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Research Article

Investigation of Thermal Insulation Performance at Different Coating Thicknesses by Using Finite Volume Method

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Abstract: In this study, the effect of coating thickness and thermal property on the temperature distribution of an internal combustion diesel piston was investigated numerically. A piston was modelled in three-dimensional, and then a grid independency test was performed. The optimum element number was selected without losing computational accuracy. The thickness values were considered as 250, 500, and 750 µm. Tungsten Carbide (WC) and Zirconia (ZrO_2) were used as coating material. Convective heat loads were applied as boundary conditions. Temperature values in different locations were used to evaluate the thermal performance of the coating layer. The numerical results showed that WC doesn't have a significant effect by the mean of thermal insulation and WC-coated piston top surface temperature is like uncoated temperature even with the higher thickness values. However, ZrO_2 has a better performance as thermal insulation material, and its effectiveness increases with higher thickness values.

Farklı Kaplama Kalınlıklarında Isıl Yalıtım Performansın Sonlu Hacim Metodu ile İncelenmesi

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Öz: Bu çalışmada, kaplama kalınlığının ve ısıl özelliğinin, içten yanmalı bir dizel motor pistonunun sıcaklık dağılımına olan etkisi sayısal olarak incelenmiştir. Piston üç boyutlu olarak modellenmiş ve ardından ağdan bağımsızlık çalışması yapılmıştır. Hesaplama hassasiyetini düşürmeden, en uygun eleman sayısı seçilmiştir. 250, 500 ve 750 µm olmak üzere üç farklı kaplama kalınlığı çalışılmıştır. Kaplama malzemesi olarak ise Tungsten Karbür (WC) ve Zirkonya (ZrO_2) kullanılmıştır. Sınır şartları olarak taşınım ısıl yükleri uygulanmıştır. Kaplama tabakasının ısıl performansını değerlendirmek için farklı konumlardaki sıcaklık değerleri kullanılmıştır. Sayısal sonuçlar göstermiştir ki, WC kaplamasının ısıl yalıtım üzerinde kayda değer bir etkisi yoktur ve kaplama yüzeyinin üzerindeki sıcaklık değerleri farklı kaplama kalınlıklarında bile kaplama yapılmayan piston ile aynıdır. Fakat, ZrO_2 ısıl yalıtım malzemesi olarak çok daha iyi bir performansa sahiptir ve bu durum artan kalınlık değerleri ile artmaktadır.

1. Introduction

The efficient use of fuels is very important today due to the increasing energy demand and costs. In addition, the efficient use of fuels is crucial in terms of reducing emission rates. Thermal losses in internal combustion engines are an engineering problem and directly affect efficiency. Similarly, thermal losses are a critical problem in diesel engine pistons. These losses cause decreases in fuel efficiency and increases in emission rates (Ramasamy et al., 2021; Wang et al., 2021).

To reduce thermal losses in diesel engine pistons, a coating process is carried out. The pistons are covered with a material with a lower thermal conductivity coefficient than the piston material and the amount of heat transferred from the combustion chamber to the piston is reduced. The coating on the piston is therefore also called the thermal barrier coating (TBC) (Vural, 2015). TBC materials decrease the piston surface temperatures while insulating the heat transfer that occurred from the combustion reaction. This effect, results to decrease heat transfer losses and an increases in the in-cylinder temperature (Aydin et al., 2015; Powell et al., 2017).

Many experimental and numerical studies have been conducted on the thermal performance and effects of TBCs. Coated diesel engine piston (Buyukkaya & Cerit, 2007; Cerit, 2011; Cerit & Coban, 2014; Gehlot & Tripathi, 2016; Baldissera & Delprete, 2018; Dhinesh et al., 2018; Wang et al., 2021; Gok & Karabas, 2022) and cylinder (Shen et al., 2012) are also investigated as different applications. Wang et al. (2021) investigated the effects of TBC material parameters like specific heat capacity, thermal conductivity, and porosity within reasonable ranges on engine combustion and emissions. Gok & Karabas (2022) stated that they obtained a lower thermal conductivity value by doping LZ with Gd and Yb and coating them on a metal substrate by plasma spraying method to obtain single and double-layered TBCs. They simulated the thermal insulation and surface temperatures on the produced coating on a diesel engine piston with the finite element method. Gehlot & Tripathi (2016) investigated the steady-state thermal analysis of a diesel engine piston coated with a ceramic coating having holes on its surface. They compared the coating which has holes with, having no holes then found a significant increase in the piston top surface temperature occurs with the coating having holes.

There is a limited number of studies that investigate the thermal barrier performance of coating materials on internal combustion engine pistons numerically. We investigated and compared different temperature values from different locations on the piston and coating layer. In addition, we considered the thickness of the coating layer and different materials. In addition, a grid-independent solution is presented in detail. In this study, the effect of 250, 500, and 750 µm WC and ZrO2 coating layer on the diesel engine piston thermal performance was investigated numerically under steady-state conditions. Piston surface temperature values are considered as performance criteria and results were compared with each other and an uncoated piston.

2. Material and Methods

2.1. Geometry and modelling

A diesel engine piston was modelled in 3D and the dimensions of the model are shown in Figure 1. The model contains fundamental geometric characteristics of a diesel engine piston. The coated piston geometry has an extra body on the piston which represents coating materials. Three different coating thicknesses (250 µm, 500 µm, and 750 µm) were investigated.

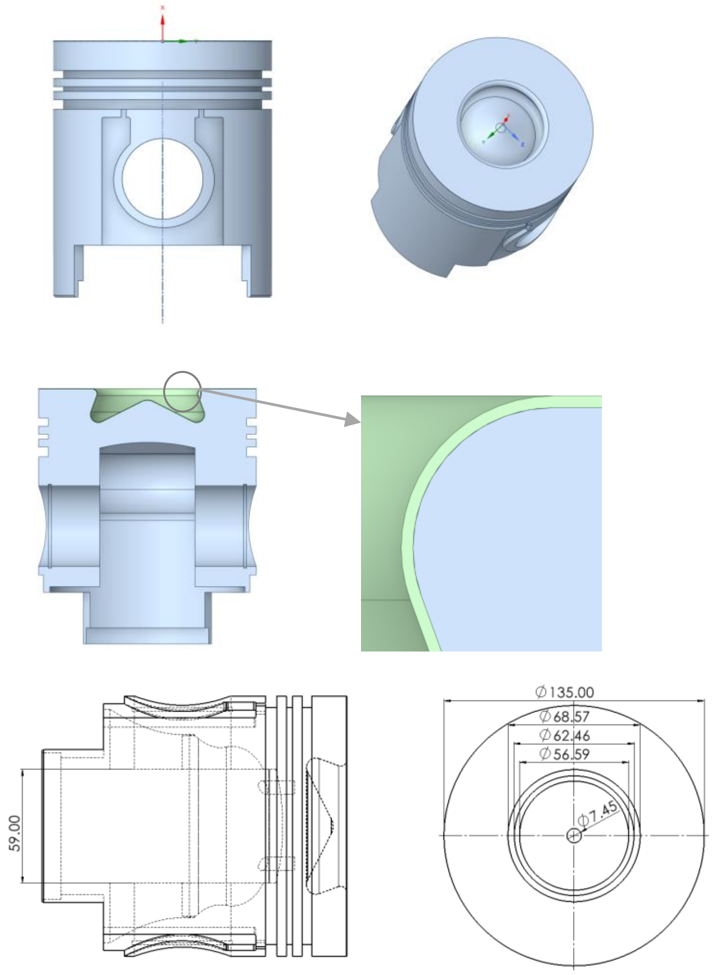


Figure 1. 3D model of the piston and dimensions.

2.2. Grid independence

Grid independence study is critical for computational studies to show that the results are consistent and independent of the element numbers. It is also important to use computational sources efficiently. In this study, three different element numbers were tested to obtain grid independence: 323 399, 797 994, and 969 609. The uncoated piston coated was used for the grid independence study. The comparison of the results was shown in Figure 2. All grids have similar performance but 797 994, and 969 609 element numbers have the same performance, so the grid has 797 994 elements number was used for further simulations to decrease the computational cost.

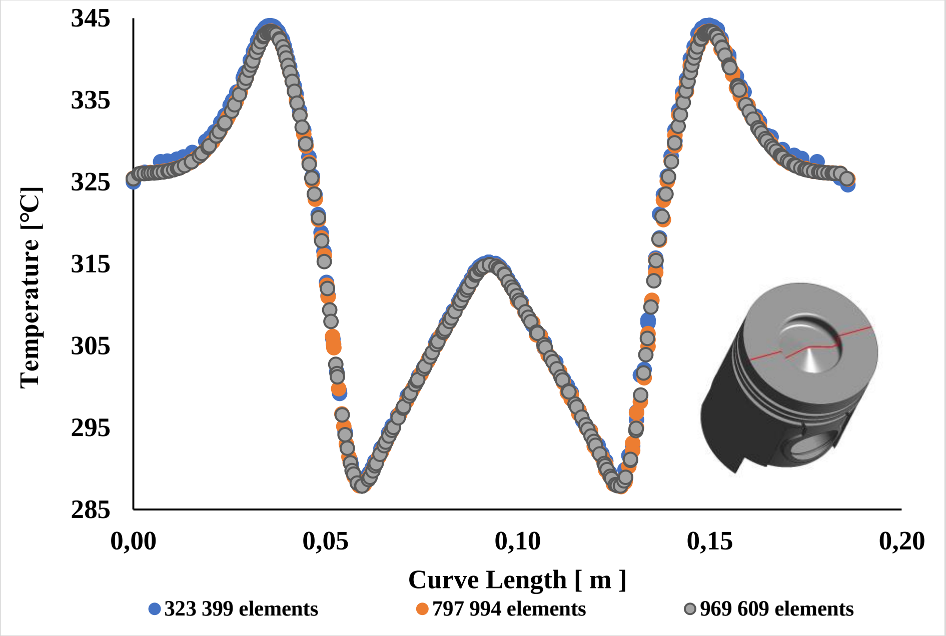


Figure 2. Comparison of different element numbers.

2.3. Boundary conditions

Seven numerical simulations were performed with four different geometries according to the coating situation and thickness values. ZrO_2 and WC were used for coating materials. Simulations were performed in steady-state conditions. The piston material is considered as AlSi and the thermal conductivity coefficient of AlSi is 155 W mK^{-1}. The thermal conductivity coefficient of WC and ZrO2 were also set as 96 W mK^{-1} and 2.7 W mK^{-1} respectively. The melting point of the WC is 2870°C, and it has a high abrasion resistance. Although the thermal conductivity coefficient is close to the AlSi alloy, which is the piston material, it can provide a surface resistant to abrasion and thermal deformation on the piston surface. These properties of the material are the main motivation to investigate the thermal insulation behavior.

Thermal loads on the piston surface were modelled as convection heat transfer and these surfaces are shown in Figure 3. The heat transfer coefficients and ambient temperatures are 800 W m^2K^{-1}-600°C (Figure 3a), 230 W m^2K^{-1}-300°C (Figure 3b), 200 W m^2K^{-1} -160°C (Figure 3c) and 1500 W m^2K^{-1} -110°C (Figure 4a) (Vural, 2015). ANSYS Fluent was used as the simulation program. Converge criteria was set as 10^{-15}.

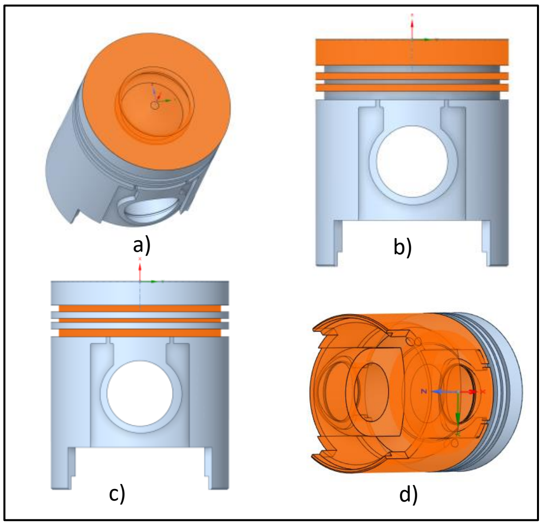


Figure 3. Surfaces in which convection boundary conditions are applied.

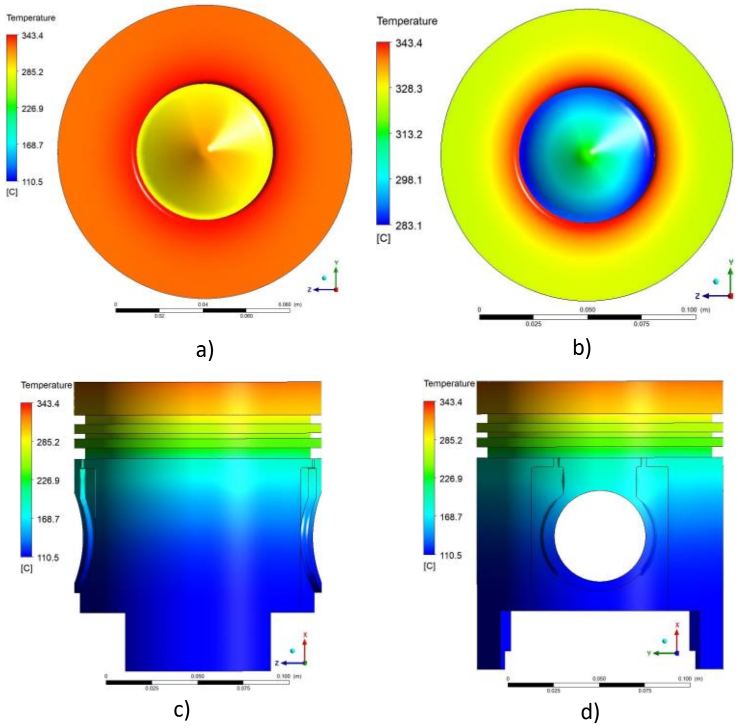
2.4. Plasma spray coating

Plasma spray coating is a method applied for coatings with very high melting points. In the plasma torch, an electric arc occurs between the anode and cathode. This arc ionizes the pressurized inert gas (such as argon, helium, nitrogen, hydrogen) used as plasma gas, resulting in the formation of plasma at high temperatures. A plasma of approximately 15,000 K temperature can be created at the center of the plasma arc. The coating powder is fed into the plasma, either from a very close nozzle exit point or from the inside. This process ensures that the powder reaches the hottest part of the plasma. The thermal energy of the plasma melts the powders, and the molten powders are propelled onto the substrate by the increased pressure in the nozzle, resulting in the coating (Özel, 2009).

3. Results

In this study, the thermal loads affecting a diesel piston were investigated both on an uncoated piston, and with two coated pistons with different coating thicknesses. WC and ZrO2 were investigated as coating materials. These two coating materials have thermal conductivity coefficients of 95 and 2.7 W mK^{-1} that providing a wide comparison range to see the effect of the thermal conductivity coefficient.

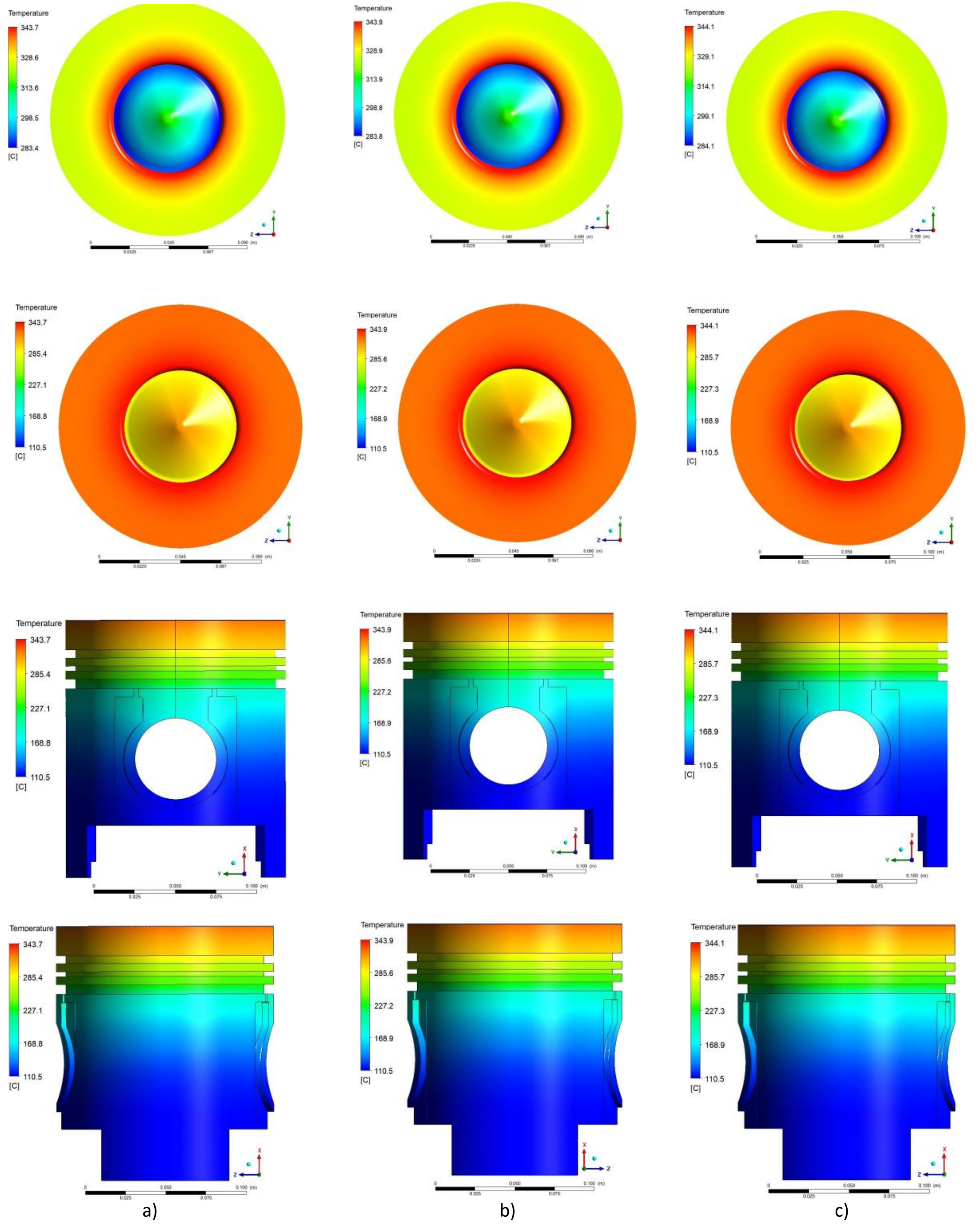
The temperature distribution on the uncoated piston surface is shown in Figure 4. The maximum temperature on the piston is 343.4 °C and the minimum temperature is 110.5 °C as expected. The reason for this is that the lowest environmental temperature in the convective heat transfer boundary condition is defined in the bottom and interior of the piston. The piston combustion chamber surface temperature is not homogeneous, and it can be seen clearly in Figure 4b which has a local colour scale. The highest temperature in the piston combustion chamber is 343.4 °C and the lowest temperature is 283.1 °C. The highest temperature in the piston combustion chamber is in the middle point.



a) b) c) d)

Figure 4. Temperature distribution on the surfaces of the uncoated piston (a,c,d is coloured with the global temperature scale and, b is coloured with the local scale).

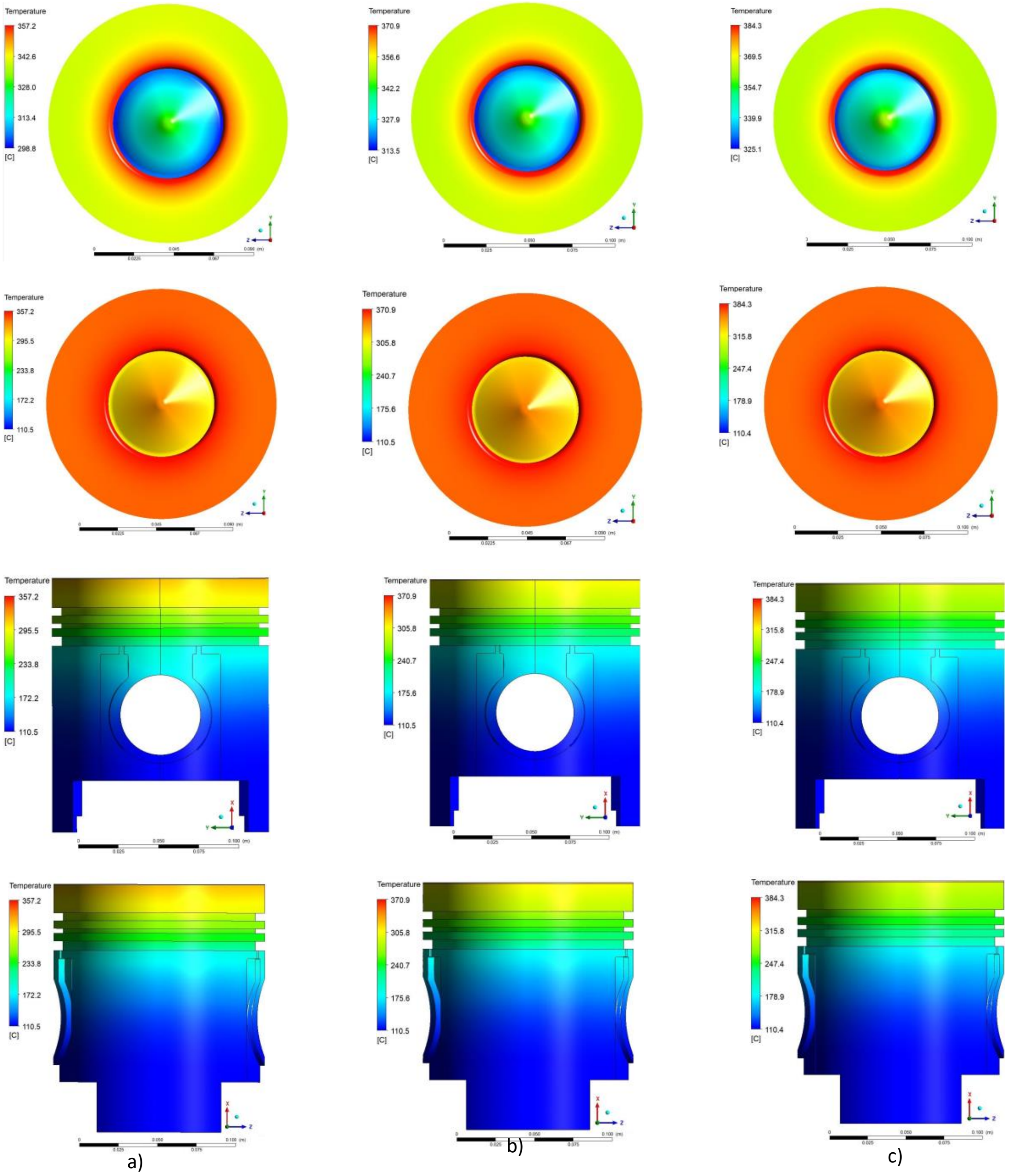
The temperature distributions over the WC-coated pistons in different thicknesses are shown in Figure 5. The maximum temperature values on the pistons are 343.7, 343.9, and 344.1 °C respectively for coating layers that have 250, 500, and 750 μm thickness. It is observed that thickness doesn't have a significant effect on the temperature distributions of WC-coated pistons because of the high conductivity coefficient (96 W mK^{-1}). The minimum temperature values are 110.5 °C for all thickness values, as on the uncoated piston. The piston combustion chamber temperature distribution is also similar to the uncoated piston. The highest temperature in the combustion cell was obtained in the middle point.



a) b) c)

Figure 5. Temperature distribution on the surfaces of a) 250μm, b) 500μm, c) 750μm WC-coated piston.

The temperature distributions over the ZrO_2-coated pistons in different thicknesses are shown in Figure 6. The maximum temperature values on the pistons are 357.2, 370.9, and 384.3 °C respectively for coating layers that have 250, 500, and 750µm thickness. The thermal behaviour of the ZrO_2 coating layer is different from the WC coating. Surface temperatures of combustion chambers with all thickness values are higher than WC-coated pistons and different from each other. It is observed that thickness has an important effect on the temperature distributions of ZrO_2-coated pistons because of the low (2.7 W mK^{-1}) conductivity coefficient. The minimum temperature values are 110.5 °C for all thickness values, as on the uncoated piston and WC-coated piston. The temperature distribution in the piston combustion chamber is the same as the other pistons in terms of temperature difference. The highest temperature in the combustion cell was obtained in the middle point.



a) b) c)

Figure 6. Temperature distribution on the surfaces of a) 250µm, b) 500µm, c) 750µm ZrO_2-coated piston.

The top surface temperature profiles of coated pistons and uncoated piston under the same thermal loads are given in Figure 7 and this figure summarizes the temperature values on the piston top surface for all thicknesses. Materials that have low thermal conductivity coefficients have a thermal insulation effect and this effect causes a decrease in heat transfer from the ambient to the piston. As a result of this, the temperature of the top surfaces of the coated pistons increases but under the coating layer, the surface temperature decreases. The lowest temperature values on the piston surface were obtained in the uncoated piston. However, the temperature profile of WC-coated pistons is only slightly different from the uncoated pistons in the steady state conditions, even for the higher thickness values.

The surface temperature values in the ZrO_2-coated pistons are higher than the piston coated with WC and the uncoated piston. The temperature is maximum at the edge between the upper surface of the piston and the combustion chamber. The top surface temperature increases with the thickness values. Maximum temperature values were obtained at the 750 µm coating thickness.

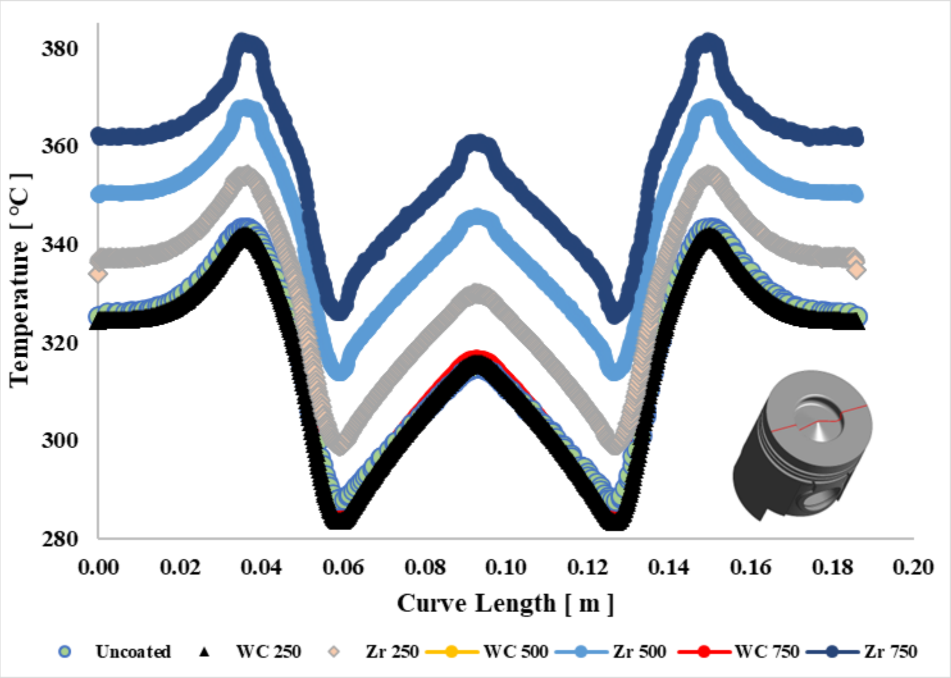


Figure 7. Temperature distributions on the top surface of the pistons.

The surface temperature profile of the uncoated piston and the temperature profiles of the coated pistons' sub-surface are shown in Figure 8. As mentioned above, the coating layer has a thermal insulation effect that decreases the heat transfer from the environment to the piston body. As a result of this effect, temperature values under the coating layer are lower than the top surface temperatures. Temperature distributions on the pistons covered with ZrO_2 have the lowest temperature values and higher thicknesses improve the insulation performance according to Figure 8. The uncoated piston has the highest temperature values, and the WC-coated pistons have similar results to the uncoated piston.

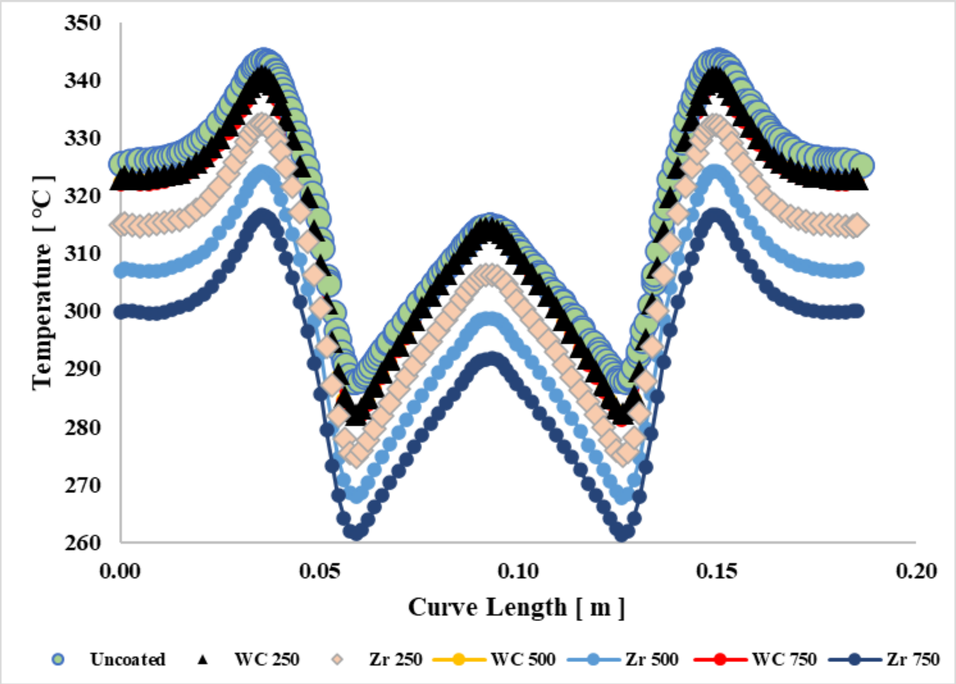


Figure 8. Temperature distributions on the sub-surface of the coating.

Temperature values at different locations on the piston and coating layer are shown in Table 1. The mean top and bottom surface temperatures of the WC coating layers are close to each other in all thickness values because of the high heat transfer rate. On the other hand, differences between the mean top and bottom surface temperatures of the ZrO_2 coating layer are 23.50, 44.98, and 64.69 °C for 250, 500, and 750 µm thickness values respectively. This relation also affects the maximum temperature values. The highest maximum temperature on the piston body is 342.858 at the uncoated piston and the lowest value is at the 750 µm ZrO_2 coated piston.

Table 1. Temperature values on the coating layer and piston

Temperature (°C)	**250 µm**		**500 µm**		**750 µm**	
	WC	**ZrO_2**	**WC**	**ZrO_2**	**WC**	**ZrO_2**
Mean coating layer	320.486	323.669	320.409	326.475	320.327	329.024
Mean piston body	217.804	213.649	217.514	209.589	217.225	205.863
Mean coating top surface	320.953	335.439	321.344	349.006	321.729	361.445
Mean coating bottom surface	320.048	311.943	319.505	304.03	318.958	296.759
Maximum value on coating	343.671	356.08	343.874	369.71	344.046	383
Maximum value on piston	342.858	334.451	342.439	326.331	341.933	318.761
Minimum value on coating	282.761	276.509	282.366	270.197	281.962	263.712
Minimum value on piston	110.497	110.478	110.495	110.459	110.494	110.442

4. Discussion and Conclusion

This study aims to investigate the temperature distributions of diesel engine pistons coated with 250, 500, and 750 µm WC and ZrO_2. According to numerical results, their performance was compared with the uncoated piston. The temperature distributions on the piston surfaces, and the lower and upper surfaces of the coating layer, were calculated and compared.

It is found that, WC is not a successful thermal insulation material because of the high thermal conductivity coefficient even in high thickness values. Furthermore, the temperature distribution of the WC-coated piston is very similar to the uncoated piston. On the other hand, the thermal performance of the ZrO_2 coating layer is better in all thickness values. It is more successful in reducing the transfer of heat generated by the combustion reaction to the piston. It is thought that this positive effect will be effective in reducing the thermal loads on the piston, as well as increasing the combustion temperature and reducing emissions and fuel consumption. The increase of ZrO_2 coating thickness increases the insulation performance but it should be noticed that this relation is not linear, and the optimum value should be investigated.

5. Acknowledgement

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