

Thermal Analysis of a Piston Coated with SiC and $MgOZrO_2$ Thermal Barrier Materials

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Abstract
In this study, motor piston was designed by using solid-works which is a computer aided modeling program and its thermal analyses were performed. In the study performed for this purpose, the motor piston (AlSi) was coated with $MgOZrO_2$ and SiC ceramic material, and its thermal analyses were performed. 3-D modeling and analyses of the piston were performed via the program. Thermal analyses of motor piston, standard piston material and coated materials were performed, and they were examined comparatively. In the thermal analyses of ceramic coated pistons compared to standard pistons, an increase of 21-26% was determined in the combustion chamber temperature of the piston, a decrease of 19-24% was determined in the pin housing of piston and a decrease of 14-17% was determined in the piston skirts.

Keywords: Pistons modeling, piston coatings, thermal analysis, ceramic coating.

1. Introduction

Combustion engines need to improve their thermal efficiency if they are to help mitigate the green house effect. In the case of diesel engines, increasing the mean effective cylinder pressure is a practical way to improve thermal efficiency. Higher mean effective pressures cause higher thermal and mechanical loads on the engine pistons [1]. There are lots of research works proposing, for engine pistons, new geometries, materials and manufacturing techniques, and this evolution has undergone with a continuous improvement over the last decades and required thorough examination of the smallest details. Notwithstanding all these studies, there are a huge number of damaged pistons. Damage mechanisms have different origins and are mainly wear, temperature, and fatigue related. Among the fatigue damages, thermal fatigue and mechanical fatigue, either at room or at high temperature, play a prominent role [2]. As one of the major moving parts in the power-transmitting assembly, the piston must be so designed that it can withstand the extreme heat and pressure of combustion [3]. Engine coating with a ceramic thermal barrier can be applied to improve reliability and durability of engine performance and efficiency in diesel engines [4-6]. Ceramics have a higher thermal durability than metals; therefore it is usually not necessary to cool them as fast as metals [7-9].

There are many factors that influence overall performance of the coatings. However, thermal shock resistance of coating materials depends on the elastic modulus, thermal expansion coefficient and thermal conductivity. Compared to ceramic coating, deposit has lower elasticity modulus and thermal conductivity, higher thermal durability [10, 11]. The coating thickness has an effect on the combustion temperature, the temperature gradient and the stress distribution in the coating and the interfacial stresses. The bond coat between the aluminum alloy and the ceramic coating plays an important role in reducing the internal stresses, which may arise between substrate and top coat due to thermal shock [12, 13]. Computer simulations of thermo analyses can significantly reduce the time and cost in designing of a piston in SI engines before the first prototype is constructed.

In the thermal barrier coating analyses performed on the piston in the previous studies, the analyses were performed by using a ceramic or ceramic compounds. This reveals the importance of the study. In this study, the piston of a internal combustion single cylinder diesel engine was modeled as 3-D in solid-works program, and the dimensions of the piston are given in Figure-1. The thermal analyses were performed by coating the model standard piston (AlSi) and interconnection coupler layer with NiCoCrAlY and SiC and $MgOZrO_2$ thermal barrier materials. And in this study, coating on piston was made by using carbide and oxide based ceramic compounds and its thermal analyses were examined through comparison. This analysis research is foreseen in advance with damage to the piston, how to avoid them will be guided during construction.

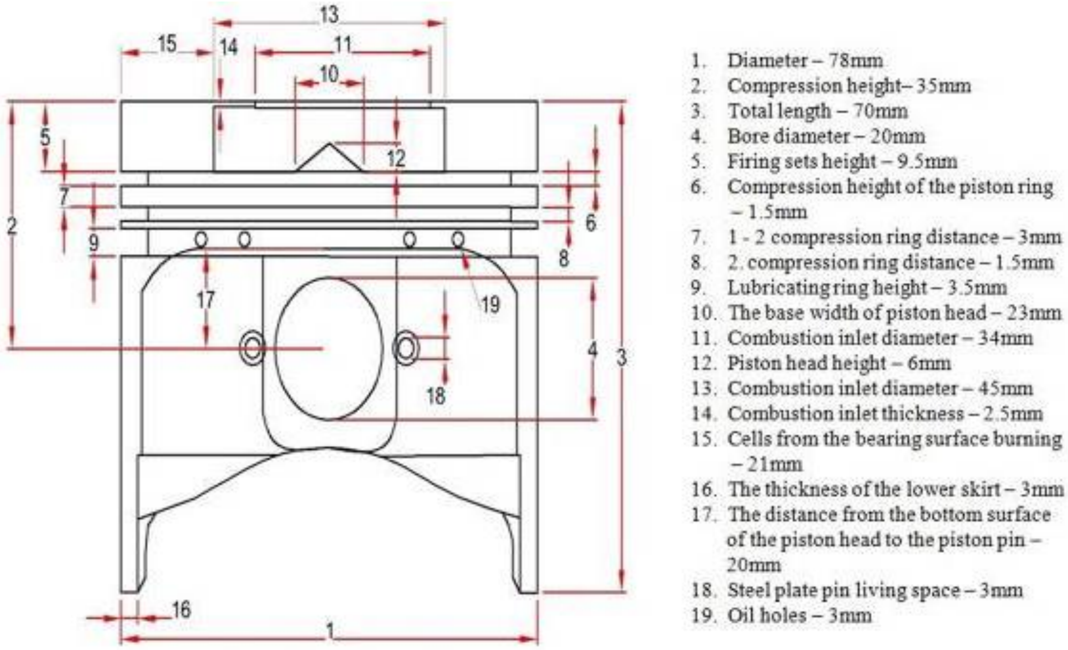

Figure 1. Piston sizes.

2. Coating Materials

During the three dimensional design of the material, the standard piston was defined as aluminum silicon material. First NiCoCrAlY material with a thickness 150 µ was coated on the piston material as interconnection coupler, and then the coating operation was performed separately by SiC and $MgOZrO_2$ materials with a thickness of 300 µ (Figure-2). In Table-1, the specifications of coating materials are provided. The materials, which will be coated under real coating conditions, are required to be grinded on the surface as much as the coating material. For this reason, real coating conditions were considered and the whole length of the material was not changed after coating.

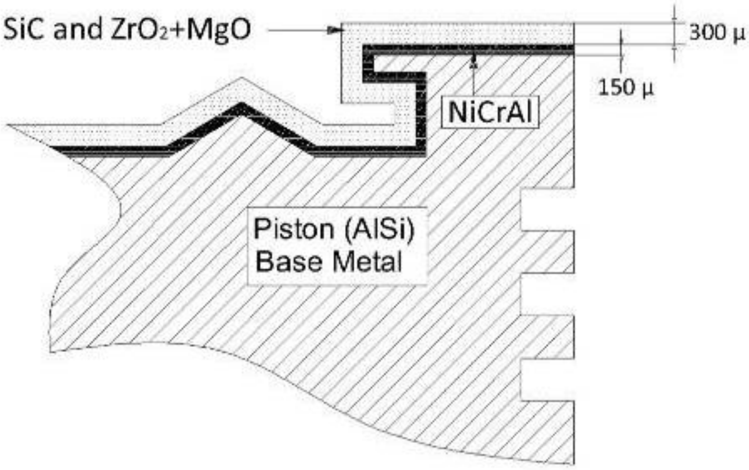

Figure 2. Thermal barrier coating thickness.

Table 1. Materials properties of the sunstrate and coating [13].

Material Properties	**Piston (AlSi)** [13- 14]	**Bond Coat (NiCoCrAlY)** [15- 16]	**SiC** [17]	**$MgOZrO_2$** [18]
Young's Modulus (GPa)	69	225	476	200
Poisson's Modules	0,33	0,30	0,19	0,32
Thermal Conductivity (W/mK)	155	6,0	41	2
Thermal Expansion Coefficient (10^6[1/°C])	21	12	5,12	8
Density (kg/m^3)	2700	7320	3210	5500
Specific Heat ($Jkg^{-1}K^{-1}$)	960	501	750	418

3. Analysis Method

For the analyses, single cylinder four-cycle diesel motor piston was modeled as 3D in solid-works program. The mathematic model of the modeled piston was formed through "MESH" command in "solid-works simulation" program. The mathematically formed model is being shown in Figure-3. The analyses were performed by defining the piston as AlSi material. Oil film and transmission coefficient of coil were ignored.

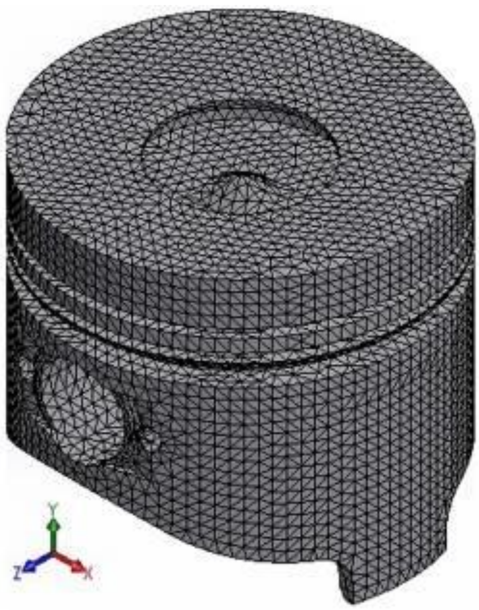

Figure 3. The finite element mesh.

In single cylinder four-cycle motors, values relevant to the temperature changes within cylinder are included in many literature studies [19]. In these studies, the temperatures affecting the piston had increased due to the temperature on coated and uncoated pistons. In the literature researches performed, the analyses were performed based on the past experiences and measurements of the authors. In this way, the inside temperature was estimated to be 650 °C with a convection coefficient of 800 W/m^2K. Lateral surface temperature of the piston was specified as 300 °C with a convection coefficient of 230 W/m2 K. Ring temperatures of the piston are defined 160 °C with a convection coefficient of 200 W/m^2K. Piston skirt and pin temperatures are defined 85 °C with convection coefficient of 60 W/m^2K [16, 20].

4. Results and Discussions

The original piston of motor was designed as 3D, and the thermal analyses were performed by the analysis module of the program. And then the piston was coated by other coating elements, and the thermal analyses were repeated with each coating material. The data -obtained after each analysis- was obtained as figures and as graphically. Thus, the effect of coating material on health expenses piston can be observed more clearly. The status after thermal analysis applied to the uncoated standard motor piston is provided in Figure-4.

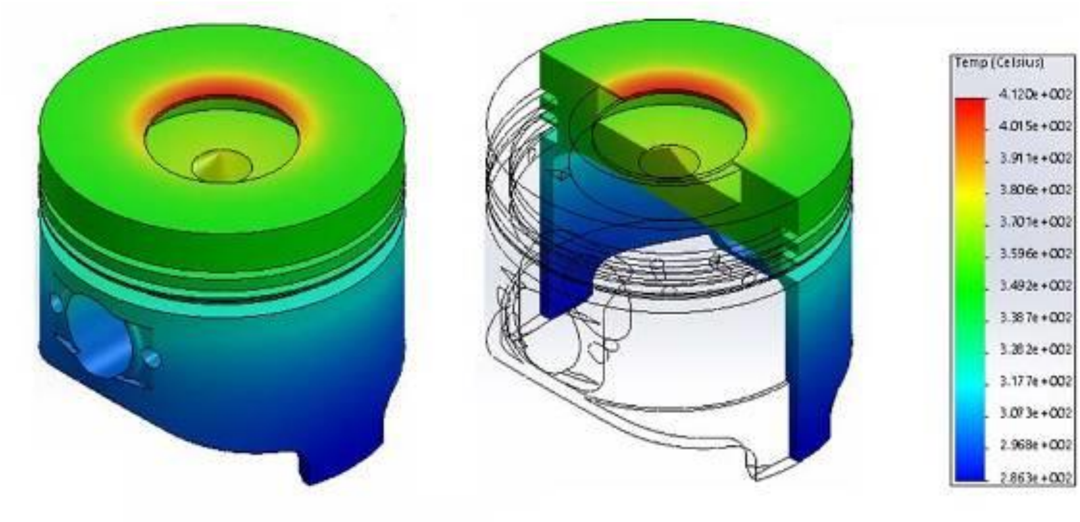

Figure 4. Standard AlSi alloy the temperature distribution of the piston.

By the studies performed, the heat transmission coefficient of AlSi materials was 155 W/mK [13, 14]. The transmission coefficient being high causes the temperature starting at combustion chamber to be transmitted until the piston skirt. When the results of thermal analyses are examined, it was determined that the highest temperature of the piston's surface was 412 ºC. It was determined that the temperature affecting the top of piston changes in between 380 ºC - 400 ºC, and that the temperature values at pin housing of piston changes in between 300 ºC - 350 ºC. Moreover, the temperature value determined at piston skirts is 286 ºC. The studies performed inform that the temperature affecting the piston skirts also affects the oil life of motor.
The change of temperatures taken along the external surface borders of the piston as starting from the skirt point of piston are graphically being seen in Figure-5. As the fuel is being produced close to the leaning surface of the area at piston's surface (piston bowl) –where combustion is being realized by the spray of fuel-, it is being observed by the examination of graph that the temperature of the piston is higher at that area.

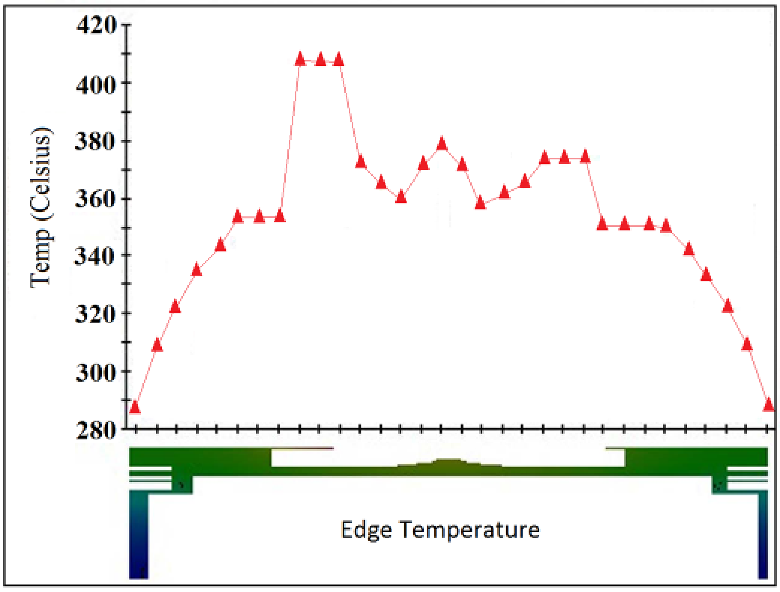

Figure 5. Standard AlSi alloy temperature reference points from the outside surface of the piston.

In Figure-6, the heat transmission of SiC coating on the piston is being observed. The thermal transmission coefficient of SiC material was determined as 41 W/mK, and the heat transmission coefficient of (NiCoCrAlY) material having intercoating layer was determined as 6.0 W/mK [16]. When the results of thermal analyses are examined, it is being observed that the heat is restrained in the piston bowl. Moreover, it is easily being observed from color transitions that the heat was not distributed to the whole surface of the piston. An higher temperature was determined in the combustion chamber compared to a standard piston. And this means that the temperature arising as the result combustion can be kept more within the cylinder. And lower temperature transitions are being observed at pin housing and skirt of piston compared to standard piston. This is being deemed as a positive development as it will increase the life of motor's lubricant.

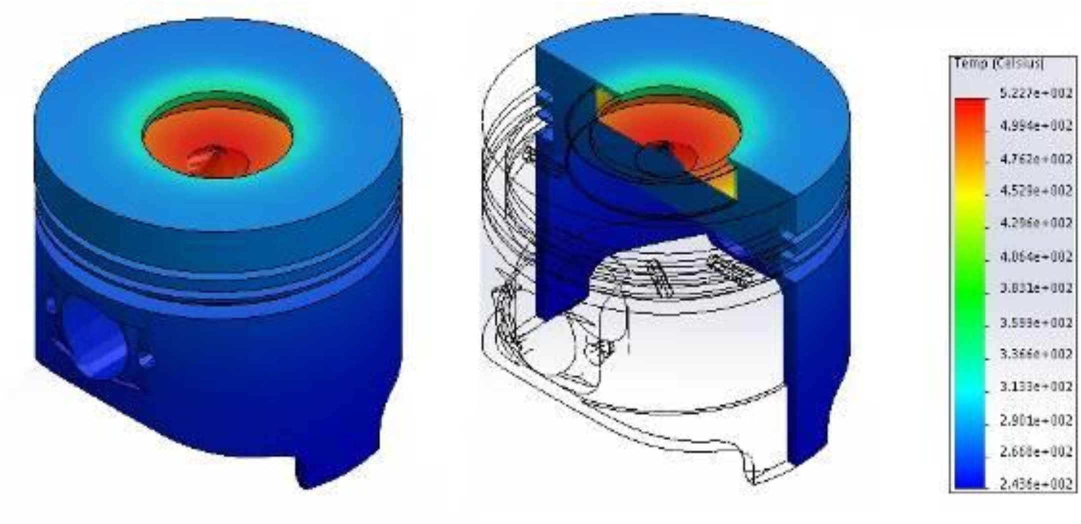

Figure 6. NiCoCrAlY intermediate coating layer, the temperature distribution of the SiC-coated pistons.

The graph of temperature values obtained from piston surfaces as the result of thermal analyses of piston with NiCoCrAlY intercoating and SiC coating is being provided in Figure-7. As the result of the thermal analysis performed, it was observed that the highest temperature value on the coated piston surface was 522,7 ºC within the piston bowl.

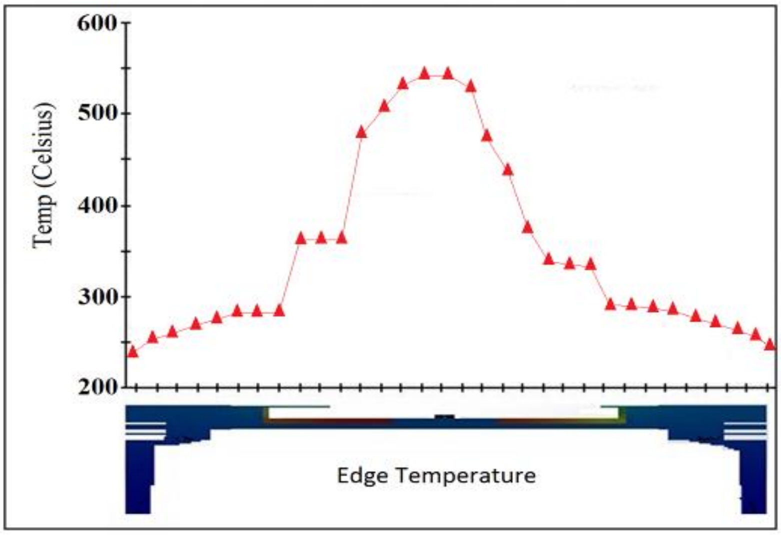

Figure 7. NiCoCrAlY intermediate coating layer, SiC coated piston received external reference surface temperature points.

Moreover, it was determined that the temperature values at pin housing of piston were 250 ºC - 270 ºC, and that it was 243 ºC at skirt part of piston. When we compare the results of thermal analysis with SiC piston having NiCoCrAlY intercoating layer and with piston of standard motor, an increase of 21.17% had been determined at combustion chamber, a decrease of 19.15% was determined at pin housing of piston and a decrease of 14.82 was determined at piston's skirt.
The graph of temperature values obtained from piston surfaces as the result of thermal analyses of NiCoCrAlY intercoating and $MgOZrO_2$ coated piston is being provided in Figure-7. In thermal analyses, the heat transmission coefficient of $MgOZrO_2$ material coated on piston's surface was taken as 2 W/mK. When the results of analysis are examined, it is being observed that the heat is being restrained on the surface of piston after coating and that the temperature values increase at the piston's bowl compared to other piston varieties. While higher temperature was observed at combustion chamber compared to standard piston, lower temperatures were obtained at pin and skirt of piston.

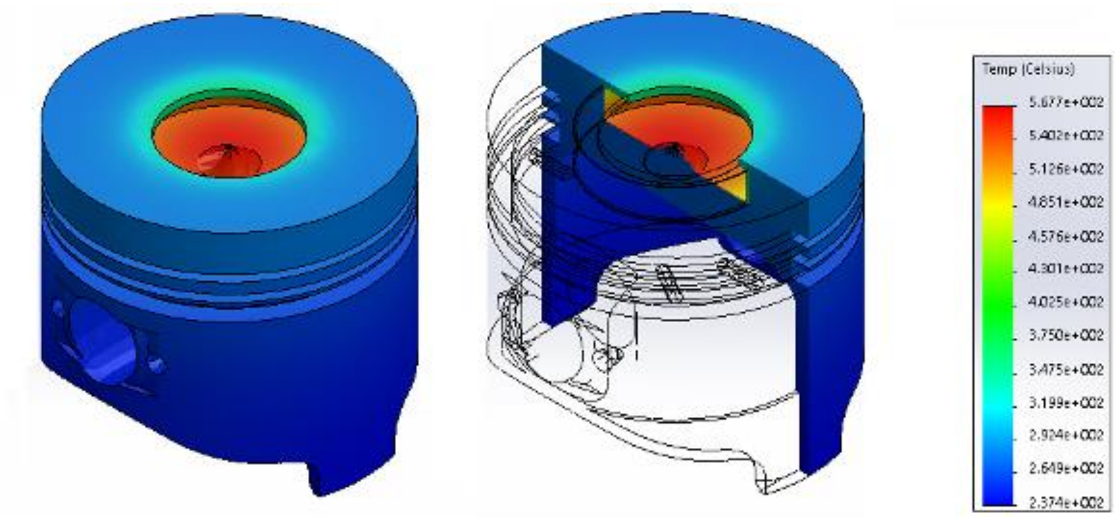

Figure 8. NiCoCrAlY intermediate coating layer, $MgOZrO_2$ coated piston temperature distribution.

The graph of temperature values obtained from piston surfaces as the result of thermal analyses of piston with NiCoCrAlY intercoating and $MgOZrO_2$ coating is being provided in Figure-9.

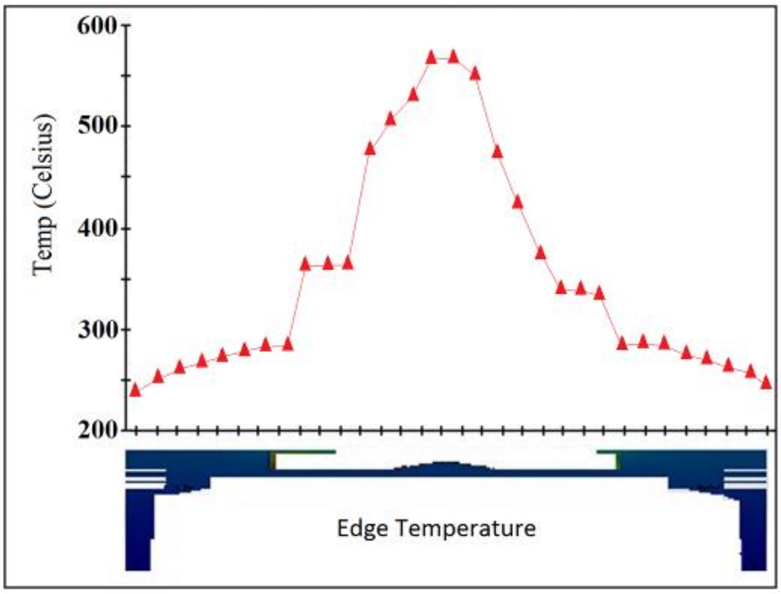

Figure 9. NiCoCrAlY intermediate coating layer, $MgOZrO_2$ coated piston received external reference surface temperature points.

It was observed that the highest temperature on the piston's surface occurred by 567.7 ºC at the area of walls of piston's bowl where the combustion was realized by the spray of fuel. Moreover, it was determined that a change in between 240 ºC - 260 ºC occurred at the piston's pin, and in between 237.4 ºC - 250 ºC at piston's skirt. As the result of coating of the piston with $MgOZrO_2$ material having NiCoCrAlY intercoating layer, it is being observed that the combustion chamber is hotter and that the temperature is lower at pin and skirt parts of piston compared to standard piston. And it was observed that lower temperature values were reached at combustion chamber and that higher temperature values were reached at pin and skirt parts of piston compared to piston coated with SiC. It is being considered that this condition had arose from heat transmission coefficients of the coating materials being used. When we compare $MgOZrO_2$ having NiCoCrAlY intercoating layer with standard piston, an increase of 26.36% was determined at combustion chamber, a decrease of 24.24% was determined at piston's pin housing and a decrease of 16.99% was determined at piston's skirt.

In Figure-10, the temperature values affecting the piston's surface are being provided. For ease of comparison, the given values indicate that the temperature values obtained on the surface of coating and piston increase. Moreover, the temperature amount transmitted to coated piston and piston's skirt and pin housing decreases. The increase of temperature restrained in the piston's bowl will positively affect the performance of motor. Similar studies in literature [20, 22] verify this.

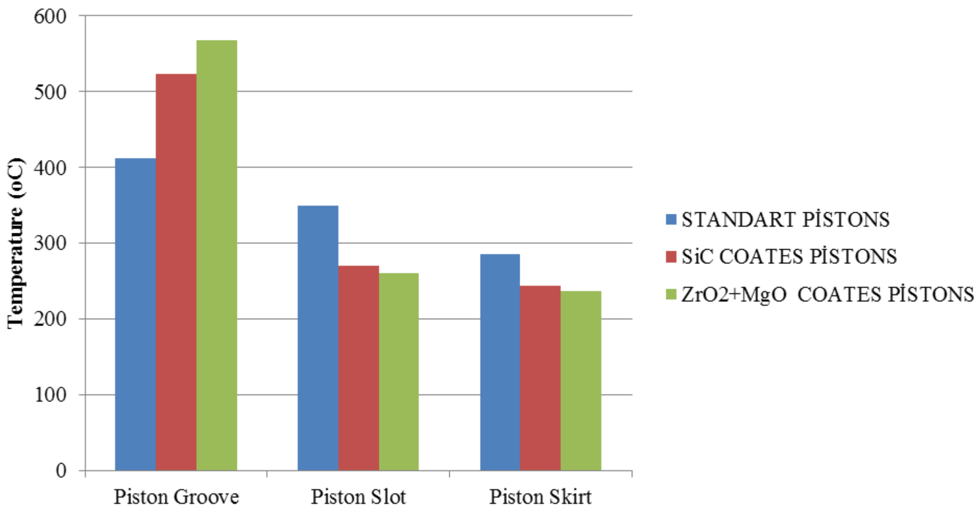

Figure 10. Temperature influencing the piston surface values are given.

5. Conclusions

In this study, it was determined as the result of thermal analyses that the highest temperature value had occurred by the piston bowl coated with $MgOZrO_2$. Temperature increase compared to standard piston was determined at a rate of 26.36%. By decreasing the heat transmission on piston coated with $MgOZrO_2$, less temperature effect on the main piston material was caused. Thus, less temperature was determined on the pins and skirts of pistons coated with $MgOZrO_2$. And in the piston coated with SiC, the temperature increase compared to piston coated with $MgOZrO_2$ was less by 5.19%, and it was higher by 21.17% compared to standard piston. In the direction of the obtained results, in pistons coated with SiC and $MgOZrO_2$ having NiCoCrAlY intercoating layer, it is being considered that the lower temperature affecting the AlSi material will increase the operation life of the material, and that lower temperature of piston's skirt parts will increase the life of motor's oil and will decrease the load of the cooling system of motor [23-25].

References

[1] Dallwoo K, Akemi I, Yasuhiro I, Katsuyuki O and Yoshiyuki I (2012). Friction Characteristics of Steel Pistons for Diesel Engines, Journal of Materials Research and Technology, 1,2, 96–102.

[2] Silva FS (2006). Fatigue on engine pistons – A compendium of case studies, Engineering Failure Analysis. 13, 480–492.

[3] Chetan S, Bhuvanesh DP, Nikhil TC and Vitthal RD (2015). Piston Analysis of IC Engine, International Journal of Advance Research and Innovative Ideas in Education (IJARIIE), Vol-1 Issue-2.

[4] Aydin H (2013). Combined effects of thermal barrier coating and blending with diesel fuel on usability of vegetable oils in diesel engines, Applied Thermal Engineering, 51, 1–2, 623–629.

[5] Nwafor OML, Rice G (1996). Performance of rapeseed oil blends in diesel engines, Applied Energy, 54, 345–354.

[6] Vural E, Ozel S, Ozdalyan B (2014). The investigation of microstructure and mechanical properties of oxide powders coated on engine pistons surface, Optoelectronıcs And Advanced Materials – Rapid Communications, 8,5-6, 515 – 520.

[7] Alkidas AC (1989). Performance and emissions achievements with an uncooled heavy duty, single cylinder diesel engine, SAE, vol. 890141.

[8] Buyukkaya E, Cerit M, (2007). Thermal analysis of a ceramic coating diesel engine piston using 3-D finite element method, Surface and Coatings Technology, 202,2, 398–402.

[9] Uzun A, Cevik I, Akcil M (1999). Effects of thermal barrier coating material on a turbocharged diesel engine performance, Surface Coating Technology, 505, 116–119 .

[10] Cerit M, Soyhan HS (2013). Thermal analysis of a combustion chamber surrounded by deposits in an HCCI engine, Applied Thermal Engineering, 50,1, 81–88.

[11] Marr MA (2009). An investigation of metal and ceramic thermal barrier coatings in a spark-ignition engine, M.S thesis, Mechanical and Industrial Engineering, University of Toronto, Canada.

[12] Esfahanian V, Javaheri A and Ghaffarpour M (2006). Thermal analysis of an SI engine piston using different combustion boundary condition treatments, Applied Thermal Engineering, 26,2 77–287.

[13] Cerit M (2011). Thermo mechanical analysis of a partially ceramic coated piston used in an SI engine, Surface and Coatings Technology, 205,11, 3499–3505.

[14] Cerit M, Ayhan V, Parlak A and Yasar H (2011). Thermal analysis of a partially ceramic coated piston: Effect on cold start HC emission in a spark ignition engine, Applied Thermal Engineering, 31 (2–3) 336.

[15] Khor KA and Gu YW (2000). Effects of stress on the performance of plasma sprayed functionally graded ZrO_2/NiCoCrAlY coatings, Materials Science and Engineering, 277,1–2, 64–76.

[16] Helmisyah AJ, Abdullah S and Ghazali MJ (2011). Structure Integrity Analysis of Piston Crown Against Thermal Stress For Compressed Natural Gas Direct Injection Engine, Regional Tribolology Conference, Bayviev Hotel, , 22-24 nowember, Langkawi Island, Malaysia.

[17] Shackelford J, Al FE (2001). Materials Science and EngineeringHandbook, Ed. James F. Shackelford & W. Alexander Boca Raton: CRC Press LLC, paper 68-123.

[18] Access Date: June 8, 2015 http://accuratus.com/zirc.html.

[19] Sroka ZJ (2012). Thermal load of tuned piston, Archives of Civil and Mechanical Engineering, 12, 342 – 347.

[20] Stang JH (1978). Designing adiabatic engine components, SAE Paper, vol. 780069.

[21] Brouwer MD, Gupta LA, Sadeghi F, Peroulis D and Adams D (2012). High temperature dynamic viscosity sensor for engine oil applications, Sensors and Actuators A: Physical, 173,1, 102–107.

[22] Buyukkaya E (1997). Effects of thermal barrier coating on a turbocharged diesel engine exhaust emissions, Ph D. thesis, Institute of Sciences and Technology, University of Sakarya, Turkey.

[23] Azadi M, Baloo M, Farrahi GH and Mirsalim SM (2013). A review of thermal barrier coating effects on diesel engine performance and components lifetime, International Journal of Automotive Engineering, 3, 1.

[24] Vedharaj S, Vallinayagam R, Yang WM, Chou SK, Chua KJE and Lee PS (2014). Experimental and finite element analysis of a coated diesel engine fueled by cashew nut shell liquid biodiesel, Experimental Thermal and Fluid Science, 53, 259–268.

[25] Vural E (2015). Thermal Analysis of Al_2O_3, TiO_2 and SiC Coatings Combustion of a Diesel Engine Piston 3D Finite Element Method, International Journal of Scientific and Technological Research, Vol 1, No 6.