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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