

Effects of Different Piston Materials and Head Design on the Thermal Performance of Four Stroke Spark Ignition Engine Piston

***Makale Bilgisi / Article Info**

Alındı/Received: 17.01.2025

Kabul/Accepted: 14.06.2025

Yayımlandı/Published: xx.xx.xxxx

Farklı Piston Malzemelerinin ve Kafa Tasarımının Dört Zamanlı Buji Ateşlemeli Motor Pistonunun Termal Performansına Etkileri

Hasancan ATAŞ , Berkay KARAÇOR* , Mustafa ÖZCANLI 

Çukurova Üniversitesi, Mühendislik Fakültesi, Otomotiv Mühendisliği Bölümü, Adana, Türkiye



© 2025 The Authors | Creative Commons Attribution-Noncommercial 4.0 (CC BY-NC) International License

Abstract

In this study, the effects of using different materials in different piston head designs for internal combustion engines on the thermal performance of the piston heads were analyzed. Three different piston head models were created using the CAD/CAM software CATIA V5 R21 and thermal analysis was performed in ANSYS Workbench. The designs were evaluated using Al 6061 and AlSiC materials to investigate the temperature distribution and heat flux performance. The analysis results showed significant differences between the two materials. Based on the results of piston head designs 1, 2, and 3, AlSiC showed superior performance due to its high thermal conductivity and temperature resistance. In the results, piston head design 2 with AlSiC showed higher performance than Al 6061 with a maximum heat flux of 8.21×10^5 W/m in piston 2 head design. However, Al 6061 offers advantages in terms of lower cost and ease of manufacture. Among the three piston head designs, piston head 2 was characterized by a balanced temperature distribution (min. 456.75°C, max. 500°C) and superior thermal performance. When using AlSiC, the maximum heat flux of 8.21×10^5 W/m² compared to 8.15×10^5 W/m² for Al 6061 showed improved thermal conductivity, resulting in exceptional stability against high temperature fluctuations.

Keywords: Piston head; Thermal analysis; AlSiC; Al 6061

Öz

Bu çalışmada, içten yanmalı motorlar için farklı piston kafası tasarımlarında farklı malzeme kullanımının piston kafalarındaki termal performans üzerindeki etkileri analiz edilmiştir. CATIA V5 R21 CAD/CAM yazılımı kullanılarak üç farklı piston kafası modeli oluşturulmuştur ve ANSYS Workbench yazılımında termal analiz yapılmıştır. Tasarımlar, Al 6061 ve AlSiC malzemeleri kullanılarak sıcaklık dağılımı ve ısı akısı performansları incelenmiştir. Analiz sonuçları, her iki malzeme arasında belirgin farklar ortaya koymuştur. Piston kafası tasarımı 1, 2 ve 3 verilerine göre, AlSiC malzemesi, yüksek termal iletkenliği ve sıcaklık dayanımı ile daha üstün performans göstermiştir. Sonuçlarda, piston kafası 2 tasarımında AlSiC malzemesi $8,31 \times 10^5$ W/m² maksimum ısı akısı ile Al 6061'den daha yüksek bir performans sergilemiştir. Ancak Al 6061, daha düşük maliyet ve üretim kolaylığı ile avantaj sağlamaktadır. Üç piston kafası tasarımı değerlendirildiğinde, Piston kafası 2, dengeli sıcaklık dağılımı (min. 456.75 °C, maks. 500 °C) ve yüksek termal performansı ile öne çıkmaktadır. AlSiC malzemesi kullanıldığında, maksimum ısı akısı 8.21×10^5 W/m² ile Al 6061'in 8.15×10^5 W/m² değerine kıyasla ısıyı daha hızlı iletme kabiliyeti sayesinde yüksek sıcaklık dalgalanmaları karşı üstün bir stabilite göstermiştir.

Anahtar Kelimeler: Piston kafası; Termal analiz, AlSiC; Al 6061

1. Introduction

Internal combustion engines have been one of the most important components in the automotive industry for many years. These engines are widely used due to their high efficiency in energy conversion and their durability. One of the most important components of the engine is the piston, which is directly exposed to high temperatures and high pressure in the combustion chamber. The durability of the piston plays a central role in the operation of the engine, as it directly influences both performance and overall service life. However, modern engine designs with requirements such as high speed, short stroke, large cylinder diameter, and high

compression ratio require properties such as low weight, high thermal conductivity, and mechanical strength in the piston design (Citak et al. 2010).

Originally, pistons were made of cast iron, which provided adequate performance for low-speed, long-stroke engines. However, cast iron pistons did not meet the requirements of modern engines. Today, piston manufacturers are addressing these needs by developing aluminium alloy pistons with specific properties developed through their research and production techniques (Crouse 1970). Pure aluminium materials are inadequate for piston applications due to their low tensile strength. For example, the tensile strength of pure

aluminium is between 92-114 N/mm² at room temperature but drops to as low as 31 N/mm² when the operating temperature of the piston reaches 300°C (Heisler. 1999). Therefore, optimizing both the material properties and the geometric design of the pistons is crucial to improving the performance and durability of the engine.

One of the biggest challenges with piston crowns is the deformation caused by excessive temperatures and mechanical stresses during combustion. This problem leads to issues such as thermal expansion, fatigue, and wear, reducing the overall performance and reliability of the engine. To effectively address these issues, careful material selection and optimization of the geometric design is required. In particular, the precise dimensioning of the piston crown, rings, and pin bosses ensures an even distribution of the thermal stresses generated by combustion (Lin et al. 2013).

The aim of this study is to analyze different piston head designs for internal combustion engines and to determine the optimal design and material combinations. Using CATIA V5 R21 software, three different piston head designs were created and thermal analyses were performed by assigning the materials Al 6061 and AlSiC to each design. Parameters such as temperature distribution, heat flux, and thermal performance of the piston heads were evaluated by analyzing with Ansys Workbench software.

The forces generated by high-temperature and high-pressure gases exert constant pressure and put the durability of the engine to the test. During its working cycle, the piston is subjected to thermal stresses due to temperature gradients (Bayram et al. 2024). A piston optimized for biofuel was coated with zirconium to reduce weight and increase strength. In this study (Krishna et al. 2014), thermal tests were performed using ANSYS on the top surface of a coated piston crown exposed to high temperatures. An analysis of the stresses caused by thermal fluctuations in different parts of the coated piston was performed. There are studies (Krishna et al. 2013) dealing with the design, analysis, and optimization of pistons that are stronger, lighter, and faster to manufacture. Engine performance depends heavily on the weight and design parameters of the piston. A three-dimensional thermal stress analysis was performed on a gasoline engine piston under the influence of combustion chamber temperature and gas pressure using ANSYS finite element analysis software (Lin et al. 2013). Taking into account the thermal boundary conditions, the stress and deformation distribution

conditions under thermal load and explosion pressure were calculated to obtain clues for design improvements. Temperature has been identified as the main factor contributing to piston failure, deformation, and high stresses. Structural optimization is one possible way to mitigate these problems by lowering piston temperatures. In the study of Guo et al. (Guo et al. 2014), the temperature field, the thermal and mechanical stress as well as the combined thermal-mechanical stress of the piston of a 2-stroke 6S35ME marine diesel engine were simulated. The spatial variation and intensity of the above strength properties are critical to the effective design of pistons, the evaluation of potential defects, and the optimization of performance. In this work, simulation parameters were used that include the piston material, combustion pressure, and temperature. In this paper (Chougule et al. 2013) as well as in the research of Monoj et al. (Manoj et al. 2018), a model for predicting the temperature gradient of thermal barrier coatings (TBCs) for different ceramic types and coating thicknesses was developed and created using ANSYS Fluent simulation software. ANSYS Multiphysics was used by Dudareva et al. (Dudareva et al. 2017) to simulate the thermal state of the piston. As part of their study, experiments were carried out with a single-cylinder engine, which represents a four-cylinder engine with two cylinders. A coating was applied to the surface of the piston crown facing the combustion chamber.

Bolek et al. (Bolek et al. 2017) investigated thermal barrier coatings of yttrium-stabilized zirconia (YSZ) and β -NiAl interdiffusion layers deposited on Inconel 713C. The computational analysis showed that stress concentrations were observed at locations beyond the interface peaks and valleys within the layered structure, but also on the semi-flat surfaces in between. Janardhana et al. (Janardhana et al. 2017) analyzed the Al-ZrO₂ combination for different volume fraction indices. A sensitivity analysis was performed to investigate the influence of various parameters, including power law exponents, thickness to width ratio, aspect ratio, boundary conditions, and amount of loading. Yerrennagoudaru and Manjunatha (Manjunatha and Yerrennagoudaru. 2017) have designed both conventional and modified pistons using Unigraphics software. The resulting properties of the flow field were then analyzed using the CFD software Fluent ANSYS-14.5. Their report included comparative temperature analyses of conventional and uncoated pistons and plots for swirl ratio, wobble ratio, and cross wobble ratio. Liu et al. (Liu et al. 2017) investigated the effects of adding ultrasonic vibrations to the laser coating process on the

development of microstructure and the dilution properties between the coating and substrate. Kocabicak et al. (Kocabicak et al. 1999) analyzed the thermal stresses developing under thermal load for Al_2O_3 -SG, ZrO_2 -12%Si+Al, and ZrO_2 -SG coatings. The systems were modelled with a layer thickness of 0.4 mm and a substrate material thickness of 4 mm. Celik and Sarikaya (Celik and Sarikaya 2004). investigated the relationship between porosity and residual stress in MgO - ZrO_2 coatings on Al-Si alloy substrates. Using the finite element method, thermal loads were applied at 550°C and it was found that the highest thermal shock resistance was achieved with 7.5% small, uniformly distributed porosity. Avci et al. (Avci et al. 1999) investigated the effects of different surfaces. Thermal and structural finite element analyses enabled the investigation of nominal and shear stresses in critical interface regions. Thermal shock resistance tests showed that ZrO_2 -SG coatings had superior performance compared to Al_2O_3 -SG and ZrO_2 (12%Si+Al) systems. Celik and Sarikaya (Celik and Sarikaya 2002) analyzed the effects of thermal stress on MgO - ZrO_2 /NiCrAlY coatings on Ni metal and AlSi alloy (LM13) substrates. The samples coated by the atmospheric plasma spray technique were subjected to thermal stress in the range of 800–1000°C. It was found that thicker coatings increased the residual stresses, while interfacial coatings reduced these stresses.

Genc et al. (Genc et al. 1997) analyzed the effects of volume, size, and distribution of porosity on thermal stresses in MgO . ZrO_2 -GG coatings. Their studies showed that low stresses were achieved with 7% small, uniformly distributed porosity away from the surface. Gu and Kho (Gu and Khor 2000) produced coatings with different thicknesses and layer architectures and then carried out evaluations of the adhesive strength and thermal shock resistance. Their investigations showed that a five-layer FGM coating had five times longer service life under thermal cycling than two-layer coatings. Avci et al. (Avci et al. 1996) used the ANSYS finite element code for crack analysis in ceramic coatings under thermal cycling. In their studies, the material properties were considered hypothetically and the stress intensity factors were evaluated. The results showed that shorter crack lengths and thinner coatings form more robust coatings. Finite element methods (FEM) provided an explanation of the stress distribution in the piston. The FEM analysis was carried out using CAE software. The main objective of this research was to understand and quantify the temperature distribution on the piston surface during the combustion process under realistic engine operating scenarios. The study explained the mesh optimization to

predict high stresses and critical areas on the component using FEM techniques. The work investigated how the thickness of the piston crown, the piston tube, and the piston crown affected the temperature distribution. All optimizations were performed based on statistical analysis and FEM analysis was performed using ANSYS for the optimal geometry.

In this study, the thermal stresses of two different alloy pistons are explained using the finite element method. The parameters used for the simulation included the operating gas pressure, temperature, and material properties of the piston. This article aims to shed light on the selection of suitable materials and designs for engine development by comparing the thermal performance of different materials used in the construction of piston crowns. Moreover, it offers a unique approach by integrating both design and material analysis, which distinguishes it from similar studies in the literature.

2. Materials

The pistons used in internal combustion engines are made of various metals and alloys. Among these materials, cast iron, steel, and aluminum alloys are commonly used. In this study, Al 6061 and AlSiC were selected as composite materials due to their different advantages for design and analysis. Al 6061 was chosen because of its lower production cost and ease of machining, making it a cost-effective option for budget-dependent applications. AlSiC, on the other hand, is more expensive but offers better thermal conductivity and temperature resistance, making it particularly suitable for high performance applications where durability under thermal stress is critical. These materials were further evaluated based on their thermal and mechanical properties to optimize the piston design. Table 1 and Table 2 indicate the characteristics of these materials.

Table 1: Properties of the material Al 6061 (Krishnan et al.2017)

Parameters	Al 6061
Elastic modulus (GPa)	68.9
Ultimate tensile stress (MPa)	260
%0,2 yield stress (MPa)	240
Poisson ratio	0.33
Thermal conductivity (W/mK)	173
Density (kg/m ³)	2700
Coefficient of thermal expansion (m/°C)	23.5 x 10 ⁻⁶

Table 2: Properties of the material AlSiC (Krishnan et al.2017)

Parameters	AlSiC (40-60) %
Young's modulus (GPa)	230
Poisson ratio	0.24
Thermal conductivity (W/mK)	197
Density (kg/m ³)	2937
Specific gravity (J/Kg x °C)	894

The reasons for choosing the AlSiC material are its individually adjustable thermal expansion coefficient, excellent thermal conductivity, lightness and durability, and the possibility of precise surface treatment. Al 6061 was preferred in the analysis due to its improved strength properties, high durability, and a balanced resistance profile against wear, deformation and fracture.

3. Methods

Three different piston head models were designed using the CAD/CAM software CATIA V5 R21, which enables precise geometric modelling. These designs were then imported into ANSYS Workbench for a Steady-state thermal analysis to evaluate the temperature distribution and heat flux performance. In this study, the ANSYS Steady-State Thermal module was used to investigate the Steady-state thermal behaviour of the analyzed system. This method was preferred to determine the temperature distribution and heat flux on the system in a time-independent manner.

3.1. Design procedure

Table 3 gives the specifications of the analyzed piston design. Equations (1)-(7) indicate the necessary size calculations when designing a piston (Krishnan et al. 2017).

Table 3: Specifications of a piston

Parameters	Values
Engine type	4 stroke, petrol engine
Number of cylinders	Single cylinder
Length (L)	80 mm
Bore diameter (D)	60 mm
Maximum power	6.03 KW at 7500 rpm
Maximum Torque	8.05 N/m at 5500 rpm
Compression ratio	8.4
Calorific value of petrol	4700 kJ/kg

$$h_1 = (t_h \text{ to } 1.2 t_h) = 4 \text{ mm} \quad (1)$$

$$h_2 = (0.75 h \text{ and } h) = 0.8 \text{ mm} \quad (2)$$

$$t_1 = 0.03D + b + 4.9 = 2.1 \text{ mm} + 2 + 4.9 = 9 \text{ mm} \quad (3)$$

$$t_2 = (0.25 t_1 \text{ and } 0.35 t_1) = 0.3 \times 9 \text{ mm} = 27 \text{ mm} \quad (4)$$

$$I_s = (0.6D \text{ to } 0.8D) = 0.74 \times 60 \text{ mm} = 23.4 \text{ mm} \quad (5)$$

$$I_1 = 0.45 \times 60 \text{ mm} = 27 \text{ mm} \quad (6)$$

$$d_o = (0.28D \text{ to } 0.38D) = 0.3 \times 60 \text{ mm} \quad (7)$$

h : Axial thickness of piston ring (mm)

h_1 : Width of top lands (mm)

h_2 : Width of ring lands (mm)

t_h : Thickness of piston head (mm)

t_1 : Thickness of the piston barrel at the cylinder head end (mm)

t_2 : Thickness of the piston barrel at the connecting rod end (mm)

D : Cylinder bore (mm)

I_s : Length of skirt (mm)

I_1 : Length of the piston pin within the bushing of the connecting rod's small end (mm)

d_o : Outer diameter of piston (mm)

b : Radial width of the ring (mm) (Krishnan et al. 2017)

3.2. CAD drawings of a piston

Figures 1,2 and 3 give the three different piston head design geometric design dimensions.

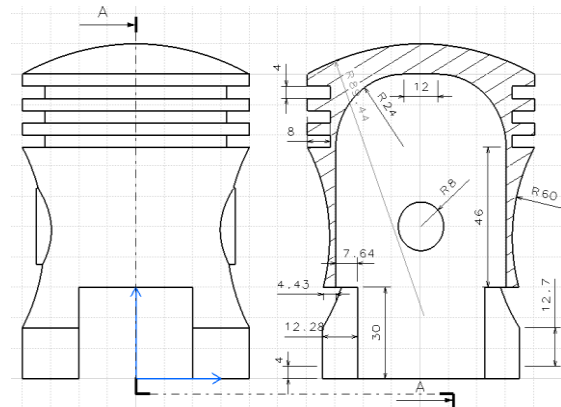


Figure 1. Technical drawing of piston head 1 design

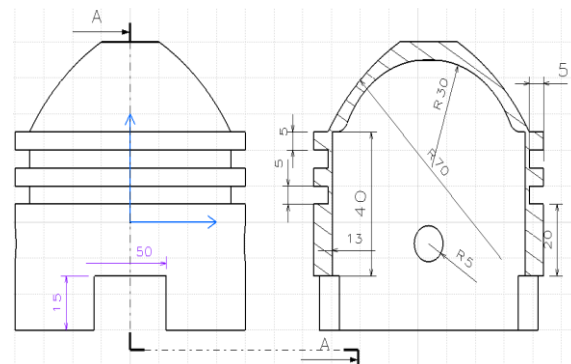


Figure 2. Technical drawing of piston head 2 design

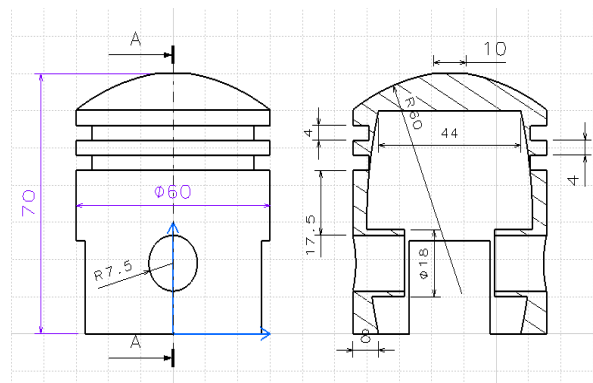


Figure 3. Technical drawing of piston head 3 design

3.3. Analysis

CAD software was used to create the system geometry, which was then imported into ANSYS for analysis. The model was simplified to remove superfluous details and optimize it for thermal simulation. Thermal properties

such as thermal conductivity, specific heat capacity, and density of the materials making up the system were taken from the literature and the manufacturer's specifications and then applied to the model.



Figure 4. a) Mesh view of piston head design 1, b) piston head design 2, and c) piston head design 3

After material properties have been assigned material properties to the model, the entire piston head is selected and meshed using the tetrahedron method. To enable a comparison between the models, the number of nodes and elements should be approximately the same. An

element size of 0.7 mm is assigned to piston head design 1, 0.6 mm to piston head design 2 and 0.45 mm to piston head design 3. Tetrahedral elements were chosen for the meshing because they can adapt to the complex geometry of the piston head. This ensures an accurate representation of curved surfaces and sharp edges while maintaining computational efficiency. In addition, the flexibility of element size allowed for detailed meshing in critical areas and coarser meshing in less critical regions, optimizing both accuracy and performance. This choice also facilitated consistent meshing across all designs and allowed for a fair comparison of thermal performance. Figure 4a, 4b and 4c reflect the mesh view of piston head design 1, piston head design 2 and piston head design 3 respectively. Also, Tables 4, 5, and 6 give the mesh quality values of piston head designs.

Table 4: Piston head 1 design mesh quality value

Nodes	765922	
Elements	448657	
Mesh metric	Element Quality	Skewness
Max.	0.99993	0.99569
Min.	0.10777	0.0001599

Table 5: Piston head 2 design mesh quality values

Nodes	773669	
Elements	450255	
Mesh metric	Element Quality	Skewness
Max.	0.99997	0.99564
Min.	0.10136	0.000037

Table 6: Piston head 3 design mesh quality

Nodes	747082	
Elements	438312	
Mesh metric	Element Quality	Skewness
Max.	0.99988	0.9988
Min.	0.10186	0.000874

The maximum value expressed in the table reflects an element quality value close to 1, e.g. 0.99993 indicates high quality elements. In this case, the maximum values for all designs are between 0.99993 and 0.99999, which seems very good. However, the minimum value is 0.10136 (the lowest value), which indicates possible quality problems in certain elements. However, depending on the type of analysis, this may be tolerable. The maximum skew values (0.995) are high but within acceptable limits. The minimum skew varies between 0.0001599 and 0.000874, which is quite good. Figure 5a, 5b and 5c show the boundary conditions of piston head design 1, piston head design 2 and piston head design 3, respectively. The boundary conditions used for the analysis were determined as 500 °C temperature, 22 W/m²K film co-efficient, and 24 °C ambient temperature according to previous studies.

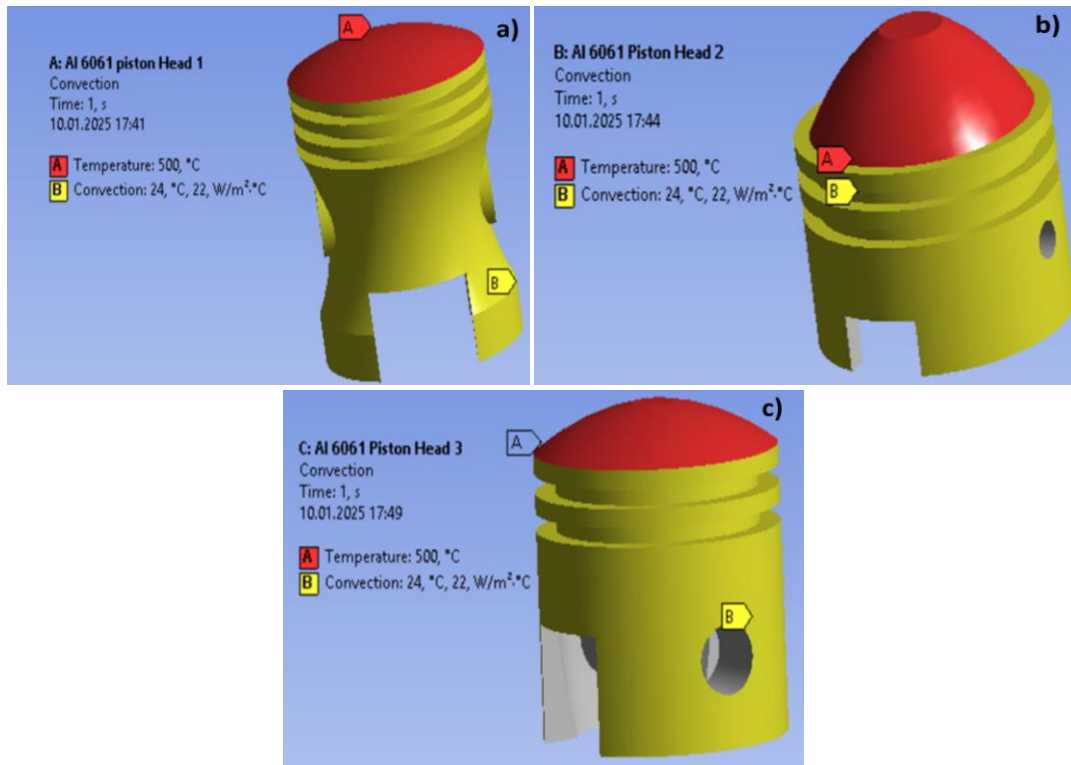


Figure 5. Boundary conditions for a) piston head 1, b) piston head 2, and c) piston head 3

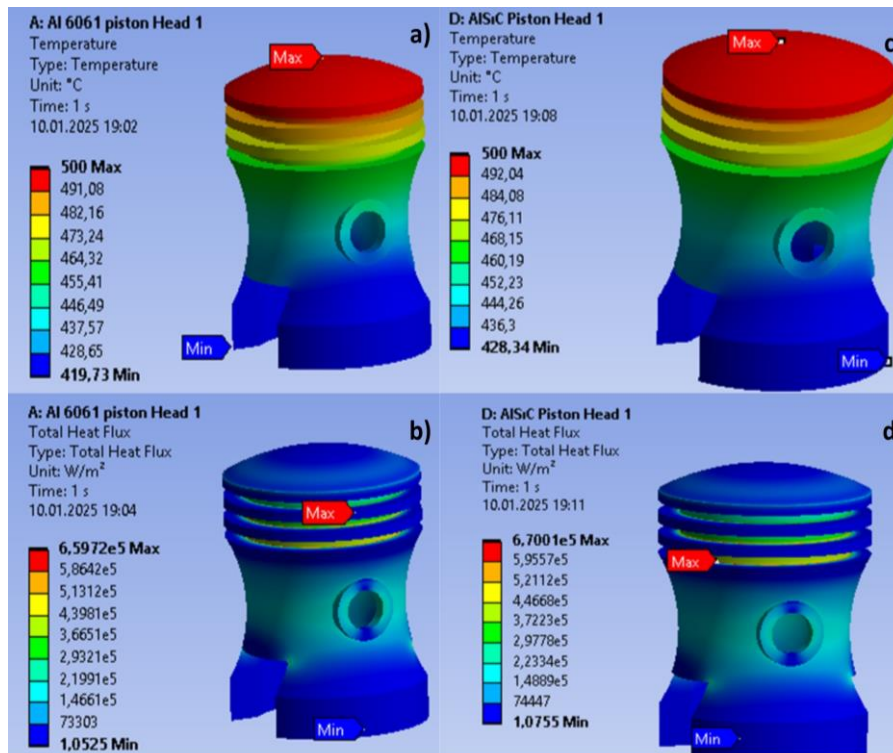


Figure 6. Thermal analysis results of a) Al 6061 piston head 1 temperature, b) Al 6061 piston head 1 total heat flux, c) AlSiC piston head 1 temperature, and d) AlSiC piston head 1 total heat flux

4. Results and Discussions

Figure 6a, 6b, 6c and 6d demonstrate the piston head temperature and heat flux values with Al6061 and AlSiC materials of piston head 1, piston head 2, piston head 3, respectively. Figure 7a, 7b, 7c and 7d indicates the piston head temperature and heat flux values with Al6061 and

AlSiC materials of piston head 1, piston head 2, piston head 3, respectively. Figure 8a, 8b, 8c and 8d displays the piston head temperature and heat flux values with Al6061 and AlSiC materials of piston head 1, piston head 2, piston head 3, respectively. Figures 9, 10 and 11 indicate how mesh independence is achieved in the results for piston head 1, piston head 2 and piston head 3.

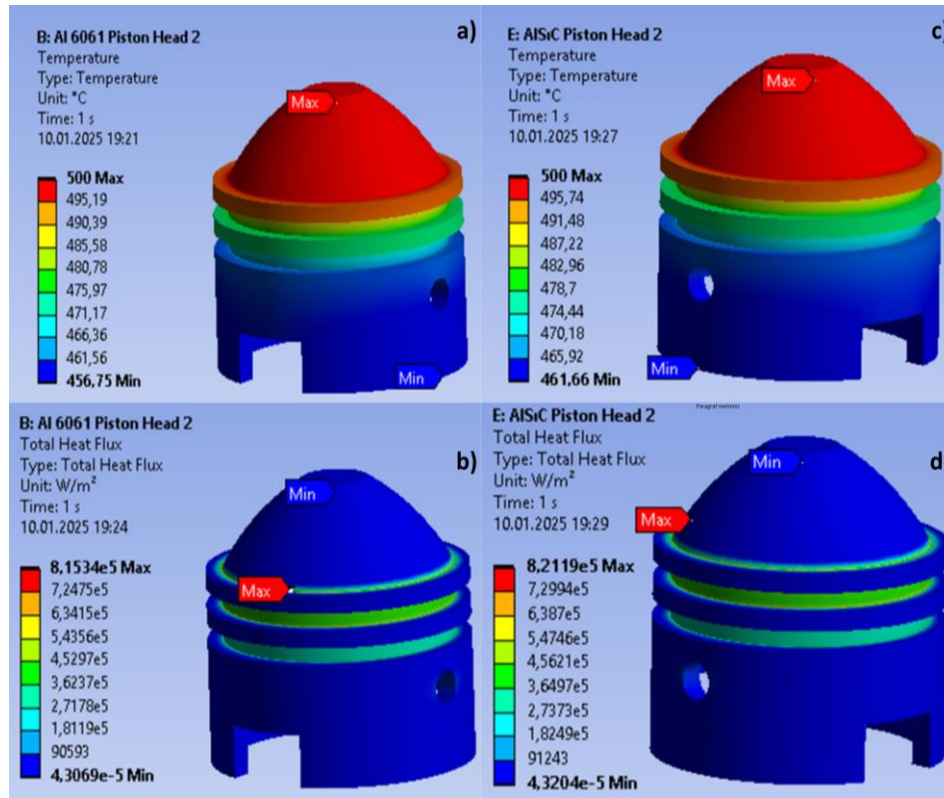


Figure 7. Thermal analysis results of a) Al 6061 piston head 2 temperature, b) Al 6061 piston head 2 total heat flux, c) AISiC piston head 2 temperature, and d) AISiC piston head 2 total heat flux

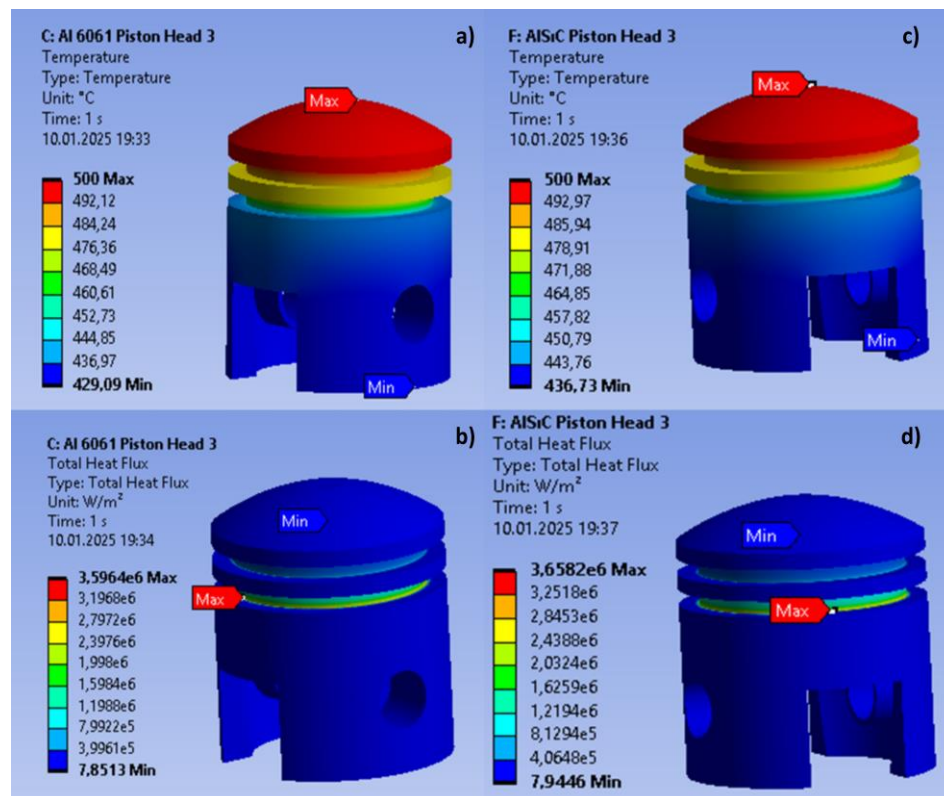


Figure 8. Thermal analysis results of a) Al 6061 piston head 3 temperature, b) Al 6061 piston head 3 total heat flux, c) AISiC piston head 3 temperature, and d) AISiC piston head 3 total heat flux

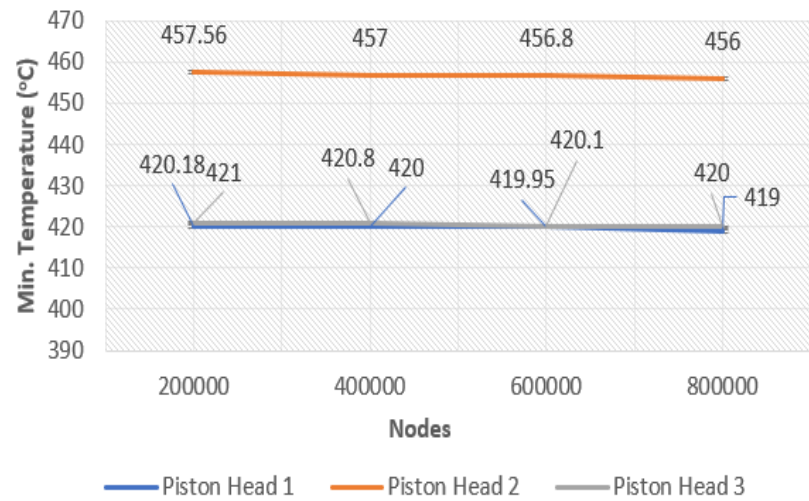


Figure 9. Mesh independence for minimum temperature results

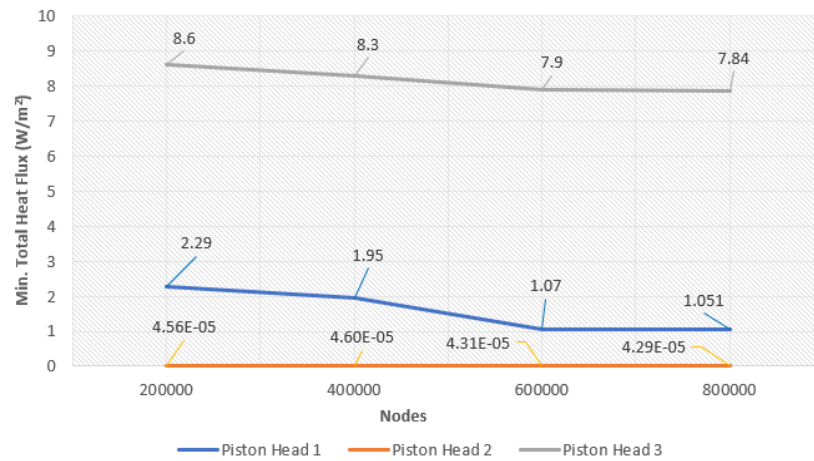


Figure 10. Mesh independence for minimum total heat flux results

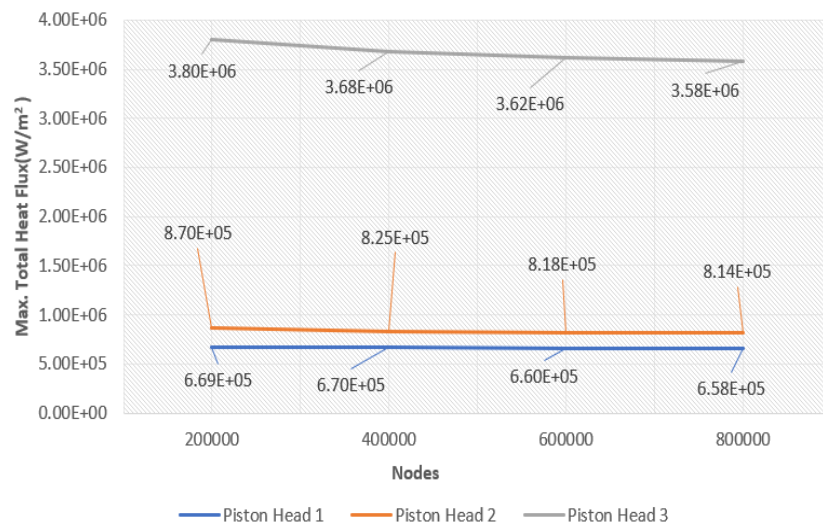


Figure 11. Mesh independence for maximum total heat flux results

Table 7, Table 8, and Table 9 indicate the temperature and total heat flux values of piston head 1, piston head 2, and piston head 3, respectively.

Table 7: Piston head 1 design thermal analysis outcomes

	Temperature (°C)		Total heat flux (W/m ²)	
	Min.	Max.	Min.	Max.
Al 6061	419.73	500	1.05	6.59 × 10 ⁵
AlSiC	428.04	500	1.08	6.70 × 10 ⁵

Table 8: Piston head 2 design thermal analysis outcomes

	Temperature (°C)		Total heat flux (W/m ²)	
	Min.	Max.	Min.	Max.
Al 6061	456.75	500	4.3 × 10 ⁻⁵	8.15 × 10 ⁵
AlSiC	461.66	500	4.32 × 10 ⁻⁵	8.21 × 10 ⁵

Table 9: Piston head 3 design thermal analysis outcomes

	Temperature (°C)		Total heat flux (W/m ²)	
	Min.	Max.	Min.	Max.
Al 6061	429.09	500	7.85	3.6 × 10 ⁶
AlSiC	436.73	500	7.94	3.65 × 10 ⁶

In their study, Prajapati et al. evaluated the structural and thermal performance of pistons used in internal combustion engines by analyzing four aluminum alloys (AlSi, AlMgSi, AlSiC12 and Al6061) using ANSYS software. AlSi exhibited the best structural behavior, while AlSiC12 showed superior thermal performance. These results underline the importance of material selection in the design of pistons. AlSiC achieved better thermal efficiency than Al6061 due to its high thermal conductivity and temperature resistance. Although the overall maximum temperature reached 800°C for both materials, AlSiC exhibited a lower minimum temperature (304.07°C) compared to Al6061 (343.07°C), indicating better heat dissipation (Prajapati et al. 2023). In detailed studies of piston head designs, the minimum temperatures increased to 419.73°C due to the design-specific heat distribution. Heat flux values also varied significantly, with AlSiC reaching a maximum of 8.2×10^5 W/m² and Al6061 8.15×10^5 W/m² in certain head configurations. These deviations confirm that both material selection and design geometry are critical factors in optimizing piston performance under thermal load.

Dixit et al., conducted a comprehensive evaluation of the structural and thermal performance of pistons made from an aluminum silicon carbide composite (AlSiC), which has been proposed as an alternative to conventional aluminum pistons. Their results showed that AlSiC exhibited superior thermomechanical behavior, including lower deformation, reduced elastic elongation and a more uniform temperature distribution under operating conditions. Consequently, the study emphasizes that

AlSiC is a more suitable candidate for high-performance piston applications due to its improved thermal resistance and mechanical integrity.

In the same study, the maximum temperature for the AlSiC material was specified as 450 °C, while the minimum temperature was measured at 361.65 °C (Dixit et al, 2015). However, when the analyses were refined to specifically examine the piston crown regions, taking into account the piston head geometry and local thermal stresses, it was observed that the minimum temperature increased to 419.73 °C. This deviation is primarily due to design-related differences and deviations in the maximum temperature values applied (Tables 8–9).

In addition, considerable differences in the heat flow values were found depending on the flask geometry. The maximum heat flux values shown in Figures 6(d), 7(d) and 8(d) were 6.7×10^5 W/m², 8.21×10^5 W/m² and 3.65×10^6 W/m² respectively. When comparing with the maximum heat flux from the general thermal analysis (1.1053×10^6 W/m²) (Dixit et al., 2015), it becomes clear that the value in Figure 6(d) is about 1.65 times higher, that in Figure 7(d) about 1.35 times higher, while the value in Figure 8(d) is about 3.3 times lower. These discrepancies are due to variations in the piston crown geometry and thermal boundary conditions applied during the simulations.

It was generally observed that AlSiC has higher minimum and maximum heat flow values, indicating that AlSiC is more efficient in terms of thermal conductivity compared to Al 6061. In Table 8 and as shown in figure 7(d), the maximum heat flux of AlSiC is 8.21×10^5 W/m², which is 0.06×10^5 W/m² higher than that of Al 6061 at 8.15×10^5 W/m² in figure 7(b). Although this difference is small, it may have an impact on the performance under the thermal load.

One of the reasons for the discrepancies in the tables is the different designs of the piston crowns. The graphical analysis of the data in Table 7 and Figure 6(a) shows a significant decrease in heat flux and temperature values, indicating that the original design struggled more under thermal load.

In Table 8 and Figure 7(b), the maximum heat flux has increased, and the temperature is higher, indicating more difficult working conditions or a higher requirement of higher power.

In Table 9 and Figure 8(c), the maximum heat flux is 4.42 times higher than in Table 7 and 4.39 times higher than in Table 8, indicating a more balanced heat distribution. Although AlSiC has demonstrated superior thermal performance, its higher production cost limits its

widespread use in cost-sensitive applications. In contrast, Al 6061 offers a cost-effective alternative with acceptable thermal and mechanical performance, making it a viable choice for designs with limited budgets.

5. Conclusions

In this study, the thermal performance of different aluminum alloys for internal combustion engines was examined, and three different piston head designs were analyzed. The obtained results were compared with Table 7, Table 8, and Table 9, which include the design analyses of the piston heads.

Although the maximum heat flux difference between AlSiC and Al 6061 seems small, it can provide a critical advantage in increasing piston durability and performance under long-term operating conditions and thermal loads. However, Al 6061 offers advantages such as low production costs and better machinability, making it a preferred option in situations where economic constraints are prominent.

To summarize, piston design and material selection are critical factors for motor performance and durability. The AlSiC material proves to be the better choice, especially for applications with high thermal loads. However, criteria such as the intended use of the motor, cost constraints and ease of manufacture should be considered in the design and material selection. Future studies could aim to further improve the performance of the pistons by using different composite materials and optimized designs.

Declaration of Ethical Standards

The authors declare that they comply with all ethical standards

Credit Authorship Contribution Statement

Author-1: Conceptualization, investigation, study design, writing – original draft.

Author-2: Methodology, investigation, Data curation, writing – review and editing.

Author-3: Investigation, Resources, supervision

Declaration of Competing Interest

The authors have no conflicts of interest to declare regarding the content of this article.

Data Availability Statement

All data generated or analyzed during this study are included in this published article.

6. References

Avci, E., Gur, M., Taymaz, I., Mimaroglu, A., & Ucar, V.1999. Comparison of Thermal Stresses Developed in Al_2O_3 -SG, ZrO_2 - (12% Si+Al) and ZrO_2 -SG Thermal Barrier Coating Systems with NiAl, NiCrAlY and NiCoCrAlY Interlayer Materials Subjected to Thermal

Loading. *Surface and Coatings Technology*.116–119, 690–693.

[https://doi.org/10.1016/S0257-8972\(99\)00121-8](https://doi.org/10.1016/S0257-8972(99)00121-8)

Avci, E., Mimaroglu, A. &, Yenihayat, O. F. 1996. Numerical Analysis of Fracture in Ceramic Coatings Subjected to Thermal Loading. *Materials and Design*. 17(3), 283–287.

[https://doi.org/10.1016/S0261-3069\(97\)00023-X](https://doi.org/10.1016/S0261-3069(97)00023-X)

Bayram, M. K., & Kantaroğlu, E. 2024. Sıkıştırma ile Ateşlemeli Bir Motorda Farklı Piston Malzemelerinin Sonlu Elemanlar Metodu ile Termal Davranışlarının İncelenmesi. *Afyon Kocatepe Üniversitesi Uluslararası Mühendislik Teknolojileri ve Uygulamalı Bilimler Dergisi*. 7(1),9-22.

<https://doi.org/10.53448/akuumubd.1431294>

Bolek, T., Dobosz, R., Kobayashi, A., Kurzydłowski, K. J., Mizera, J., Sienkiewicz, J., & Sitek, R. 2017. Simulation of the Influence of the Interface Roughness on the Residual Stresses Induced in (ZrO_2 + Y_2O_3) + NiAl-Type Composite Coatings Deposited on Inconel 713C. *Vacuum*. 136,221-228.

<https://doi.org/10.1016/j.vacuum.2016.11.003>

Celik, E., & Sarikaya, O. 2002. Effects of Residual Stress on Thickness and Interlayer of Thermal Barrier Ceramic MgO-ZrO_2 Coatings on Ni and AlSi Substrates Using Finite Element Method. *Materials and Design*. 23(3), 645–650.

[https://doi.org/10.1016/S0261-3069\(02\)00047-X](https://doi.org/10.1016/S0261-3069(02)00047-X)

Celik, E., & Sarikaya, O. 2004. The Effect on Residual Stresses of Porosity in Plasma Sprayed MgO-ZrO_2 Coatings for an Internal Combustion Diesel Engine. *Materials Science and Engineering A*. 379(1), 11–16.

<https://doi.org/10.1016/j.jmse.2003.12.019>

Chougule, V. H., & Khatawate, V. 2013. Piston Strength Analysis Using FEM. *International Journal of Engineering Research and Applications*. 3(2), 1724–1731.

Citak, R., Uyaroglu, A., & Yucesu, H. S. 2010. Piston arızalarının analizi. *Selçuk Üniversitesi Journal of Technical-Online Teknik Bilimler Meslek Yüksekokulu*. 9(2), 110-130.

Crouse, W. H. 1970. *Automotive engine design*. New York: McGraw-Hill.

Dixit, N., John, A., Malhotra, V., & Mathew, J. T. 2015. Design and analysis of piston by SiC composite material. *International Journal for Innovative Research in Science & Technology*. 1(12), 578-590.

Dudareva, N. Y., Enikeev, R. D., Ivanov, V. Y. 2017. Thermal Protection of Internal Combustion Engines Pistons. *Procedia Engineering*. 1382–1387.

- <https://doi.org/10.1016/j.proeng.2017.10.649>
- Genc, S., Kocabicak, U., & Mimaroglu, A. 1997. Influence of Porosity Characteristics in MgO–ZrO₂-GG Coating Subjected to Thermal Loading. *Materials and Design*. 18(2), 77–80.
[https://doi.org/10.1016/S0261-3069\(97\)00042-3](https://doi.org/10.1016/S0261-3069(97)00042-3)
- Gu, Y. W., & Khor, K. A. 2000. Effects of Residual Stress on the Performance of Plasma Sprayed Functionally Graded ZrO₂/NiCoCrAlY Coatings. *Materials Science and Engineering A*. 277, 64–76.
[https://doi.org/10.1016/S0921-5093\(99\)00565-1](https://doi.org/10.1016/S0921-5093(99)00565-1)
- Guo, H. J., Munyao, Zhiyuan, Y., & Zou, Y. X. 2014. Simulation of Thermal-Mechanical Strength for Marine Engine Piston Using FEA. *Journal of Engineering Research and Applications*. 4(3), 319–323
- Heisler, H. 1999. *Vehicle and engine technology* (2nd ed.). SAE International.
- Janardhana, G. R., Kumar, P. N., & Kumar, P. S. R. 2017. Static Analysis of Al-ZrO₂FG Thick Plate Using Graded FEM. *Materials Today: Proceedings*. 4(3), 8117–8126.
- Kocabicak, U., Mete, O. H., Mimaroglu, A. & Sarikaya, O. 1999. Comparison of the Developed Thermal Stresses in Al₂O₃-SG, ZrO₂-12%Si+Al and ZrO₂-SG Coating Systems Subjected to Thermal Loading. *Materials and Design*. 20(3), 287–290.
[https://doi.org/10.1016/S0261-3069\(99\)00041-2](https://doi.org/10.1016/S0261-3069(99)00041-2)
- Krishna, M. M., Murthy, P. V. K., Rajam, C. V., & Rao, G. P. 2013. Design Analysis and Optimization of Piston using CATIA and ANSYS. *International Journal of Innovative Research in Engineering & Science*. 1(2), 41–51.
- Krishna, M. V. S., Murthy, P. V. K., & Rajam, C. V. 2012. Non-linear static structural analysis of optimized piston for bio-fuel using ANSYS. *International Journal of Management, IT and Engineering*, 4(1), 148–168.
- Krishnan S B., Vallavi MS A., M A., & A H. 2017. Design and analysis of an IC engine piston using composite material. *European Journal of Advances in Engineering and Technology*. 4(3), 209–215
- Liu, M., Ma, G., Miao, Q., Niu, F., Wu, D., & Yan, S. 2017. Microstructure Evolution and Mechanical Properties of Ultrasonic Assisted Laser Clad Yttria Stabilized Zirconia Coating. *Ceramics International*. 43(7), 9622–9629.
<http://dx.doi.org/10.1016/j.ceramint.2017.04.103>
- Lin, Z., Xu, D., & Zhang, H. 2013. An analysis to thermal load and mechanical load coupling of a gasoline engine piston. *Journal of Theoretical and Applied Information Technology*, 48(2), 911
- Manjunatha, K., & Yerrenagoudaru, H. 2017. Combustion Analysis of Modified Inverted “M” Type Piston for Diesel Engine with Platinum Coating and Without Coating by Using CFD. *Materials Today: Proceedings*. 4(3), 2333–2340.
<https://doi.org/10.1016/j.matpr.2017.02.082>
- Manoj, K. S., Matthew, N., Ramaswamy, P., Reghu, V. R., Shankar, V. 2018. A Model to Predict the Influence of Inconsistencies in Thermal Barrier Coating (TBC) Thicknesses in Pistons of IC Engines. *Materials Today: Proceedings*. 5(3), 12623–12631.
- Prajapati, A., Singh, A., Talankar, A. A., & Vishwakarma, A. (2023). Structural & Thermal Analysis of V6 Engine's Piston for Different Alloys of Aluminum. *International Journal on Emerging Technologies*. 14(2), 53–56.