^2 K), $V_C(t)$, P(t) and T(t) are the instantaneous volume of a cylinder (m^3), temperature (K), pressure (105 Pa) and, and SP the mean piston speed (m/s), respectively.

α and b are the calibration constants which are about 130 and 1.4 as defined by Hohenberg [15]. The values of temperature and heat transfer coefficient at different regions of piston are taken from the literature [13] as shown in Fig. 2. The values of thermal boundary condition are tabulated in Table 3. Before applying the boundary conditions, some assumptions are made [5].

- The effect of piston motion on the heat transfer is neglected.
- The rings do not twist.
- The rings and skirt are fully engulfed in oil and there is no cavitation.
- The conductive heat transfer in oil film is neglected.

Table 3
Convection boundary conditions [13].

Region	Heat transfer coefficient [w/m^2 °C]	Temperature [°C]
A	700	700
B	500	225
C	400	180
D	400	170
E	400	160
Ring-F	400	200
Ring-G	400	180
Ring-H	400	160
Ring-I	400	140
J	1500	110
K	1500	110

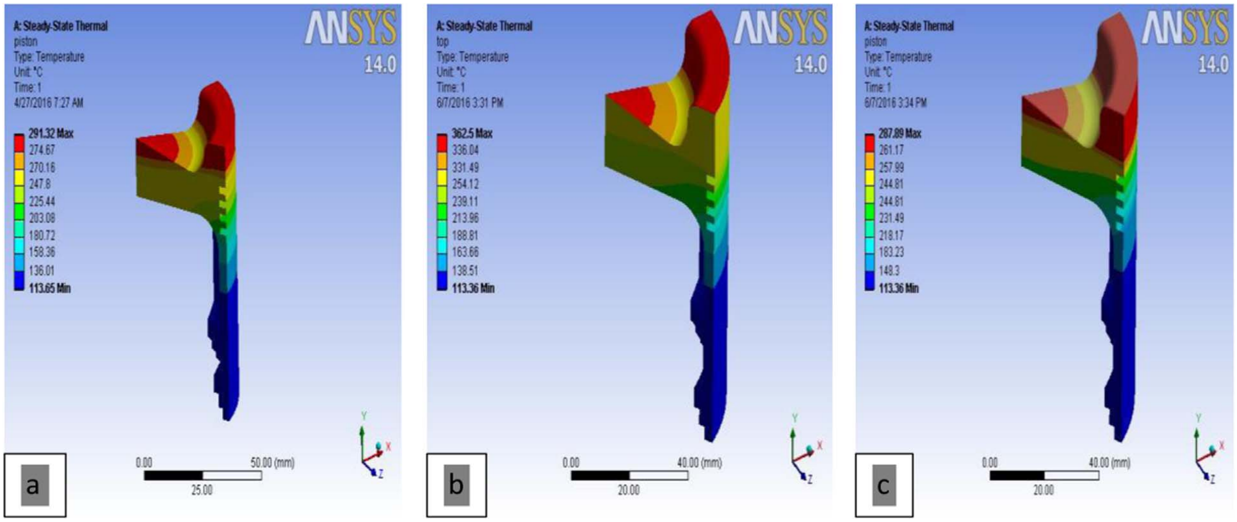


Fig. 4. Temperature distribution for (a) uncoated piston (b) Top surface of Y-PSZ coated (c) Substrate surface of Y-PSZ coated.

7. Result and discussion

The finite element method is used to determine the temperature distribution for uncoated and Y-PSZ coated piston. For this purpose steady-state thermal analysis has been carried out using commercial code Ansys. The temperature distribution for the uncoated and coated piston is shown in Fig. 4. Maximum temperature occurs at the piston's center and at the bowl lips of the piston and minimum temperature is at the bottom of the piston. The values of maximum and minimum temperatures for uncoated piston are obtained about 291.32 °C and 113.65 °C respectively. The maximum temperature at the top surface of coated piston is about 362.5 °C and for substrate surface maximum temperature is about 287.89 °C. The minimum temperature for both cases is 113.26 °C. Top surface temperature for coated piston is increased by 71.18 °C or by 24.43% and substrate temperature is decreased by 3.42 °C or 1.17%.

With the same boundary conditions, thermal analysis of piston has Y-PSZ coating with holes is carried out. Fig. 5 shows the temperature distribution on the top surface of coated piston with holes for the radius of 1.5 mm, 2 mm and 2.5 mm. From the figure it was observed that only the values of temperatures are changed but no changes to the counter plots occurs. The maximum top surface temperature values corresponding to the 1.5 mm, 2 mm, and 2.5 mm radius holes are 402.93 °C, 444.54 °C and 540.96 °C. Compare to the uncoated piston temperature of the top surface is increased by 38.31%, 52.59% and 85.69% for 1.5 mm, 2 mm, and 2.5 mm radius respectively. Compare to the coated piston without holes temperature increases by 11.15%, 22.63% and 49.23% for 1.5 mm, 2 mm and 2.5 mm radius holes respectively.

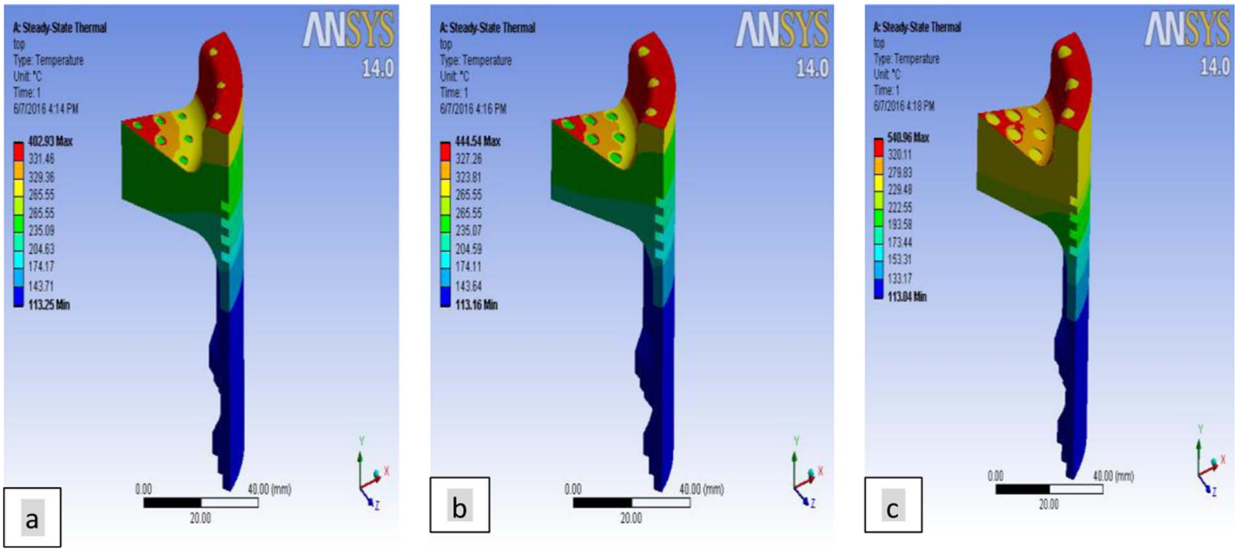


Fig. 5. Top surface temperature distribution for (a) 1.5 mm, (b) 2 mm, (c) 2.5 mm radius holes created on ceramic surface.

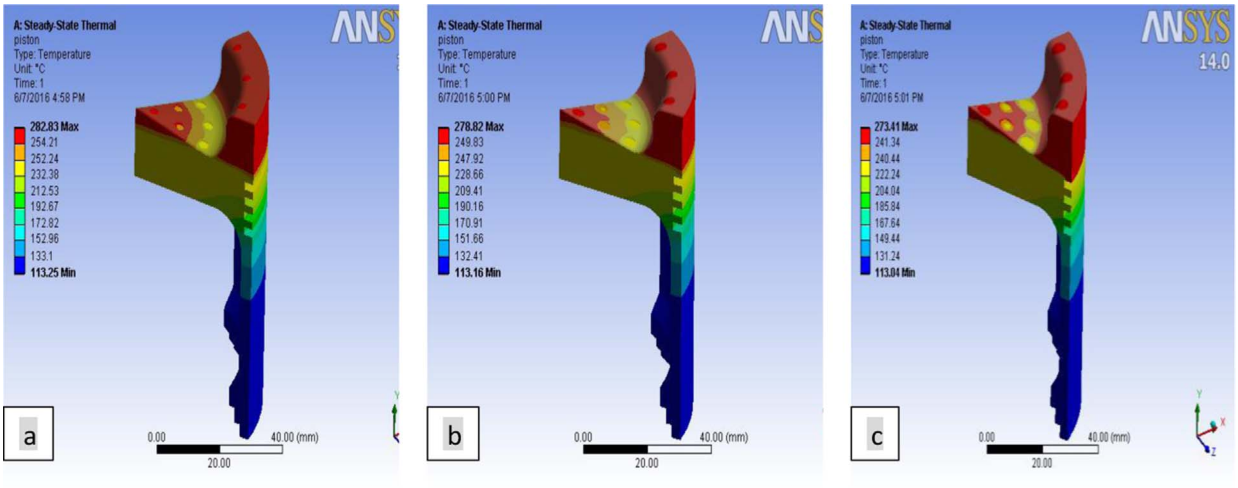


Fig. 6. Substrate surface temperature distribution for (a) 1.5 mm, (b) 2 mm, (c) 2.5 mm 2.5 radius holes created on ceramic surface.

Table 4
Maximum temperature distribution of piston top and substrate surface with various design conditions [°C].

Condition	Maximum top surface temperature	Maximum substrate surface temperature
Uncoated	291.32	–
Y-PSZ coating without holes	362.5	284.89
Y-PSZ coting with 1.5 mm radius of holes	402.93	282.83
Y-PSZ coting with 2 mm radius of holes	444.54	278.82
Y-PSZ coting with 2.5 mm radius of holes	540.96	273.41

Fig. 6 shows the temperature distribution on the substrate surface of coated piston with holes for the radius of 1.5 mm, 2 mm and 2.5 mm. For the substrate surface only the value changes and counter plots remain the same. The maximum substrate surface temperature values corresponding to the 1.5 mm, 2 mm, and 2.5 mm radius holes are 282.83 °C, 278.82 °C and 273.41 °C. Compare to the uncoated piston temperature of the substrate surface is decreased by 2.91%, 4.2% and 6.14% respectively. Compare to coated piston without holes, the temperature decreases by 1.75%, 3.15% and 5.02% for 1.5 mm, 2 mm and 2.5 mm radius holes respectively.

The various results obtained from the analysis are discussed systematically. Because of the low thermal conductivity of ceramic material compared to piston material the coated piston has higher temperature than uncoated piston. From the above analysis it is observed that the piston's top surface temperature is increasing and the substrate surface temperature decreasing as the radius of holes increases. On the consideration of temperature distribution in radial direction the temperature of the piston is decreasing from the crown center to the bottom of the bowl then after the increasing toward the bowl lips again decreasing at the edge of the crown surface. This occurs due to the cooling near the cylinder wall the flam propagation decreases. The higher temperature of top surface improves the engine performance by increasing the amount of burned fuel and reduces the hydro carbon emissions. It is known that the strength of material decreases with the higher temperature, thus it is important that the temperature of the substrate should be lower as observed in the above analysis. The obtained temperature distribution is similar as Cerit and Coban [13] observed in their analysis. The results obtained from the analysis for maximum temperature of piston's top surface and substrate surface with different design conditions are tabulated in Table 4.

8. Conclusion

From the above analysis, it is clear that TBC help to increase the temperature of the piston. The maximum temperature for top coating surface and substrate surface occurs at the center of the piston and at the piston's rim area. The temperature is increased from the bottom of the piston to the head. Coated piston has a significantly higher temperature than uncoated piston and after that the top surface temperature is increased by increasing the radius of the holes. The corresponding top surface maximum temperature for the uncoated, coated piston, coating with 1.5 mm radius hole, 2 mm radius hole and 2.5 mm radius hole is 291.32 °C, 362.5 °C, 402.93 °C, 444.54 °C and 540.96 °C respectively. The Maximum temperature on the top surface is observed for coating having hole of 2.5 mm radius which is about 540.96 °C and 85.69% and 49.23% higher compared to uncoated and coated piston. On the other hand substrate temperature of coated piston is lower than uncoated and decreasing as the hole's radius is increases. The substrate surface temperature for the coated piston, coating with 1.5 mm radius hole, 2 mm radius hole and 2.5 mm radius hole is 287.89 °C, 282.83 °C, 278.82 °C and 273.41 °C respectively. The minimum temperature on substrate surface is observed for coating having hole of 2.5 mm radius which is about 273.41 °C and which is 5.02% lower than coated piston.

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