Journal of Mechanical Engineering Vol: 2, No 3, 2025, Page: 1-12

Thermo-Mechanical Analysis and Durability Optimization of the Piston

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DOI:
https://doi.org/10.47134/jme.v2i3.4075
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Received: 07-05-2025
Accepted: 19-06-2025
Published: 28-07-2025

Abstract: *The present take a look at investigates the thermal and mechanical behavior of an internal combustion engine piston under various operational conditions. A complete thermo-mechanical evaluation became performed to evaluate temperature distribution, heat transfer characteristics, pressure accumulation, and viscoplastic stress across one of a kind piston regions. The findings screen that thermal loads notably effect the flame facet, first ring groove, and the beneath-crown oil aspect, with stated versions among rated and idle conditions. The stabilized 5th cycle analysis highlights temperature-triggered strain concentrations, with viscoplastic stress stages last inside ideal limits. Furthermore, lifetime estimation based on thermo-mechanical fatigue (TMF) evaluation confirms that the piston layout sustains more than three,000 cycles, making sure sturdiness without full-size chance of failure. The study underscores the importance of thermal boundary conditions in ring grooves, emphasizing the function of heat transfer coefficients (HTCs) in temperature regulation. These insights contribute to optimizing piston cloth choice and thermal management strategies for more advantageous engine reliability and efficiency.*

Keywords: *Thermal-Mechanical Fatigue (TMF), Finite Element, fatigue, durability, structural mechanics*

Introduction

The piston is a part that works under excessive thermal loads, notably determining the durability and overall performance of an inner combustion engine. As one of the maximum important shifting parts, the piston endures high temperature fluctuations, mechanical stresses, and frictional forces at some stage in operation. These factors affect its structural integrity, thermal efficiency, and common lifespan (Elhadi et al. 2021).

Extensive research has been undertaken on fabric selection, the development of surface, and innovative manufacturing approaches to improve piston durability. Contemporary pistons are typically constructed from aluminum alloys because of their lightweight traits and advanced thermal conductivity. Nonetheless, accelerated running temperatures and combustion pressures may additionally bring about thermal enlargement, wear phenomena, and fatigue failure (Amroune et al. 2019; Mohamad et al. 2020; Mohamad et al. 2021). Consequently, unique computational and experimental evaluations are essential for optimizing piston configuration, decreasing thermal stresses, and improving heat dissipation. Kumar and Kumar (2022) carried out an intensive evaluation of piston fall apart in internal combustion engines, highlighting the mechanical and thermal stresses that result in fatigue and seizure resulting from contact with the piston ring, grooves, and cylinder liners. The study identifies key failure mechanisms and explores preventive measures, particularly through coatings. A specific analysis of the tribological and mechanical residences of diverse coatings, which include hardness, elastic modulus, coefficient of friction, surface roughness, and the rate of wear, is provided. The overview offers insights into the choice of premier coating materials, approaches, and parameters to beautify piston device durability and decrease damage from strain, fatigue, wear, and friction.

Kuttin et al. (2024) check out piston structural development for increased durability and efficiency. Fatigue damage was illustrated in this study, depending on the cyclic gas strain pressure produced and inertial stresses, with an emphasis on weight loss to increase fuel efficiency. A composite matrix of aluminum and silicon carbide (AlSiC-12) is used to enhance wear resistance. Finite element analysis (FEA) evaluates stresses, strains, deformations, and temperature distributions. The results show that AlSiC-12 outperforms Al-6061 due to its superior wear resistance and lighter weight, making it the preferred material for internal combustion engine pistons. Soni (2023) presents the design and analysis of an internal combustion engine piston, which transmits the thrust of burned gases to the connecting rod. The piston is modeled using Fusion 360 and analyzed in ANSYS software. The study examines the effects of thermal and thrust loads on an aluminum alloy piston, eliminating complexities related to thermal load variations. Structural and thermal analyses in ANSYS identify critical values, providing insights into the piston's performance and durability under operational conditions. Lee and Ku (2021) investigate the impact of piston geometry, stress, temperature, and deformation on piston performance. The study examines four piston head designs flat-top, bowl, square bowl, and dome pistons modeled in SolidWorks. Static structural and steady-state thermal analyses in ANSYS Workbench assess stress, deformation, and temperature distribution. Topology optimization is applied to remove excess material, reducing the piston's weight by approximately 5%. Results show that the bowl piston exhibits the lowest stress, deformation, and temperature, while the optimized piston performs better than the original in all measured parameters. Delprete et al. (2018) review the mechanical power loss in lubricated and bearing surfaces of internal combustion engines, emphasizing friction reduction as a cost-effective method to lower gas emissions and enhance efficiency. The study highlights the significance of piston secondary motion, which arises from unbalanced forces and moments, leading to small translations and rotations within clearance limits. This motion impacts mechanical friction power loss, lubrication at the piston skirt/liner interface, and radiated engine noise. The evaluation examines key factors influencing lubrication and tribological overall performance, which includes piston layout parameters, lubricant rheology, oil cycle mechanisms, and working situations. The examination synthesizes technical elements, studies findings, and challenges related to piston skirt/liner lubrication and piston dynamics.

This takes a look at makes a speciality of the structural and thermal analysis of the piston body to evaluate its performance underneath operational conditions. Finite element analysis (FEA) and experimental strategies are utilized to assess stress distribution, deformation, and temperature gradients. By know-how those elements, powerful layout adjustments may be proposed to enhance durability and performance. Additionally, future advancements in coating technology and opportunity substances are mentioned to in addition improve piston reliability in high-overall performance applications.

2. Workflow for Piston Structure Analysis

Finite Element Analysis (FEA) workflow is used to assess the mechanical and thermal conduct of a system, probably an engine component, through computational simulations. The system is split into several ranges, starting with pre-processing, wherein the advanced fabric model (AMM) parameters are diagnosed, and a stable mesh is created to discretize the issue for numerical simulations. Mechanical and heat transfer (HT) boundary situations are then defined, accompanied by means of computational analysis to assess heat supply inside the jacket. The FEM solver is utilized to perform structural and thermal simulations, details as in figure 1.

In the first phase of FEA, the global material properties are assigned, and a steady-state heat transfer analysis is conducted. Validation steps ensure accuracy by checking the heat balance and comparing finite element results with experimental data. If discrepancies are found, iterations are performed to refine the simulation. The second phase of FEA focuses on transient thermal and mechanical behavior, where a Thermo-Mechanical Fatigue (TMF) cycle is defined, and transient heat transfer effects are simulated. A transient stress/strain analysis is performed using the AMM to assess material response under variable operating conditions. Finally, in the post-processing stage, the results are analyzed to predict the component’s lifetime based on stress, strain, and fatigue calculations. This iterative approach ensures that simulation outcomes are validated against experimental data, leading to accurate durability assessments of engine components.

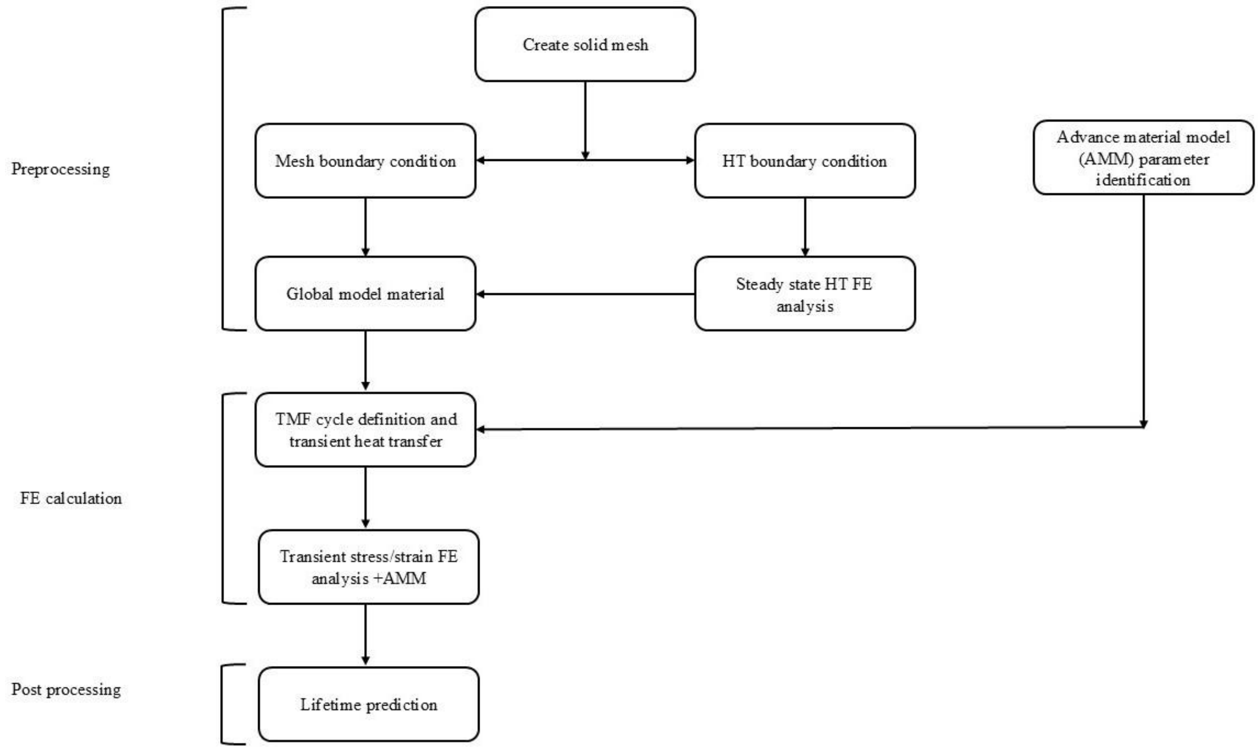


Figure 1. Workflow for piston structure analysis

The model as shown in figure 2 is meshed with a fine grid of elements, indicating a numerical approach for analyzing structural and thermal behavior. The different colors represent distinct materials or components, with the blue region likely depicting the piston body, the red section indicating the piston pin, and other structural elements shown in different shades. The meshing suggests a high-resolution simulation aimed at evaluating stress distribution, thermal expansion, and fatigue behavior under engine operating conditions. The cut-section view allows for a detailed observation of the internal structure.

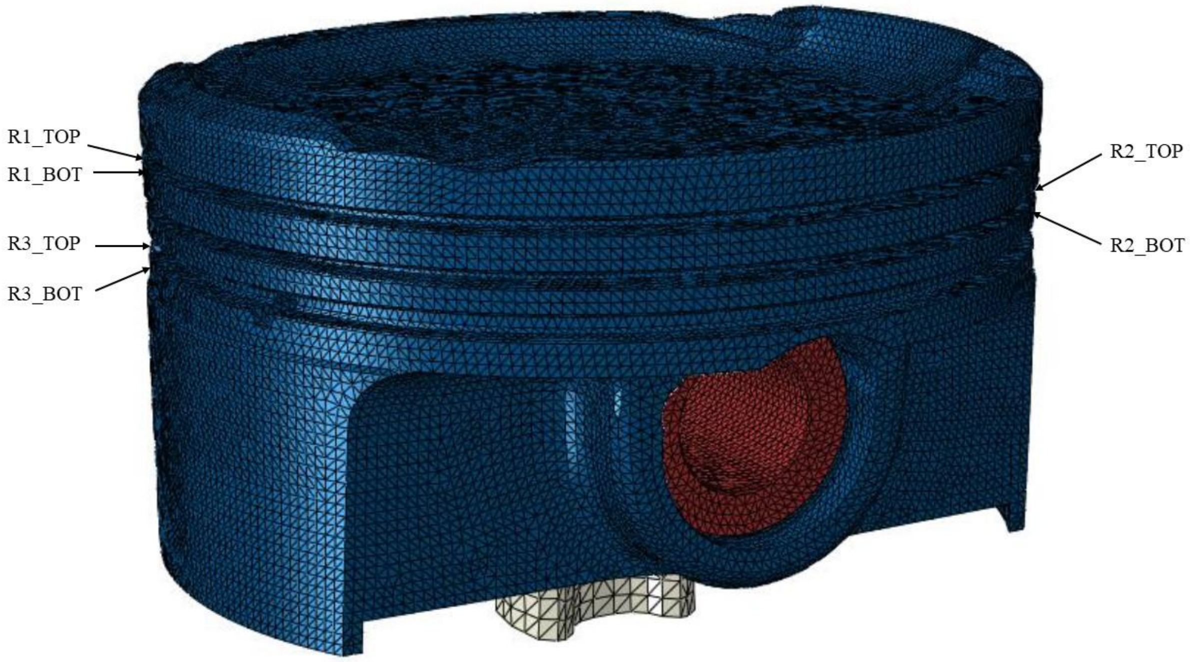


Figure 2. Piston cross section

Finite Element Model and Results

The mechanical and thermal performance of materials beneath operational conditions supplies valuable insights for designing resistance to heat and robotically strong additives. Figure three (a) illustrates the elastic modulus (GPa) plotted in opposition to temperature (°C). The fashion shows a slow lower in elastic modulus as temperature increases, with an extra substantial drop past 200°C, followed with the aid of a moderate stabilization at higher temperatures. This behavior indicates a discount in the cloth's stiffness with growing temperature, which is common for metals and alloys utilized in high-temperature programs, together with engine additives. Figure (b) displays the thermal growth coefficient (1/K) as a function of temperature. The statistics indicate a gradual increase in thermal growth with rising temperature, indicating that the cloth expands more at higher temperatures.

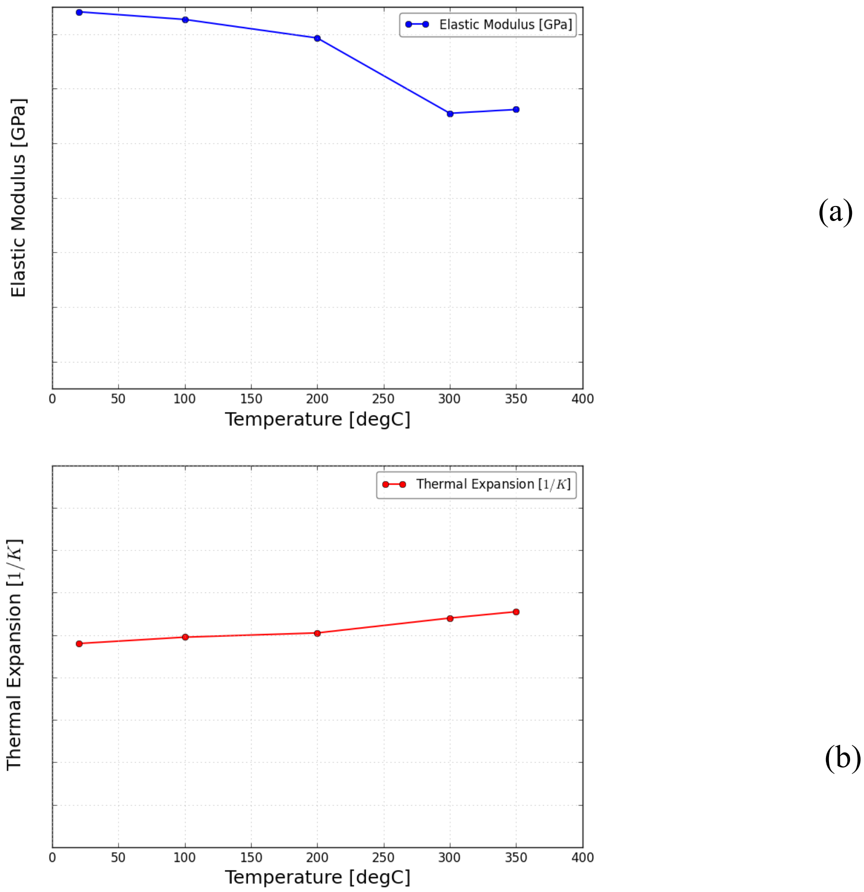
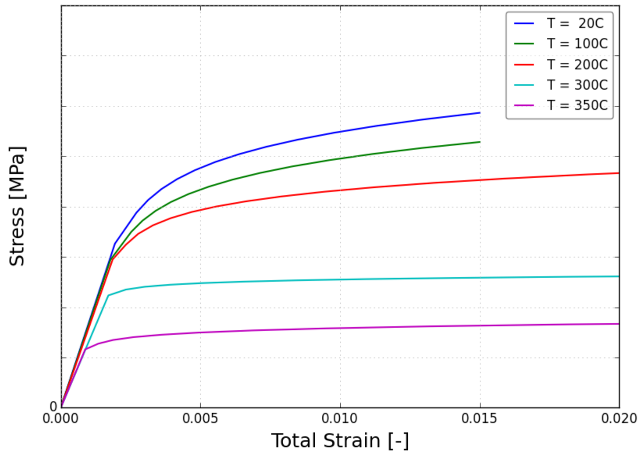
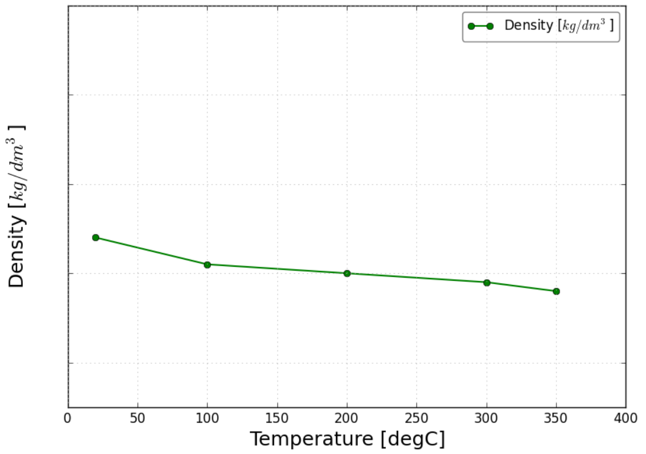


Figure 3

Figure 3(c) illustrates the relation between stress (in MPa) and strain for exclusive temperatures starting from 20°C to 350°C. The curves display a decreasing trend in stress with increasing temperature, indicating a decrease in the strength of the material, strain, and stiffness at elevated temperatures. At high value of temperatures, the material is well-known to show extra strain for a given stress. Figure 3(d) represents the variant of density (kg/m³) with temperature. The trend suggests a slow lowering in density as temperature increases; that is expected due to the material's thermal expansion. As temperature rises, the volume of materials already increases while their mass remains steady, leading to a reduction in density.



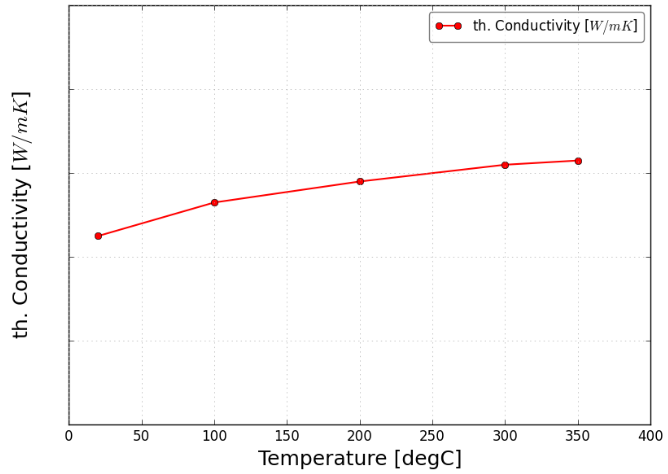
(c)



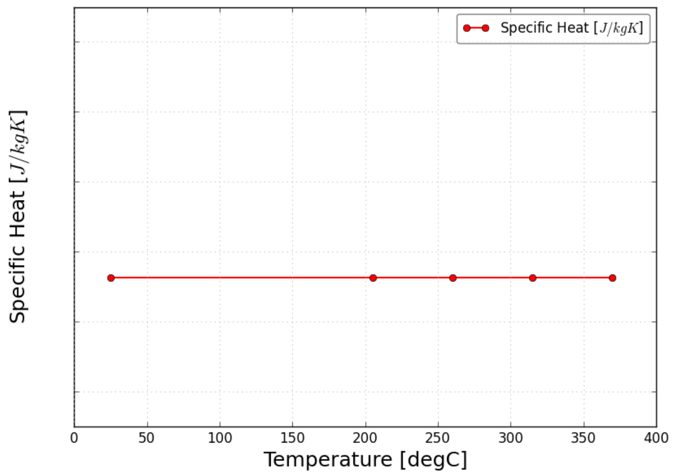
(d)

Figure 3

The thermal conductivity (W/m·K) relationship with the temperature (°C) was shown in Figure 3(e). The pattern shows gradual increases in thermal conductivity with rising temperature, indicating that the material was more efficient at conducting heat at quick rises in temperature. This behavior is common in metals, where lattice vibrations increase with temperature, enhancing heat transfer. The figure 3(f) represents specific heat capacity (J/kg·K) as a function of temperature. The curve remains relatively constant, indicating that the material's ability to store heat does not change significantly with temperature.



(e)



(f)

Figure 3. (a, b, c, d, e, f) Material properties for piston

Heat transfer

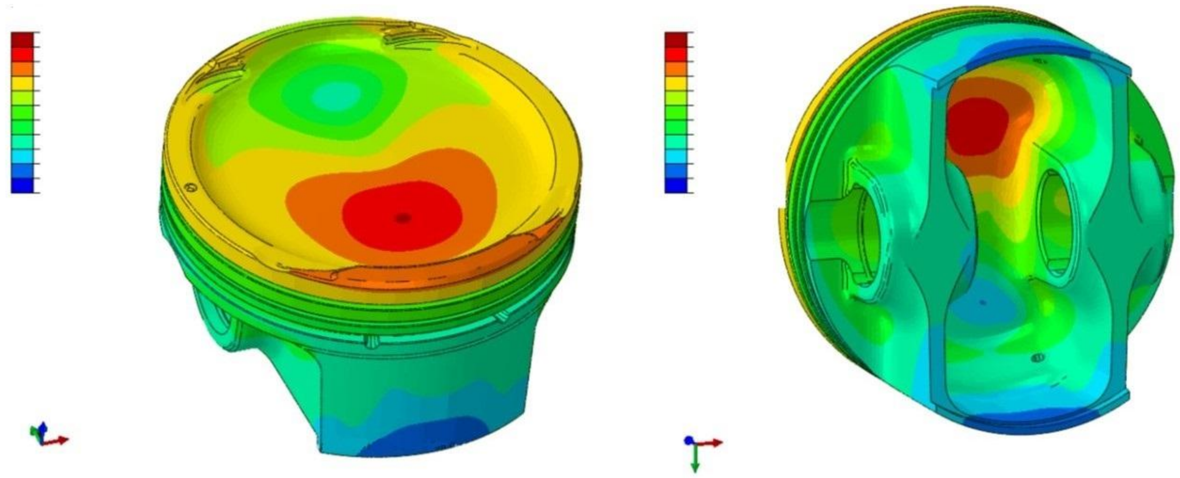
The thermal boundary conditions in the ring grooves of a piston, showing heat transfer coefficients (HTC) and temperature (T) values at different locations (R1_TOP, R1_BOT, R2_TOP, etc.) during different simulation loops. The data provides insights into how thermal loads and heat dissipation evolve through successive cycles, affecting the piston's thermal behavior, details in Table 1.

Table 1: Thermal boundary – Ring grooves

	Loop					
Parameter	Initial		1		2	
	HTC W/(m²·k)	T (°C)	HTC W/(m²·k)	T (°C)	HTC W/(m²·k)	T (°C)
R1_TOP	3060	103.4	2720	96.4	3000	93
R1_BOT	14270	103.4	14550	96.4	14520	93
R2_TOP	3160	90.7	1260	84.4	710	79.3
R2_BOT	5050	90.7	5780	84.4	6170	79.3
R3_TOP	90	88.9	90	88.9	90	87.1
R3_BOT	18640	88.9	18640	88.9	18640	87.1

Figure 4 presents heat transfer analysis for a piston under rated and idle conditions. It highlights temperature distributions across different piston regions, with higher temperatures observed on the flame side, first ring groove, and under the crown (oil side). The results indicate that thermal loading significantly varies between operating conditions, impacting material stress and durability. Additionally, the temperature profile along the axial position indicates key regions where thermal gradients are most pronounced.

Rated



Idle

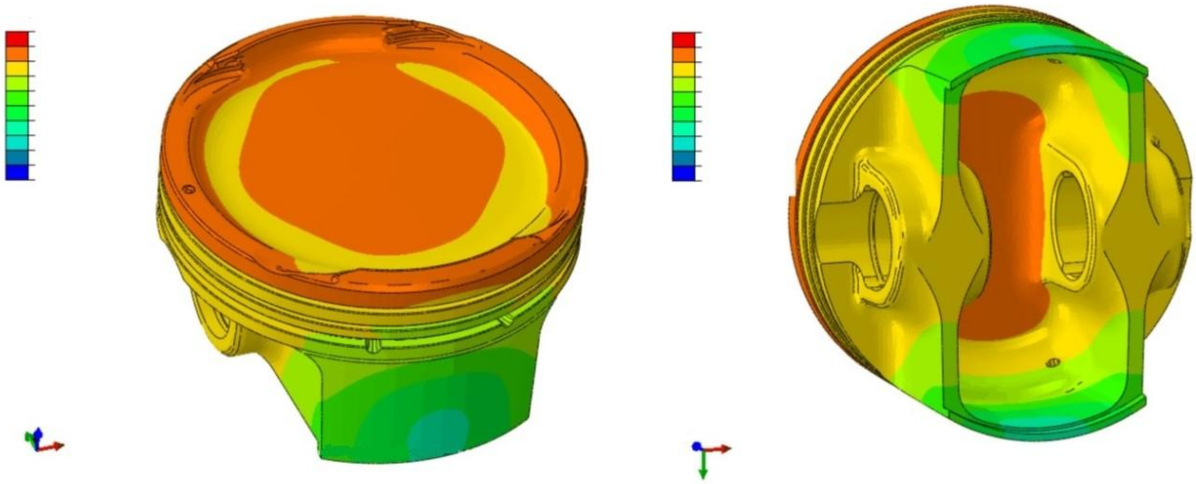


Figure 4. Heat transfer analysis for a piston under rated and idle conditions.

Thermal – Mechanical Fatigue

In the figure 5 each TMF cycle consists of hot and cold cycles, with gas (red) and oil (blue) operating conditions shown separately. During the hot cycle, the engine operates under rated conditions, with gas rated at a high constant level and oil rated increasing gradually before stabilizing. The cold cycle follows, where gas returns to idle, and oil gradually decreases to idle as well. This pattern repeats over multiple cycles, with a stabilization phase occurring around the 5th TMF cycle, indicating a stabilized thermal and mechanical response. Additionally, a 30-hour aging period is incorporated between cycles to simulate long-term material degradation and operational effects. The cycle time definition is based on data from a similar engine TMF test, ensuring realistic engine operating conditions for fatigue analysis.

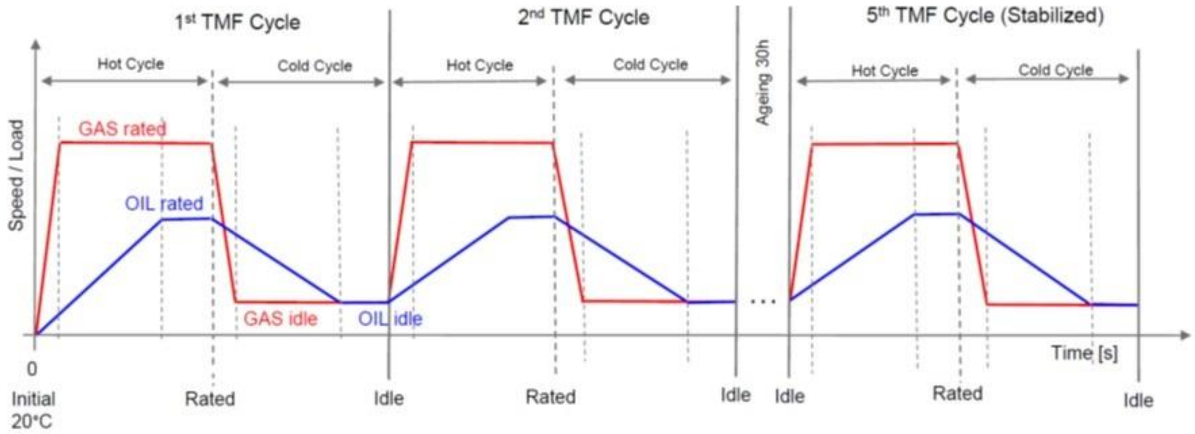
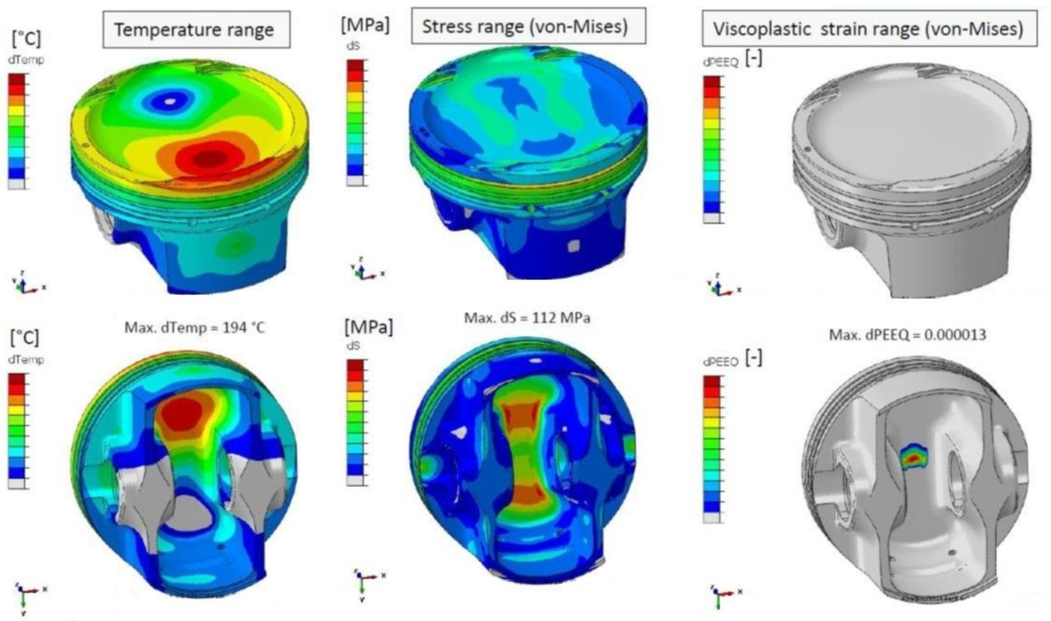


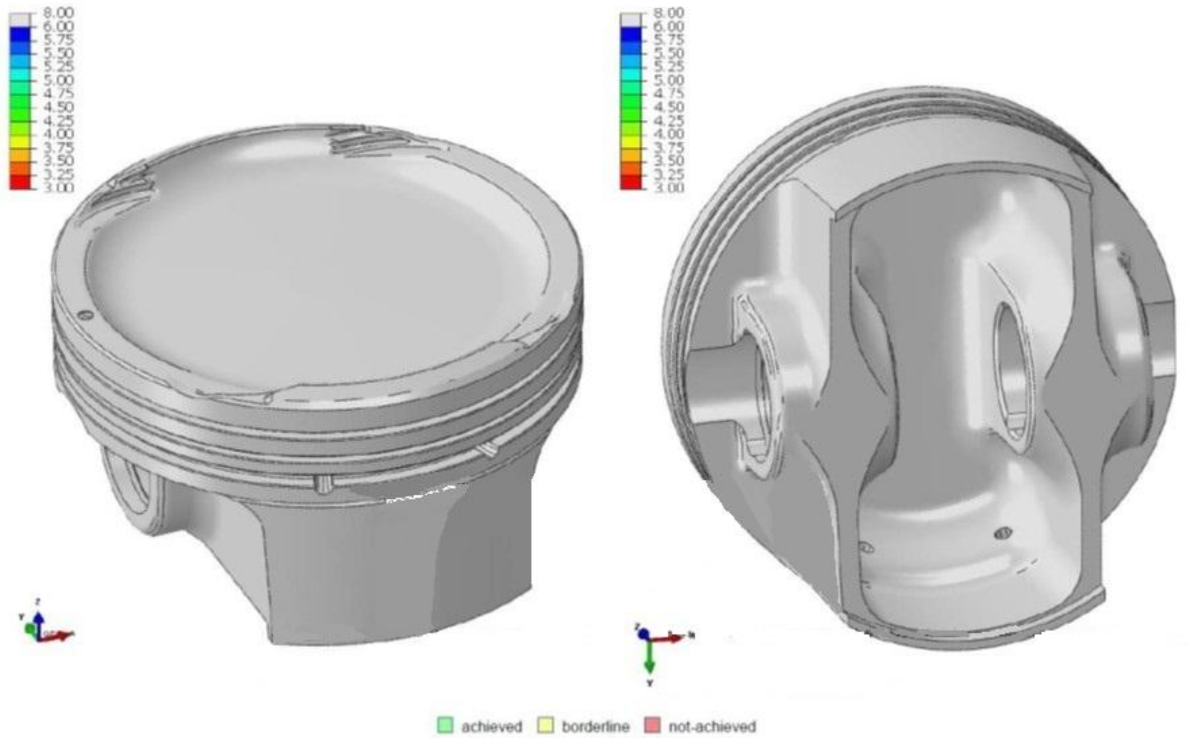
Figure 5. TMF cycle definition for an engine test, illustrating variations in speed/load over time for gas and oil conditions across multiple cycles.

Range of the stabilized 5th cycle

The figure 6 (a) presents an analysis model and results for the stabilized 5th cycle of a piston under TMF conditions. It includes temperature, stress, and viscoplastic strain distributions, highlighting critical regions subjected to thermal and mechanical constraints. The left section shows temperature distribution, with a maximum ΔT of 194°C, stress distribution in terms of von Mises stress, and viscoplastic strain range, indicating that strain accumulation remains minimal after the last cycle. These results emphasize the stiffness-induced constraints that influence stress and strain variations. Figure 6 (b) focuses on lifetime estimation, showing that the number of cycles to crack initiation in all piston regions exceeds 3000 cycles, which is beyond Society of Automotive Standard limit. This confirms that the piston design poses no significant risk for TMF failure, achieving the required durability standards. The evaluation validates the piston's structural integrity underneath high-temperature engine conditions, helping its long-term period operational reliability.



(a)



(b)

Figure 6. (a, b) Temperature, stress and viscoelastic Strain range of the stabilized 5th cycle.

Conclusion

This research work highlights the complete assessment of TMF conduct in engine pistons, focusing on thermal, mechanical, and viscoplastic stress responses over multiple cycles. The findings demonstrate that temperature variations, stress distribution, and viscoplastic strain accumulation remain inside desirable limits, making sure structural integrity. The lifetime estimation analysis confirms that the piston withstands greater than 3000 cycles earlier than crack initiation. These outcomes validate the piston's durability beneath real engine working situations, supplying important insights for optimizing material selection, layout improvements, and predictive renovation techniques. Future studies might also cognizance on advanced material coatings, alternative alloys, and extra refined TMF modeling techniques to in addition enhance piston toughness and performance in high-overall performance engines.

References

Abdullah, M., & Karim, A. (2020). Strategic financial management in private education institutions. *Journal of Educational Finance and Policy*, *45*(2), 134–147. https://doi.org/10.1007/s11256-020-09587-3

Ahmad, S., & Rahman, H. (2021). The role of community participation in funding secondary education. *Asian Education Studies*, *6*(1), 45–53. https://doi.org/10.5539/aes.v6n1p45

Alawiyah, T., & Maulidiyah, N. (2023). Diversifikasi sumber pendanaan pendidikan di sekolah swasta. *Jurnal Ekonomi dan Pendidikan*, *20*(2), 103–110.

Amroune, S., Belaadi, A., Menasri, N., Zaoui, M., Mohamad, B., & Amin, H. (2019). New approach for computer-aided static balancing of turbine rotors. Diagnostyka, 20(4). https://doi.org/10.29354/diag/114621

Bakar, R., & Susanti, I. (2022). Pengelolaan dana pendidikan berbasis transparansi dan akuntabilitas. *Jurnal Administrasi Pendidikan*, *29*(1), 55–67.

Basri, H., & Mardiyah, S. (2020). Peran kepala sekolah dalam pengelolaan keuangan pendidikan. *Jurnal Manajemen Pendidikan Islam*, *8*(1), 33–41.

Brown, D., & Evans, R. (2021). Financial sustainability of non-government schools in developing countries. *International Journal of Education Economics and Development*, *12*(3), 189–204.

Delprete, C., & Razavykia, A. (2018). Piston dynamics, lubrication, and tribological performance evaluation: A review. International Journal of Engine Research, 21(5), 725–741. https://doi.org/10.1177/1468087418787610.

Dewi, A. K., & Saputra, H. (2021). Analisis strategi keuangan di sekolah menengah swasta. *Jurnal Kajian Pendidikan*, *8*(4), 215–223.

Elhadi, A., Amroune, S., Zaoui, M., Mohamad, B., & Bouchoucha, A. (2021). Experimental investigations of surface wear by dry sliding and induced damage of medium carbon steel. Diagnostyka, 22(2), 3–10. https://doi.org/10.29354/diag/134116

Gunawan, H., & Junaidi, A. (2022). Pengaruh bantuan operasional sekolah terhadap kinerja keuangan sekolah swasta. *Jurnal Pendidikan dan Ekonomi*, *11*(2), 145–152.

Huda, M., & Santoso, B. (2023). Kolaborasi sekolah dan yayasan dalam manajemen pendanaan. *Jurnal Kepemimpinan dan Pendidikan*, *14*(1), 78–89.

Idris, M., & Harahap, A. (2020). Optimalisasi sumbangan alumni dalam pembiayaan pendidikan. *Jurnal Sosioteknologi Pendidikan*, *5*(3), 122–130.

Irawan, A., & Subekti, A. (2022). Perencanaan keuangan strategis sekolah berbasis kebutuhan. *Jurnal Pendidikan dan Pengajaran*, *9*(1), 54–63.

Kumar, S., & Kumar, M. (2022). Tribological and mechanical performance of coatings on piston to avoid failure—A review. Journal of Failure Analysis and Prevention, 22(5), 1346–1369. https://doi.org/10.1007/s11668-022-01436-3

Kurniawan, D. (2023). Strategi pendanaan pendidikan melalui kewirausahaan sekolah. *Jurnal Pendidikan Vokasi*, *13*(1), 77–86.

Kuttin, K. W., Yaw, A. O., Duodu, E. A., & Kuttin, A. W. (2024). Thermo-structural Comparative Analysis of Internal Combustion Engine Piston by Finite Element Methods. Journal of Engineering Research and Reports, 26(11), 46–61. https://doi.org/10.9734/jerr/2024/v26i111314

Lee, H., & Lee, Y. (2021). Parent-school financial cooperation in private secondary schools: Challenges and solutions. *Journal of Educational Management*, *39*(2), 99–114.

Lee, Z. R., & Ku, P. X. (2021). Geometry design and optimization of piston by using finite element method. Journal of Physics: Conference Series, 2120(1), 012013. https://doi.org/10.1088/1742-6596/2120/1/012013

Lestari, S., & Arifin, Z. (2022). Evaluasi sistem pelaporan keuangan sekolah berbasis digital. *Jurnal Akuntansi dan Pendidikan*, *13*(1), 90–100.

Lubis, F. A., & Ramli, M. (2024). Analisis sumber pendanaan dan efektivitas penggunaannya di sekolah swasta menengah. *Jurnal Manajemen Pendidikan Islam*, *11*(2), 132–140.

Mahmudi, A., & Sari, D. (2021). Pengaruh iuran orang tua terhadap kualitas layanan pendidikan. *Jurnal Kebijakan Pendidikan Nasional*, *5*(2), 55–66.

Mohamad, B., Karoly, J., Zelentsov, A., & Amroune, S. (2020). A hybrid method technique for design and optimization of Formula race car exhaust muffler. International Review of Applied Sciences and Engineering, 11(2), 174–180. https://doi.org/10.1556/1848.2020.20048

Mohamad, B., Karoly, J., Zelentsov, A., & Amroune, S. (2021). A comparison between hybrid method technique and transfer matrix method for design optimization of vehicle muffler. FME Transactions, 49(2), 494–500. https://doi.org/10.5937/fme2102494M

Nugroho, R., & Yuliani, L. (2020). Manajemen keuangan berbasis akuntabilitas sosial di sekolah. *Jurnal Evaluasi dan Kebijakan Pendidikan*, *9*(3), 201–212.

Rahmawati, D., & Munir, M. (2023). Model kolaborasi sekolah dengan pemangku kepentingan dalam pembiayaan pendidikan. *Jurnal Inovasi Pendidikan*, *6*(2), 99–108.

Soni, A. K., Godara, S. S., Gade, R., & others. (2023). Modelling and thermal analysis for automobile piston using ANSYS. International Journal of Interactive Design and Manufacturing, 17(5), 2473–2487. https://doi.org/10.1007/s12008-022-01042-5

Sulastri, E., & Fitriani, H. (2021). Analisis efektivitas penggunaan dana BOS di sekolah swasta. *Jurnal Ekonomi dan Pendidikan*, *18*(1), 41–50.

Yusuf, A., & Widodo, W. (2024). Strategi pendanaan pendidikan di era digital: Studi kasus sekolah swasta menengah. *Jurnal Ilmu Pendidikan dan Humaniora*, *12*(1), 113–124.