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STEADY AND TRANSIENT THERMO-MECHANICAL BEHAVIOR OF A DIESEL ENGINE PISTON

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The main objective of this investigation is to evaluate the influence of the selected material for the piston crown in a direct-injection diesel engine on both mechanical and thermal stresses during steady-state and transient phases. To accomplish this goal, emphasis was placed on the SNVI (DEUTZ) piston within the framework of this research paper. The design of the piston was executed using SolidWorks software, and the simulation was carried out employing the finite element method with ANSYS 16.5 software. Following this, a deformation analysis was conducted for each material to compare the results and determine the most high-performing characteristics.

Keywords: Diesel engine, Piston materials, Finite Element Analysis, Computational Fluid Dynamics (CFD), Boundary conditions, Thermal Stress Mechanical Stress, ANSYS software.

1. Introduction

In a diesel engine, the piston plays a crucial role and is subjected to extreme thermal and mechanical stresses. As a moving component, it undergoes a reciprocating motion inside the cylinder. Its main function, together with the cylinder head, is to convert the mechanical energy from the combustion gases into a force transmitted to the crankshaft through the connecting rod. Additionally, the piston must ensure optimal sealing to prevent combustion gases from escaping achieved through the use of piston rings (compression ring, oil control ring, and scraper ring). However, this component faces the highest loads in the system because the pressures in the combustion chamber can reach high values approximately 180 to 200 bar [1]. The piston's velocities can reach around 25 m/s, and the temperatures at the top of the piston can reach about 400 °C. This

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combination of severe constraints essentially makes the piston the most stressed element in the diesel engine.

It should be not forgotten that climatic conditions in Algeria, particularly in desert areas, can be extremely severe, with temperatures that can exceed 45°C. These hostile climatic conditions can have a significant impact on the thermal and mechanical behavior of diesel engines, as well as on their service life. The use of special alloys and heat-resistant materials for pistons is one possibility for optimizing diesel engine performance in extreme climatic conditions.

The thermal behavior of the piston is a branch of materials science that focuses on studying the properties of materials as their temperature varies. The engine's power largely depends on the piston's ability to withstand two types of loads: thermal and mechanical stresses to which it is subjected. It is essential for the piston to be designed with lightness to minimize the inertia exerted on surrounding parts. Currently, the use of the finite element method allows for in-depth studies of the thermo-mechanical stresses present in pistons [2].

In the scientific literature, numerous in-depth studies have been conducted on simulations of internal combustion engines, particularly focusing on pistons. Kamo et al. [3] conducted a study on optimizing piston coating thickness. They found that thin coatings offer advantages in terms of durability and result in a moderate increase in surface temperature compared to thicker coatings. Mereuta [4] compared two types of diesel pistons made from different materials (aluminum alloy 6061 and gray cast iron). He used computer-aided design software to analyze the distribution of static and thermal stresses on these pistons, as well as their deformation states. For the piston made of aluminum alloy 6061 the results showed that the maximum temperature reached 573 K, the minimum Von Mises stress was 75.7 MPa, and the minimum deformation value was 0.0243 mm. The study conducted by Yousif Badri et al. [5] explored the effect of two parameters, namely the piston crown thickness and piston boss thickness, on the stresses experienced by the piston. Their findings revealed that the optimal design for the piston is achieved with a 3 mm thick piston crown and piston boss thicknesses of 2 mm. Srikanth Reddy et al. [6] utilized the commercial simulation software ANSYS to investigate the effect of functionally graded coatings (an aluminum piston coated with aluminum and zirconium) on the thermal behavior of the piston with the aim of reducing stress concentrations at the upper end of the piston. The results demonstrated that the maximum stress was reduced by 30 MPa (from 85 MPa to 55 MPa) and the maximum deformation was reduced from 0.051762 mm to 0.025884 mm.

Desilva et al. [7] conducted a study on piston fatigue in various applications, although fatigue is not considered a primary factor in piston damage it remains a significant issue, especially concerning specific fuel consumption. This has led to a reduction in piston weight by using thinner walls, resulting in higher stresses. Dorga et al. [8] used two types of aluminum alloy pistons (one uncoated and the other coated with ceramic), a thermal barrier analysis was performed. They found that the ceramic-coated piston exhibited a lower maximum temperature compared to the uncoated piston. Specifically, the temperature of the piston increased by approximately 28% with the zirconium-stabilized magnesium oxide ($ZrMgO_3$) coating, 22% with the mullite ($3Al_2O_3$-$2SiO_2$) coating, and 21% with the alumina (Al_2O_3) coating. These ceramic coatings thermally insulate the piston's surface, thereby increasing the temperature of the engine's combustion chamber and improving its thermal efficiency. Singh et al. [9] focused on the design and optimization of piston materials to achieve a smaller and more efficient engine, using simulation software such as PROE and ANSYS. They concluded that a silumin piston (an aluminum-silicon alloy) exhibits excellent physical properties, which helps reduce material costs and optimize engine efficiency by minimizing its weight.

This work focuses on the study of the steady and transient thermal and mechanical behavior of a direct injection diesel engine piston. This engine used for this specific research is a diesel engine manufactured by Algerian Company for manufacturing German engines brands Daimler-Mercedes-Benz and Deutz. The calculations are performed using the commercial simulation software ANSYS. The objective of this paper is to accurately determine the mechanical stresses (Von-Mises) present in the piston and to analyze the deformations to assess whether they can withstand the load generated by the gases in two scenarios: steady-state and transient mode.

2. Geometry and modeling

2.1 Engine specifications

The characteristics of the diesel engine used in this study are listed in Table 1.

Table 1

Melting points and elemental analyses

Parameters	Values	Units
Crankshaft radius	60	mm
Connecting rod length	224	mm
Cylinder bore	119.68	mm
Stroke	120	mm
Piston assembly mass	1700	g
Connecting rod mass	1400	g
Compression ratio	17:1	-
Injection timing angle	15° BTDC	Deg
Engine speed	1600	RPM
Rod ratio	0.2679	-
Crank angular velocity	167.4667	Rad/s

2.2 Geometrical Modeling of piston

In order to facilitate analysis and modeling of the studied piston, the sketch of its original shape was drawn using SolidWorks 2015, while adhering to its actual dimensions as indicated in Figs 1 and 2. Subsequently, the drawing was exported to ANSYS Workbench to conduct a thermal-structural analysis.

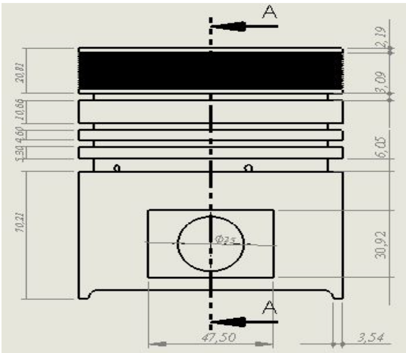


Fig. 1. Front view displaying the intelligent dimensions of the component.

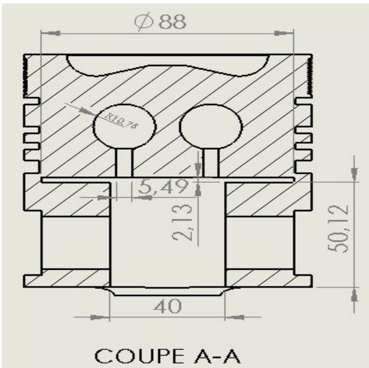


Fig. 2. Cross-sectional view A-A displaying the intelligent dimensions of the component.

2.3 Piston material

Given the significance of the thermal and mechanical properties of the piston material, most pistons are manufactured using steel, cast iron, and forged aluminum [10]. For this study, three types of piston materials have been selected, and their mechanical and thermal properties are presented in Table 2.

Table 2

Properties of selected piston materials [11]

Material	Elastic modulus (GPa)	Poisson's ratio	Density (kg/m^3)	Thermal conductivity (W/mK)	Thermal expansion coefficient [x10^{-6} K^{-1}]
Steel (Cr-Mo)	190	0.3	7800	150	13
Aluminum alloy	55	0.3	2700	150	24
Gray cast iron	160	0.3	7200	35	12

2.4 Meshing of piston

In the piston meshing process used in this simulation (see Fig. 3), an unstructured 3D mesh was created using Hypermesh, with an element size of 1 mm [11]. Subsequently, a verification of the obtained model was performed for the free edges, and a geometry cleaning step was carried out. To achieve accurate results, it was crucial to consider the connectivity between the elements of all piston materials [12]. The 3D Tetra Mesh model (see Table 3) was used for all three models that needed to be analyzed.

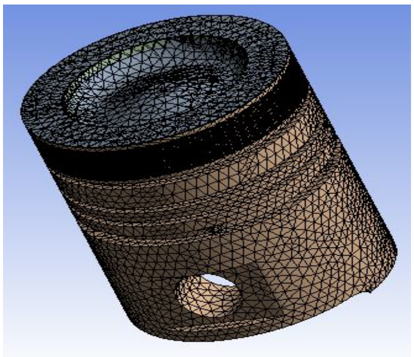


Fig. 3. Three-dimensional mesh of the used piston model.

Table 3

Meshed model of the used Piston

Element size	1.8
No. of elements	53577
No. of nodes	14353
Type of element	Tetra4

2.5 Modeling

For the meshing process, the surface meshing of the tetrahedral type was carried out separately for each of the three materials. This mesh was then checked considering the following parameters: connectivity, Jacobian, and aspect ratio [13]. Next, a check is carried out on the obtained mesh model for the free edges which need to be removed, if necessary, before proceeding with the 3D tetrahedral meshing. In this study, the piston head is simultaneously subjected to gas pressure and the heat flux resulting from the combustion process, while the piston pinhole is considered fixed. A water-cooling system is used to ensure the dissipation of heat from the piston. The simulation software ANSYS 16.5 was used to conduct the numerical simulations.

2.6 Boundary conditions

Inside the defined domains, boundary conditions are introduced on the three-dimensional geometry. These boundary conditions define the physical assumptions of the problem and directly impact the accuracy of the finite element simulation results [14]. The model is discretized based on the symmetric boundary condition. The total number of elements in each model is approximately 100 000. The applied boundary conditions are of Neumann type since the heat exchange between the piston and its surroundings (consisting of lubricating oil and cooling water) is primarily convective in nature [14]. The heat transfer coefficient at the ring lands and the skirt is determined using the following formula:

$$h = 8.235 \times \left(k/D_h\right) \tag{1}$$

k : thermal conductivity, D_h : hydraulic diameter

The heat transfer coefficient at the crown is computed using the following equation [14]:

$$h_c = 226.6 \times p_{\max}^{0.8} \times T^{-0.4} \left(v_p + 1.4\right)^{0.8} \tag{2}$$

T : temperature of the fluid around the crown, $p_{\max}$: maximal pressure, v_p : mean piston speed.

The expression for the heat transfer coefficient beneath the crown is as follows:

$$h_{uc} = 900 \times \left(N/4600\right)^{0.35} \tag{3}$$

The formula for the heat transfer coefficient at the inner region of the skirt can be expressed as follows:

$$h_S = 240 \times \left(N/3600\right)^{0.35} \tag{4}$$

Table 4 presents the calculations of heat transfer coefficients and mass temperatures in different piston areas.

Table 4

Convective boundary conditions

Area	Heat transfer coefficient (W/mm^{2}^{0}C)	Bulk Temperature (^{0} C)
A	560	741
B	400	741
C	88	180
D	384	180
E	246	180
J	88	180
I	390	160

The temperature boundary conditions applied to the piston areas and the scraper ring segment is 180 °C for area F, 160 °C for area G and 160 °C for area H

Fig. 4 illustrates the application of thermal boundary conditions in different piston areas.

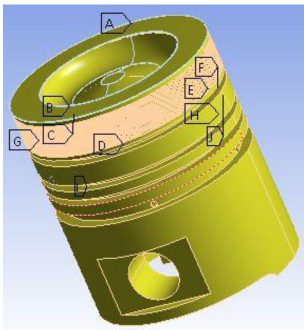


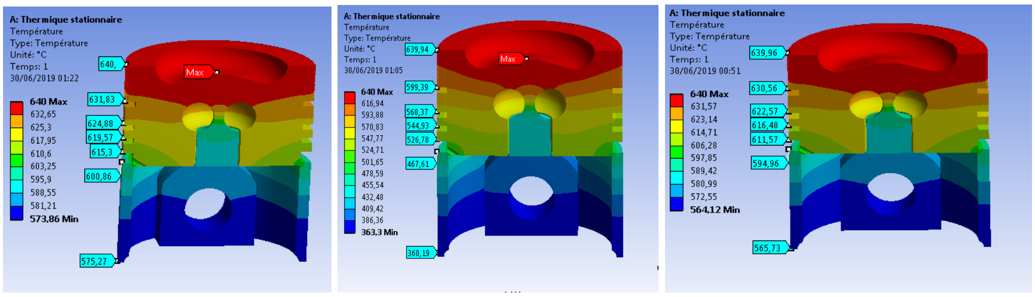
Fig. 4. Convective heat transfer areas.

3. Results and discussions

3.1 Steady State mode

Figs. 5.a, 5.b, and 5.c show the piston temperature distribution for each material. According to the results, it can be observed that the instantaneous temperature values gradually decrease from the top to the bottom of the piston. Regardless of the material used, the head always remains the critical region unlike the skirt and internal bosses of the piston. The minimum temperature values obtained for steel, aluminum alloy, and gray cast iron are 573.86°C, 363.3°C, and

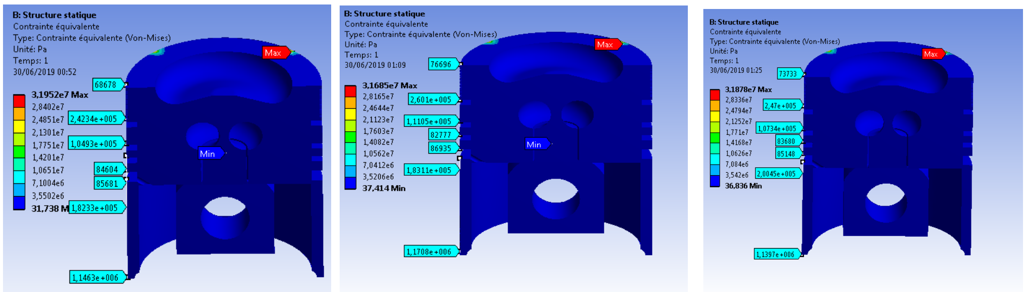
564.12°C, respectively. Independent of material, the temperature reaches its maximum value in the head and decreases towards the interior.



(a) Steel piston (b) Aluminum alloy piston (c) Gray cast iron piston

Fig. 5. Temperature distribution for the three piston materials.

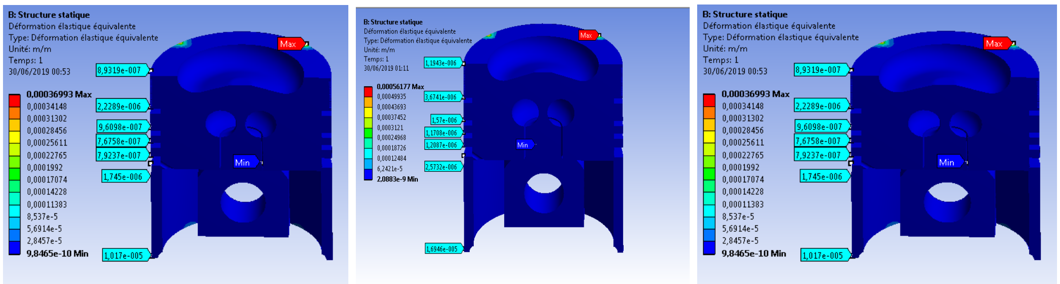
Figs. 6.a, 6.b, and 6.c present the mechanical stress distribution on the 3D piston model for different materials. Cross-sectional views are attached showing temperature probes to display some values at different parts of the piston. Over the entire geometry, the piston is not subject to any significant mechanical stress, except at the outer edges of the piston head and skirt. The piston with the aluminum alloy is the least stressed among them. This indicates that the pistons exhibit better resistance to mechanical stresses, and the lateral forces provide significant balance against the combustion gas load.



(a) Steel piston. (b) Aluminum alloy piston (c) Cast iron piston

Fig. 6. Mechanical stress field distribution for the three types of pistons.

Figs 7.a, 7.b, and 7.c provide cross-sectional views to visualize the results of elastic deformations for the three piston materials (steel, aluminum alloy, and gray cast iron). It can be observed that the deformations are not significant or almost negligible on the entirety of the pistons, especially on the outer surfaces of the two oil scraper segments for all three materials. The maximum deformation values are noticed on the lower sides of the attachments of the bosses, on the axis, and on the edges of the head.

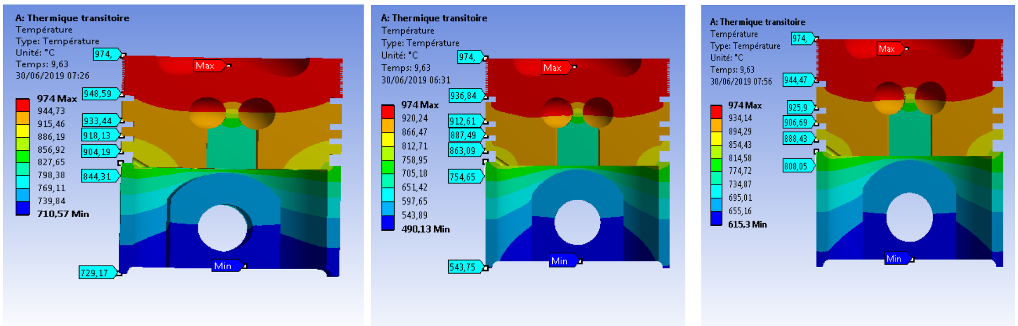


(a) Steel piston (b) Aluminum alloy piston (c) Gray cast iron piston

Fig. 7. Elastic deformation field distribution for the three types of pistons.

3.2 Transient mode

Figs. 8.a, 8.b, 8.c and 9 show the temperature distribution for the three selected piston materials. These results are compared for steady-state and transient conditions respectively. The temperature under transient conditions is significantly higher than under steady-state conditions, due to the temperature variation during the engine cycle. For example, the maximum temperature is increased significantly at the piston head during the transient mode.



(a) Steel piston (b) Aluminium alloy piston (c) Gray cast iron piston

Fig. 8. Temperature distribution for different times in the three types of pistons.

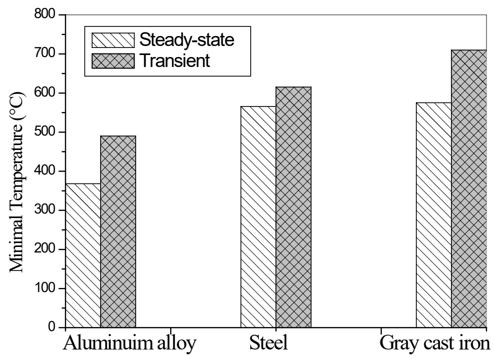
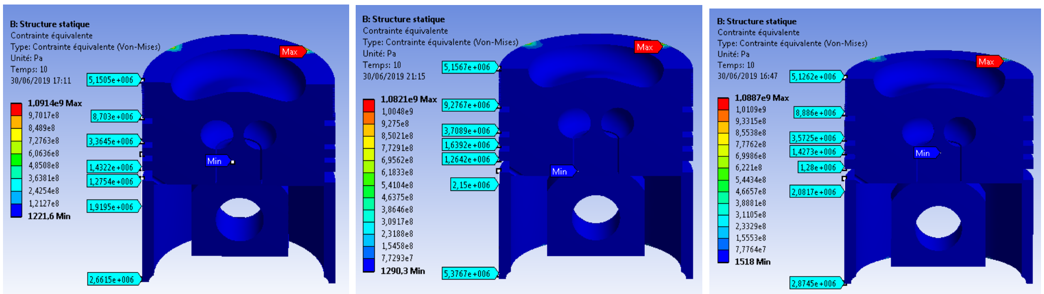


Fig. 9. Comparison of the maximal temperature in state and transient mode for the three materials.

Figs. 10.a, 10.b, 10.c, and Fig. 11 show the results of the mechanical stress analysis for the three piston materials.



(a) Steel piston (b) Aluminum alloy piston (c) Gray cast iron piston

Fig. 10. Von-Mises stress distribution for the three piston materials.

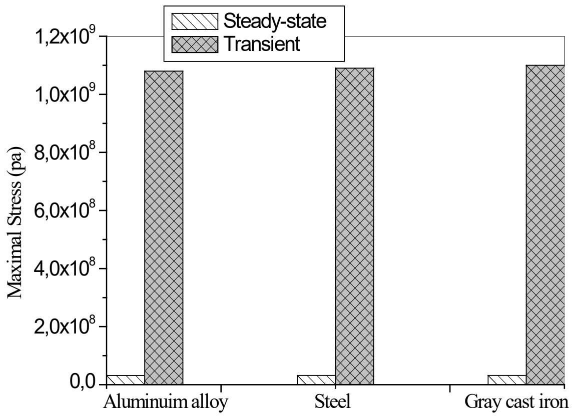
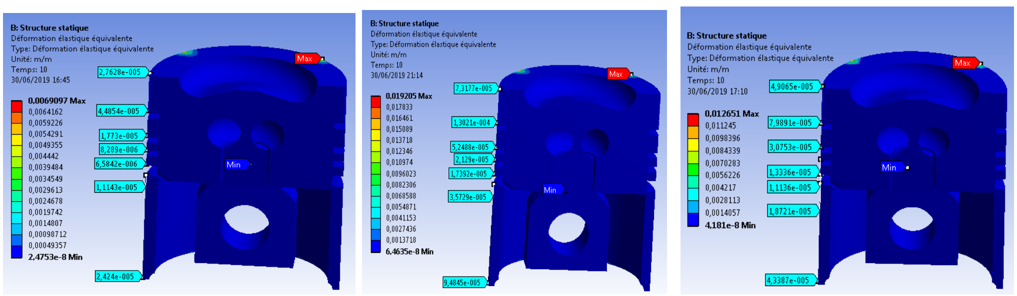


Fig. 11. Comparison of maximal stress in state and transient mode for the three piston materials.

Figs. 12.a, 12.b, 12.c and 13 present for the three piston materials the equivalent deformation distribution in the piston during the transient state for the conducted thermo-mechanical simulations.



(a) steel piston (b) Aluminum alloy piston (c) Gray cast iron piston

Fig. 12. Equivalent deformation distribution for the three piston materials.

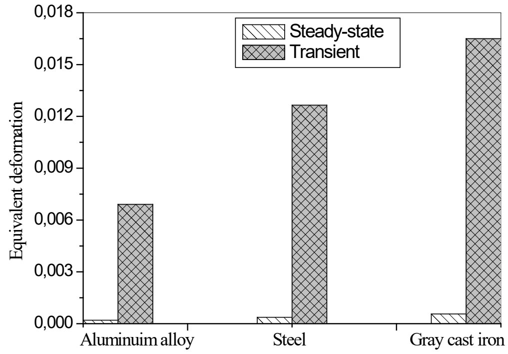


Fig. 13. Comparison of maximal equivalent deformation in state and transient mode for the three piston materials

4. Conclusions

Following the analysis conducted on the impact of the piston material on its thermo-mechanical behavior under stable and variable conditions, the following conclusions can be drawn:

1. The choice of piston material significantly affects the temperature distribution throughout the piston during engine operation. The use of an aluminum alloy provides excellent thermal conductivity, allowing for more efficient heat dissipation compared to steel and gray cast iron. Consequently, pistons made of aluminum alloy tend to reach lower operating temperatures. On the other hand, steel and gray cast iron, having lower thermal conductivity, result in higher temperature gradients within the piston's structure.

2. Under both steady-state and transient conditions, the mechanical properties of the piston material play a crucial role in determining the extent of mechanical deformation experienced during engine operation. Steel, as a solid and rigid material, offers superior resistance to mechanical deformation compared to aluminum alloy and gray cast iron. Conversely, aluminum alloy may undergo more deformation due to its lower strength and higher coefficient of thermal expansion. Gray cast iron may exhibit moderate characteristics of mechanical deformation.

3. During steady and transient conditions, the von Mises stress is influenced by the mechanical properties of the piston material. Steel generally shows lower Von Mises stress values due to its high strength and ductility, making it more resistant to deformation induced by stresses. In contrast, aluminum alloy can display higher Von Mises stresses, especially under transient conditions, increasing the risk of plastic or permanent deformation. Gray cast iron falls somewhere between steel and aluminum alloy in terms of Von Mises stress behavior.

For future optimization work, it is intended to consider simulation tests with other piston materials that offer better convective properties, and to validate these with experimental results. Additionally, the goal is to investigate the utilization of suitable coating materials, such as Ni-Cr-Al and Mg-Zr-O3, to further improve the piston's thermal performance.

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