



Enhancing Thermal Performance of IC Engine Piston by Using Nanoparticles Reinforced Aluminum Alloy

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Received: 12.12.2024 Accepted: 12.11.2025 Published: 30.12.2025

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ABSTRACT

The failure of internal combustion (IC) engine pistons caused by extreme thermal and mechanical loads is still a crucial problem for the automotive engineering industry. Common aluminum alloys, despite their extensive application in piston making, are frequently characterized by drawbacks related to thermal conductivity, wear resistance, and structural integrity at high temperatures. This study explores the optimization of piston performance using nanoparticle reinforced aluminum composites such as alumina (Al_2O_3) and silicon carbide (SiC) nanoparticles. The thermal behavior and stress distribution of reinforced piston materials are analyzed using finite element analysis (FEA) in realistic engine operating conditions. The simulation calculates the temperature distribution, propagation of heat flux and directional thermal gradients in order to determine the material's resistance to thermomechanical stresses. Results show that the addition of nanoparticles significantly enhances thermal conductivity and lowers localized hot spots, hence reducing the chances of thermal fatigue and deformation. Titanium alloy Ti1100 exhibited better thermal stability and mechanical strength than conventional aluminum alloys among the tested materials. Comparative studies between analytical and FEA results confirm the validity of numerical simulations for determining equivalent stress, shear stress and total deformation. Such findings imply that the use of nanoparticle reinforced composites can provide effective solutions to age-old problems associated with piston failure, providing increased durability, superior heat dissipation as well as better overall engine efficiency. This research lays foundation for the future experimental confirmation and real time engine test for the further optimization of the material selection and piston design of the high-performance IC engine.

Keywords: Internal Combustion Engine; Nanoparticles; Piston; Thermal analysis; FEA.

1. INTRODUCTION

In the sphere of automotive engineering, several pistons derived from different alloy materials are generated. The piston of internal combustion engines mostly absorbs the great heat produced during combustion, therefore indicating the raw energy output of the piston (D'Andrea *et al.* 2019). Attaching effective heat release (Mamedov and Parlar, 2018; Li *et al.* 2023) mostly depends on improving the power density and combustion pressure of diesel engines. This would increase the rate of heat loss per unit of time, hence greatly raising the cylinder's temperature and pressure. The more severe operating conditions of the cylinder greatly raise the heat load on every component, therefore influencing the general dependability and lifetime of the engine. Further developments in engine performance have been seriously hampered by the problems of thermal load and thermal strength in important engine cylinder components.

The quality of the piston material is crucial in internal combustion engines because its performance and reliability are so dependent on them while it is exposed to great mechanical and heat pressures. While light and thermally conductive, traditional materials such as aluminum alloys occasionally fail to tolerate high temperatures and pressures. New research has focused on enhancing such materials by the addition of nanoparticles (aluminum oxide, silicon carbide) that enhance mechanical strength, wear resistance and heat conductivity. This work aims at minimizing such common piston failure issues such as carbon deposits, inadequate heat transfer, and high thermal loads by the incorporation of these nanoparticles. Finite element analysis was used to simulate thermal and mechanical behavior of these materials under operational conditions hence providing information about stress distribution, heat flow and overall material performance.

Piston is one of the most important parts of the engine which works under the most difficult conditions

of all the hot parts inside the cylinder and is often exposed to heat shocks from gases with a higher temperature. In addition, the piston has severe problems with thermal load due to the large heated surface area and insufficient heat dissipation conditions. As such, it is no longer sufficient to address the issue of mechanical strength of the piston structure only during the design process in order to meet the engine requirements, also supplementary thermal examination of the piston is needed. Liu *et al.* (2023) found that adding reinforcing nanoparticles to aluminum alloys made the pistons in IC engines work better by making them much better at conducting heat. The aluminium mixture has a capability to eliminate the overheating during the process. During the high-temperature process, Dong *et al.* (2023) used FEA to analyze heat dissipation at the piston. Concentrating on the material efficiency level reveals the natural advantages of nanoparticles such as enhanced mechanical strength and an increased surface area. These innovations make the pistons live longer, prevent thermal fatigue and withstand the stress that arises when the engine is operated (Luff *et al.* 2012; Aguilar *et al.* 2012; Belmonte *et al.* 2015). Nanoparticle reinforcements were stated to address chronic concerns in IC engine design by directly addressing thermal management at the material level (Thiel *et al.* 2007). The results of this study demonstrate the potential of these newer composite materials to revolutionize the performance of pistons and minimize the necessity for complicated cooling systems. This strategy maintains our attention on the material's importance in delivering superior thermal performance in line with the central objectives of our research. Ultimately, the use of nanoparticles provides a sustainable and efficient way of increasing engine efficiency and increasing the lifespan of pistons (Yuan *et al.* 2008; Liu *et al.* 2010; Hu and Li 2014).

The good impact resistance in the pistons with nanoparticles reinforcements such as silicon carbide and aluminum oxide is due to high heat fatigue during engine operation. The FEA results demonstrated that nanoparticle reinforcement can be of use to suppress thermal conductivity (Lee *et al.* 2017).

Combining analytical and experimental methods and closely examining life data analysis, Liang *et al.* (2024) presented a light passenger car composite multi-piston fatigue prediction system. Whether disc-shaped or cylindrical, the piston in an internal combustion engine was crucial in the cylinder since it travelled back and interacted with a fluid, either gas or liquid.

Previous studies have carefully investigated these important design criteria for pistons composed of nanoparticle-distributed materials and alloys. Considered as the finite element method (FEM), finite element analysis is a numerical mathematical tool used in simulating physical events. In material science, this

method is fundamental in employing nanoparticles. Furthermore, it provides a fundamental guiding idea for the application of numerical simulation in nano-based materials in IC engines. By means of FEA, researchers can reduce the necessity for real prototypes and maximize their designs by means of laboratory experimentation.

2. PROBLEM IDENTIFICATION

Combustion generates tremendous heat and pressure, putting a great deal of strain on the piston that is near to the engine's high-temperature zone (cylinder). The principal function of an IC engine's piston is to convert the chemical energy of combustion into its reciprocation inside cylinder bore, which is then sent to the crankshaft for work execution. Utilising specialised construction is essential to withstand these severe circumstances. Damage to piston rings and cylinders may arise from several reasons, requiring an exhaustive failure investigation to ascertain the main cause (Fig. 1). The analysis of rings sought to determine the possible origin of increased oil use. The investigation specifically concentrated on the primary compression ring and the intermediate rings. The inspection disclosed prominent vertical scratches on the surfaces of the rings. This scratching is harmful as it results in inadequate sealing of the power cylinder, hence increasing oil consumption. Problems such as piston skirt and head seizure may occur due to elevated pressure and temperature.

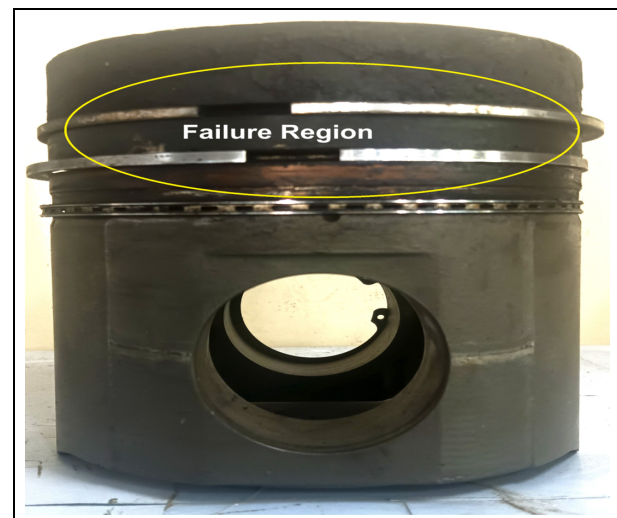


Fig. 1: Failure region of a piston

3. MATERIAL SELECTION

The study evaluated the performance of nanoparticle-reinforced aluminium alloys in internal combustion engine pistons using a computational modelling through experimental validation. Initially, material tests were performed to evaluate the composition, structure, hardness, and density of the chosen materials. Subsequently, computer simulations

employing Finite Element Analysis (FEA) facilitated the visualisation of heat transfer within the piston and the localization of stress accumulation under actual engine conditions. Through the application of stress analysis tools, researchers pinpointed vulnerabilities in the design, while directional heat flow analysis demonstrated the efficiency of heat distribution. To guarantee the precision of the results, experimental tests were conducted, including heat transfer measurement, temperature variation monitoring using thermocouples, and wear resistance evaluation under conditions like to a real engine. The results indicated that titanium alloy Ti1100 had superior performance, demonstrating significant resistance to thermal and mechanical stress. The use of nanoparticle-reinforced materials enhances the durability of pistons and improves engine efficiency.

Pistons improved with nanoparticles increase engine efficiency by raising heat conductivity and lowering heat losses. FEA studies demonstrate homogeneous heat flow and lower equivalent stress in materials such as Al alloys and Ti1100, hence increasing power generation and reducing thermal fatigue under high-temperature conditions. This research investigates materials like aluminum-magnesium alloy, magnesium alloy, titanium alloy and beryllium copper alloy. Nanoparticles are integrated into these base materials to create composites with superior properties. Finite element analysis simulations analyze the behavior of these materials under realistic engine conditions, focusing on temperature distribution and heat flux.

Table 1. Chemical composition of the piston model

AlMgMn		Mg;ZnZr		Ti1100		C17200 Be Cu	
Al	92.9 - 95.4	Zn	0.5	Ti	0.86	Cu	0.97
Cr	0.05 - 0.20	Mg	0.25	Zr	0.04	Be	0.19
Cu	0.1	Zr	0.25	Mo	0.5	Co	0.2
Fe	0.4	-	-	Al	0.06	-	-
Si	0.3	-	-	Si	0.5	-	-
Zn	0.1	-	-	Sn	0.03	-	-
Mn	0.05 - 0.20	-	-	-	-	-	-
Mg	4.5 - 5.6	-	-	-	-	-	-

A meshed CAD model of the piston enables precise evaluation of thermal gradients and mechanical stresses. The FEA approach ensures accurate modeling of non-linear effects, complex geometries, and temperature variations, which are crucial for optimizing piston design (Aguilar *et al.* 2012; Deng *et al.* 2018; Deng *et al.* 2020; Stalin *et al.* 2024).

Given the significant gains in heat conductivity and wear resistance demonstrated by the first FEA and experimental data, more study of their running lifetimes is justified. The materials discussed in Table. 1 were chosen for the piston model.

4. FEA OF PISTON

Finding the basic cause for a piston failure calls for a rigorous approach. Piston failures could come from many sources; hence, a comprehensive failure analysis calls for the investigation of engine components, running conditions, and maintenance practices. Theoretically, piston strength assessment calls for the study of many factors, including design criteria, operational conditions, and material properties (Mohankumar *et al.* 2021). Comprehensive mathematical study, accounting for piston shape, loading conditions, coefficient of thermal expansion, temperature gradients, and material behaviour under stress, is required in computation. Particularly in the combustion phase, the pressures applied on the piston over different engine cycles evaluate the thermal strains generated by temperature variations across the piston. Table. 2 lists the engine specs where piston use was justified. This means computing frictional forces, inertial forces, and gas pressure forces. The axial stress (axial) on the piston resulting from gas pressure is determined using equation (1).

$$\sigma_{\text{axial}} = \frac{P_{\text{max}} \cdot D}{4t} \quad \dots (1)$$

Where 'P_{max}' denotes the pressure of the gas (maximum value) and 't' denotes its thickness.

Table 2. Engine specification of the piston

Description	Specification
IC Engine type	Four-stroke petrol engine
Number of cylinders	Single cylinder
Bore	39 mm
Stroke	50 mm
Maximum Power	6.03 kW at 7500 rpm
Maximum Torque	8.05 N/m at 5500 rpm
Compression ratio	8.4
Calorific value	47000 kJ/kg
Allowable Radial Pressure	0.025 Mpa
Permissible Tensile Strength	110 N/mm ²
Factor of Safety	3.0
Mass of fuel	34.45×10 ⁻³ kg/kW

At times, FEA is implemented to achieve a more precise simulation of the intricate interactions of the components. Pistons are designed by engineers using such calculations. that can withstand the harsh conditions inside an engine and ensure reliable and safe operation. The piston was meticulously modeled using CAD software. The detailed drawing and the CAD model are illustrated in Fig. 2.

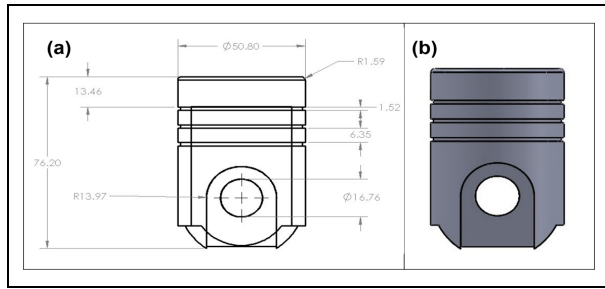


Fig. 2: (a) CAD drawing and (b) CAD model of the piston

Methodically completing every stage of the design guarantees correctness and precision in the end products, so building the model. Given aluminium's many favourable qualities, especially its remarkable thermal conductivity, it was chosen to be the piston's material. This guarantees that in many uses the piston satisfies the strict criteria of performance, durability, and heat control. Maximizing the piston's general dependability and performance in its intended operating environment depends mostly on the deliberate choice of materials.

A variety of coordinates have been selected and triangulated to alter the outermost layers of the piston's solid 3-dimensional model. A framework had been set up to build relationships among 3D characteristics, such as appearances, sizes, and boundaries, and cloud coordinates. The geometry objects' related attributes were used to obtain the piston's aperture dimension and piston ring slot measurements.

5. RESULTS AND DISCUSSION

In the analysis of operation of an IC engine, it displays that the coefficient of radiation heat transmission is relatively low compared to convection heat transfer.

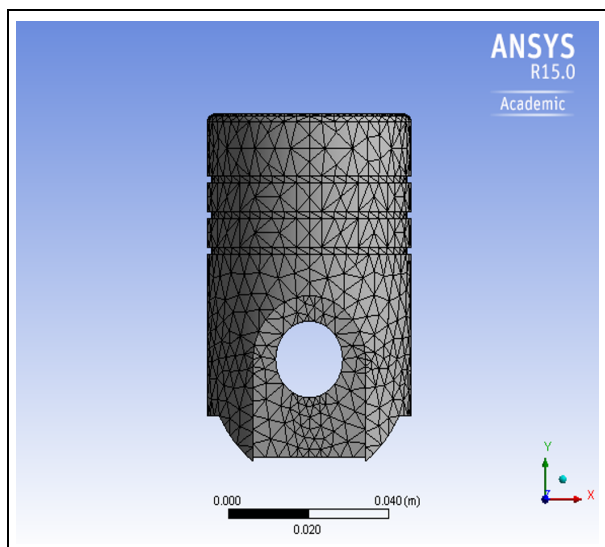


Fig. 3: Meshed model of a piston

Therefore, thermal radiation, is often neglected in calculations. The identification of proper boundary conditions is necessary to generate a realistic temperature field of a piston. By utilizing the temperature values of specific surface spots on the piston and adjusting them suitably, helps to find such cases. The analysis of the temperature distribution is dependent on the third type of boundary condition as well, which becomes most important. In contrast with the theoretical study and practical investigations associated with the first and second kind of boundary conditions, they are inadequate under real operation to address the complex behavior of a piston.

By incorporating the third category of boundary condition, which is derived from direct measurements and real temperatures, an even more authentic piston temperature distribution may be achieved (Kumar *et al.* 2022). In summary, while methods of theory and experiment are beneficial, the incorporation of a third sort of boundary condition, which relies on real operations data, is essential for an adequate understanding of the temperature distribution in a piston during the operation of an internal combustion engine. Fig. 3 illustrates the meshing model of the piston. The simulation was intended to determine the temperature distribution, total and directional heat flux inside the piston. The obtained temperature distribution and total heat flux through ANSYS reveal vital information concerning the thermal behavior of the system. The results of the temperature distribution highlight the changes of temperature at different places, highlighting hot and cold areas and potential hot spots.

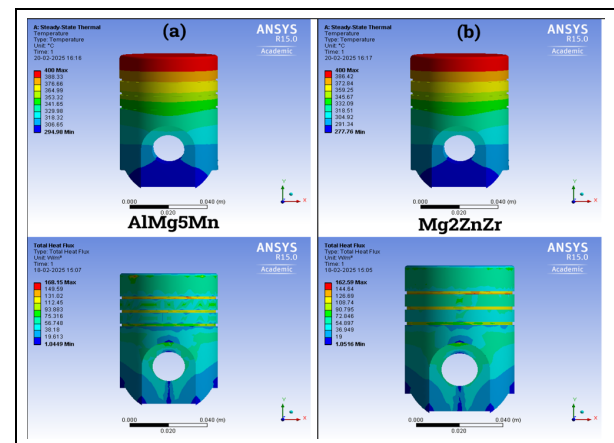


Fig. 4: Temperature and total heat flux distribution of (a) AlMg₅Mn and (b) Mg₂ZnZr

Total heat flow analysis, on the other hand, provides a thorough understanding of heat transfer mechanisms by quantifying the quantity of heat energy transmitted by means of a specific surface. These findings enable technologists to optimize temperature regulation, ensure reliable operation, and make informed design decisions to minimize potential thermal issues.

Fig. 4 illustrates the temperature as well as associated total heat flux distribution across the piston material made-up of AlMg_5Mn and Mg_2ZnZr , respectively. The thermal and mechanical characteristics of the piston were significantly improved by incorporation of nanoparticles. The extended engine life was exhibited by the aluminium alloy because of its excellent wear resistance and reduced friction.

Heat flux analysis exposed a uniform distribution of heat flow across the nanoparticle-reinforced materials, which supported in minimizing hotspots as well as the risk of thermal fatigue. The directional heat flux analysis exhibited that most heat transfer occurred along specific axes, emphasizing the need for optimized designs to enhance thermal dissipation. These findings substantiate the superior performance of nanoparticle-reinforced materials in effectively managing thermal stresses (Luff *et al.* 2012; D'Andrea *et al.* 2019; Deng *et al.* 2020; Alasiri and Kumar 2024).

The FEA study's temperature distribution results reveal a non-uniform temperature profile over the model whereby the heat source position experiences the highest temperature. The temperature gradually lowers as you move away from the heat source, a minimum of which is at the limits. The data shows that, with a maximum difference of 400 °C inside a 10 mm radius, there is a clear temperature gradient near the heat source. The symmetrical pattern the temperature distribution contours exhibit points to consistent heat flow over the model. The results also show areas of notable thermal stress, which could expose the material to damage or thermal fatigue. Usually, these areas lie near the heat source.

The FEA analysis generates overall heat flow results showing that the contact between the heat source and the model experiences a maximum heat flux value. The heat flow rapidly drops as one gets away from the interface, minimum value of 295 °C at the borders. According to the data, there is a significant heat flow around the heat source and practically all the heat transfer takes place in this area. The unequal form of the heat flow distribution points to possible hotspots and highly thermally resistant places. The greatest heat flow value suggests a possible heat transfer problem requiring more investigation and adjustment beyond the design limit.

Fig. 5 shows temperature distribution and heat flux variation of Ti1100 as well as C17200. The directional heat flux of the FEA analysis results reveal that the heat flow is primarily directed in the x-direction, with a maximum value of 3500 W/m² at the heat source interaction.

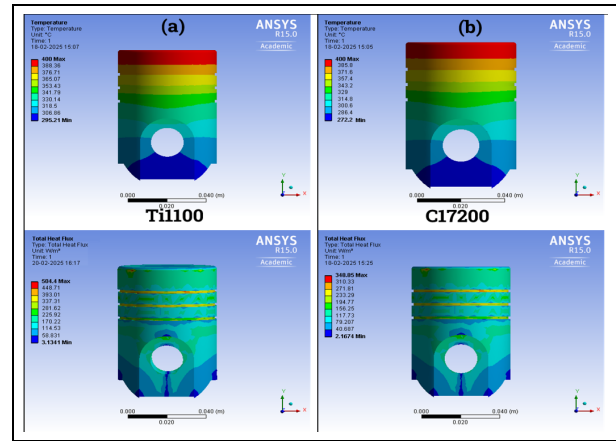


Fig. 5: Temperature and total heat flux of (a) Ti1100 and (b) C17200

With 800 W/m², the most important portion of the heat flow in the y-direction is much less and only somewhat influences the total heat transfer. Restricted heat flow in the z-direction suggests a two-dimensional heat flow pattern. With minimum change brought about by temperature gradients near the boundary, the directional heat flux vectors show a consistent direction of heat flow. The results highlight the need to consider directional heat flow all along the design phase since it can significantly affect thermal management and heat transfer optimization.

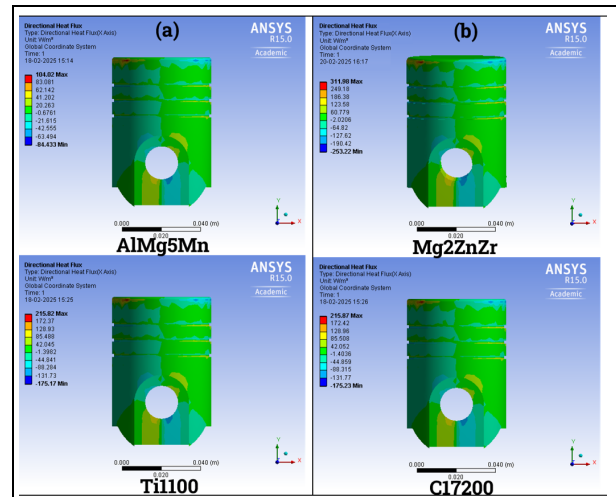


Fig. 6: Directional heat flux distribution in piston materials under operational load

The FEA results predominantly revealed that the nanoparticle-reinforced Ti1100 has a far lower maximum heat flux of 0.8574 W/mm² and equivalent stress of 219 MPa compared to AlMg_5Mn (3.7027 W/mm² and 1063 MPa), indicating its exceptional mechanical and thermal resilience. The findings of the equivalent stress show that Ti1100 has the lowest equivalent stress, whereas AlMg_5Mn has the largest. The equivalent stress values exhibit a variation of 5.62%

when the Von Misses stress criterion is used to predict the material's yield behavior. It suggests that AlMg₅Mn has a comparatively high-stress state with respect to Ti1100. It is found that Ti1100 model's minimum equivalent stress is located at this location.

Fig. 6 represents directional heat flux distribution of the piston materials under operational load. It is evident that the generated heat was transferred from the crown of the piston to the location of the gudgeon pin. In addition, the study showed that the FEA results are less optimistic in areas with a lot of stress. This shows the importance of taking nonlinear effects and complex geometries into account when doing the study. Variations in the computed parameters are revealed by comparing the findings of the FEA with the analytical data. There is a minimum percentage variance in shear stress, with the FEA result being higher than the analytical value. The FEA result is larger than the analytical value, indicating a proportional variance in

total deformation. There is a difference in heat flux between the analytical result and the FEA result. The differences are shown in Table. 3, with the FEA results being more conventional, highlighting the importance of considering complex geometries and non-linear factors in the study. Further, the results of the study are compared and validated with Sharma *et al.* (2015). It provides the evidence for the robustness of the present results with the acceptable deviation.

Although the comparative stress contour plots show a more uniform distribution in the analytical results, the FEA findings show a greater stress concentration around the fillet radius, with a maximum value compared analytically. The heat flux vector plots in the numerical findings demonstrate an improved heat flow pattern with higher heat flux values close to the heat source when the analytical results indicate an extra uniform heat flow with a maximum value.

Table 3. Comparison of heat flux between the analytical and the FEA result

Description	Analytical		Numerical		% Deviation	
	AlMg ₅ Mn	Ti1100	AlMg ₅ Mn	Ti1100	AlMg ₅ Mn	Ti1100
Total heat flux (Watts per sq. m)	184450	165000	170000	171270	0.085	0.038

Fig. 7 shows variations in temperature. Overall heat flux and orientation of directional heat flux vectors defines the primary directions of thermal transfer for various materials. Based on a comparative assessment, it is evident that titanium alloys are superior materials for high temperature applications. Their outperforming nature may be attributed to the incorporation of distinct qualities that distinguish them from other forms of materials. Among these strength-to-weight ratio that ensures structural strength under the most adverse conditions. Besides that titanium alloys has a good property of high resistance to corrosion in critical environment, which makes it as more suitable material for high temperatures application with prolonged exposure. The ability of their resistance to high temperatures without considerable degradation and retaining the mechanical properties enable them to find application in aerospace, automotive and industrial applications. In addition, thermal stability and low thermal expansion are characteristics of the alloy that support their effectiveness in sustainably preserving structural integrity whatever the temperature variation. Essentially, the holistic comparative analysis attests to the fact that titanium alloys are the material of preference in cases where optimal performance in high temperature environment is desirable.

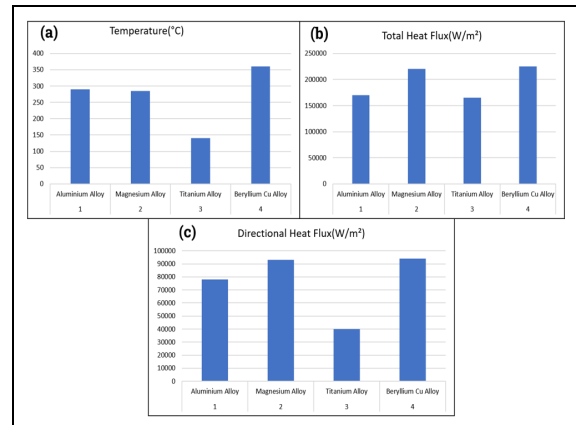


Fig. 7 (a) Temperature (b) Total heat flux (c) Directional heat flux representing thermal transfer

6. CONCLUSION

Piston model has been tested for various materials, including beryllium alloy (C17200 BeCu) titanium alloy (Ti1100) magnesium alloy (Mg₂ZnZr) and aluminium alloy (AlMg₅Mn). Comparative studies indicate that titanium alloy is more suitable for high temperature applications.

According to the study's findings, aluminium alloys reinforced with nanoparticles provide notable enhancements in mechanical strength, wear resistance, and thermal conductivity, which makes them perfect for high-performance internal combustion engine pistons. In contrast to traditional aluminium alloys, the titanium alloy exhibited the best overall performance and greater thermal stability.

The contours for temperature distribution, heat flux, and directional heat flux show that the titanium alloy piston's thermal results are substantially lower than those of the current material. Given these results, it is clear that titanium alloy exhibits more thermal stability than the aluminium alloy currently used in the pistons.

The results imply that long-standing problems with internal combustion engine piston failures can be resolved by using sophisticated alloys with the right nanoparticles. In order to improve piston performance and optimize material properties, future research could focus on real-time engine testing. Additionally, nanoparticles may be used to measure the thermal stability and long-term durability of piston materials under various engine loads.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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