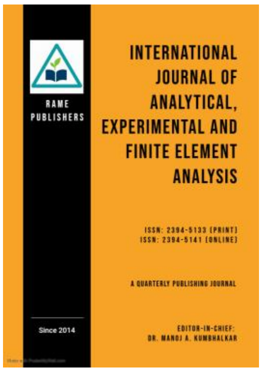
International Journal of Analytical, Experimental and Finite Element Analysis
Volume 13, Issue 1, May 2026, pp 34 - 40
https://doi.org/10.26706/ijaefea.13.1.20260103

Comparative Thermomechanical Analysis of Advanced Piston Materials for Internal Combustion Engines Using Finite Element Analysis

Sahil Verma, Srinivasa Rao Pulivarti*

[1] Department of Mechanical Engineering, CCET, Bhilai, India

*Correspondence: srinivas.indore@gmail.com



Article – Peer Reviewed
Received: January 10, 2026
Accepted: March 10, 2026
Published: March 30, 2026

Cite this article: Sahil Verma, Srinivasa Rao Pulivarti, "Comparative Thermomechanical Analysis of Advanced Piston Materials for Internal Combustion Engines Using Finite Element Analysis", *International Journal of Analytical, Experimental and Finite Element Analysis*, RAME Publishers, vol. 13, issue 1, pp. 34-40, 2026.
https://doi.org/10.26706/ijaefea.13.1.20260103

Abstract: The piston is one of the most critical components of an internal combustion (IC) engine, operating under severe thermal and mechanical loading conditions. Material selection for pistons significantly influences engine efficiency, durability, thermal stability, wear resistance, and fuel economy. This research paper presents a comparative thermomechanical analysis of four piston materials—Al 6061, Al-GHS-1300, Al-SiC composite, and Ti-6Al-4V titanium alloy—using Finite Element Analysis (FEA) in ANSYS Workbench. A piston model was developed and analyzed under coupled thermal and structural loading conditions representative of modern IC engine operation. Parameters such as total deformation, equivalent von Mises stress, and equivalent elastic strain were evaluated for each material. The results indicate that Ti-6Al-4V demonstrates superior thermomechanical performance with the lowest deformation and strain values, making it highly suitable for high-performance applications. Al-SiC emerged as the most balanced engineering solution for production engines due to its favorable stiffness, thermal stability, and wear resistance. Al 6061 showed acceptable performance for naturally aspirated engines but exhibited higher deformation and stress concentration under elevated loading conditions. Al-GHS-1300 demonstrated promising lightweight properties and moderate stress resistance; however, excessive deformation limited its practicality for production applications. The study validates simulation outcomes with existing literature and concludes that advanced composites and titanium-based alloys offer significant potential for next-generation high-efficiency piston systems.

Keywords: Internal combustion engine, piston materials, finite element analysis, thermomechanical analysis, aluminum alloy, titanium alloy, metal matrix composite, ANSYS Workbench.

1. Introduction

Internal combustion engines continue to play a significant role in transportation, industrial machinery, and power generation systems. Among the various engine components, the piston is subjected to the most severe operating conditions due to its direct exposure to combustion gases, cyclic loading, and reciprocating motion [1-2]. The piston experiences high thermal gradients, intense gas pressure, and frictional interactions, making its design and material selection crucial for engine efficiency and durability [3-4].

Modern engines require lightweight yet strong materials capable of withstanding elevated temperatures and cyclic stresses while minimizing thermal deformation and wear [5-6]. Traditionally, cast iron pistons were used because of their strength and wear resistance. However, the increasing demand for fuel efficiency and higher engine speeds led to the widespread adoption of aluminum alloys due to their lower density and superior thermal conductivity. Despite these advantages, aluminum alloys suffer from high thermal expansion and limited strength at elevated temperatures [7-8].

To overcome these limitations, researchers have explored advanced materials such as titanium alloys and metal matrix composites (MMCs). Titanium alloys offer excellent strength-to-weight ratio and fatigue resistance, while MMCs such as aluminum-silicon carbide (Al-SiC) provide improved stiffness, wear resistance, and thermal stability. In recent years, computational tools such as Finite Element Analysis (FEA) have become essential for evaluating piston performance under simulated operating conditions before physical manufacturing [9-11].

This study focuses on the comparative thermomechanical analysis of different piston materials using ANSYS Workbench. The objective is to evaluate the structural and thermal performance of Al 6061, Al-GHS-1300, Al-SiC, and Ti-6Al-4V under identical operating conditions and determine the most suitable material for modern IC engine applications.

2. Literature Review

Extensive research has been conducted on piston materials and their influence on engine performance. Several researchers have used computational techniques and experimental investigations to evaluate piston behaviour under thermal and structural loading conditions.

Balahari Krishnan S et al. (2017) [1] investigated Al-SiC composite pistons and reported that silicon carbide reinforcement significantly reduced deformation and improved wear resistance when compared with conventional aluminium pistons. Their findings demonstrated that metal matrix composites (MMCs) provide enhanced thermal stability and superior mechanical properties suitable for high-performance engines.

Namrata Sengar et al. (2016) [2] carried out thermal analysis of automobile pistons and observed that the piston crown experiences maximum thermal stress because of direct exposure to combustion gases. Their study identified Al 6061 alloy as a balanced material with favourable thermal conductivity and acceptable structural performance for conventional engine applications.

A. N. Kumar et al. (2019) [7] evaluated different piston materials using ANSYS software and concluded that material selection has a major influence on stress distribution, thermal expansion, deformation, and fatigue resistance. Their work emphasized the importance of advanced lightweight materials for modern high-speed and high-efficiency engines.

S. Rajakumar and M. Karthiyaraj (2020) [5] compared aluminium alloy, carbon graphite, and tungsten pistons through structural and thermal analyses. Their results showed that although aluminium alloys provide better heat dissipation, alternative materials such as tungsten and carbon graphite exhibit superior structural strength and higher resistance to thermal stresses.

Yash Dhamecha et al. (2020) [4] performed a comparative analysis of titanium alloy and aluminium-based piston materials. Their study concluded that Ti-6Al-4V titanium alloy offers excellent mechanical strength, fatigue resistance, and dimensional stability under severe loading conditions. However, they also noted that titanium alloys require improved thermal management strategies because of their relatively lower thermal conductivity.

M. Viswanath et al. (2021) [6] analysed pistons made from Ti-6Al-4V and various aluminium alloys using ANSYS-based simulations. Their results indicated that titanium alloys provide better strength and fatigue resistance, whereas aluminium alloys remain advantageous for lightweight and cost-sensitive engine applications.

The reviewed literature highlights the growing importance of advanced materials and computational simulation techniques in piston design optimization. Previous studies mainly focused on individual materials or limited comparisons under specific loading conditions. However, comprehensive comparative analysis of multiple advanced piston materials under identical thermal and structural loading environments remains limited. Therefore, the present study aims to address this research gap through detailed finite element analysis of Al 6061, Al-GHS-1300, Al-SiC, and Ti-6Al-4V piston materials under realistic engine operating conditions.

3. Results and Discussion

The finite element analysis (FEA) results obtained from ANSYS Workbench provided a detailed understanding of the structural behaviour of the piston under the applied combustion pressure of 13.65 MPa. The analysis was performed for four different piston materials, namely Al 6061, Al-GHS-1300, Al-SiC composite, and Ti-6Al-4V titanium alloy. The results were evaluated in terms of total deformation, equivalent von Mises stress, and equivalent elastic strain. These parameters are essential for understanding the structural stability, load-carrying capability, and durability of the piston under operating conditions. The contour plots generated through the simulations helped identify the critical regions subjected to maximum loading and deformation, particularly around the piston crown, ring grooves, and pin boss regions. The results clearly demonstrated that material properties such as elastic modulus, thermal expansion coefficient, and yield strength strongly influenced piston performance.

The finite element model was developed using a highly refined mesh consisting of 951,371 nodes and 657,394 elements as shown in Figure 1, which ensured accurate representation of the piston geometry and reliable stress distribution. The combustion pressure was uniformly applied on the piston crown surface, while fixed and frictionless supports were introduced to simulate realistic boundary conditions. The crown region consistently showed the highest response values for all materials because it directly experiences combustion pressure during engine operation. The results obtained for each material are discussed below.

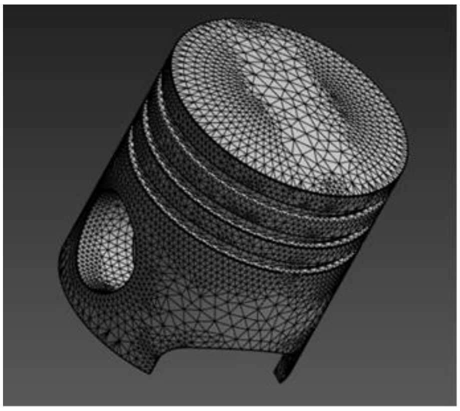


Figure 1. Meshed model

3.1 Results for Al 6061

The total deformation analysis of Al 6061 showed a maximum deformation of 3.15 mm concentrated at the piston crown center as shown in Figure 2. The deformation gradually reduced toward the lower skirt and pin boss regions. The higher deformation observed in this material was mainly due to its relatively low stiffness and high thermal expansion coefficient. Excessive crown deformation can lead to piston slap, blow-by gases, and reduced volumetric efficiency in high-load engine applications.

The equivalent von Mises stress distribution indicated a maximum stress value of approximately 248 MPa near the piston crown center and crown fillet region. This value approached the yield strength of Al 6061-T6 alloy, indicating the possibility of localized yielding under repeated loading conditions. Stress concentration was observed mainly around the crown edges and ring groove regions due to geometric discontinuities.

The equivalent elastic strain analysis showed a maximum strain of nearly 2% at the piston crown apex. The strain distribution confirmed the presence of plastic deformation zones near the crown surface. Such high strain values may accelerate fatigue crack initiation, ring groove wear, and loss of compression over prolonged engine operation.

Overall, Al 6061 demonstrated acceptable performance for naturally aspirated and low-cost engine applications because of its lightweight nature and good thermal conductivity. However, its comparatively high deformation and stress levels make it less suitable for high-performance or turbocharged engines operating under severe thermal and pressure conditions.

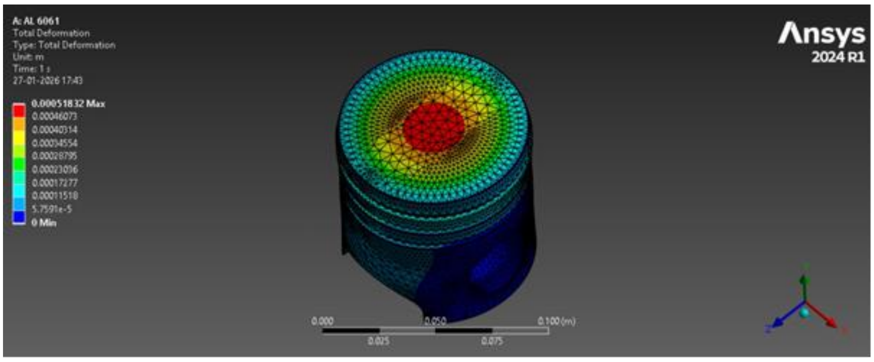


Figure 2. Equivalent Elastic Strain of Al 6061

3.2 Results for Al-GHS-1300

The Al-GHS-1300 material exhibited the highest total deformation among all the analysed materials, with a maximum value of 3.62 mm at the piston crown center as shown Figure 3. The deformation pattern showed significant radial expansion across the crown surface. This behaviour was mainly attributed to the mismatch in thermal expansion characteristics between the aluminium matrix and graphene reinforcement. The excessive deformation may lead to piston instability, ring sealing problems, and cylinder wall contact during operation.

The equivalent stress analysis revealed a maximum stress of approximately 170 MPa concentrated near the crown center and crown-to-skirt transition region. The stress distribution appeared more uniform compared to conventional aluminium alloys because graphene reinforcement improved load transfer and reduced localized stress concentration. The material remained within safe stress limits under the applied loading condition.

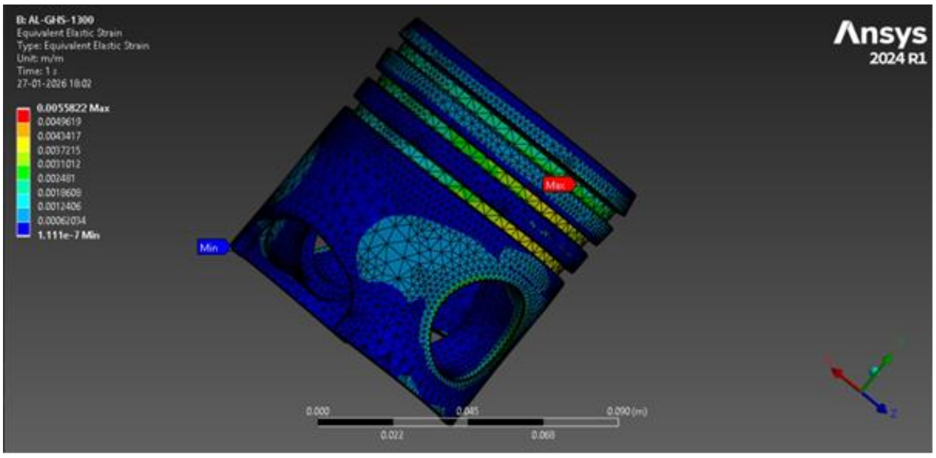


Figure 3. Equivalent Elastic Strain of Al-GHS-1300

The equivalent elastic strain reached approximately 1.8% at the crown center. Although the strain value was lower than that of Al 6061, the material still exhibited considerable deformation. The graphene nanoplatelets contributed to improved ductility and fatigue resistance, reducing the possibility of sudden crack initiation.

The results indicated that Al-GHS-1300 possesses promising lightweight characteristics and moderate stress resistance. However, the excessive deformation observed limits its practical application in commercial IC engines. The material may be more suitable for experimental lightweight engine systems and future hybrid vehicle technologies where reduced mass is prioritized.

3.3 Results for Al-SiC Composite

The Al-SiC composite piston showed significantly improved structural performance compared to conventional aluminium alloys. The total deformation was limited to 2.02 mm, which was substantially lower than that of Al 6061 and Al-GHS-1300. The lower deformation resulted from the high stiffness and reduced thermal expansion coefficient provided by silicon carbide reinforcement. The deformation remained well distributed across the piston surface, indicating improved dimensional stability.

The equivalent von Mises stress reached a maximum value of approximately 217 MPa near the piston crown and crown-to-skirt junction. Although stress concentration was present in the crown region, the stress values remained well below the yield strength of the composite material. The higher modulus of elasticity enabled the material to distribute loads more effectively and reduce local stress amplification.

The equivalent elastic strain for Al-SiC was approximately 1.5%, indicating controlled deformation and improved resistance to plasticity. The strain distribution remained smoother and more uniform than the aluminium-based materials, which contributes to enhanced fatigue resistance and longer service life.

The Al-SiC composite demonstrated an excellent balance between lightweight construction, thermal stability, stiffness, and wear resistance as shown in Figure 4. These properties make it highly suitable for turbocharged gasoline engines, diesel engines, and high-performance automotive applications where dimensional stability and durability are critical.

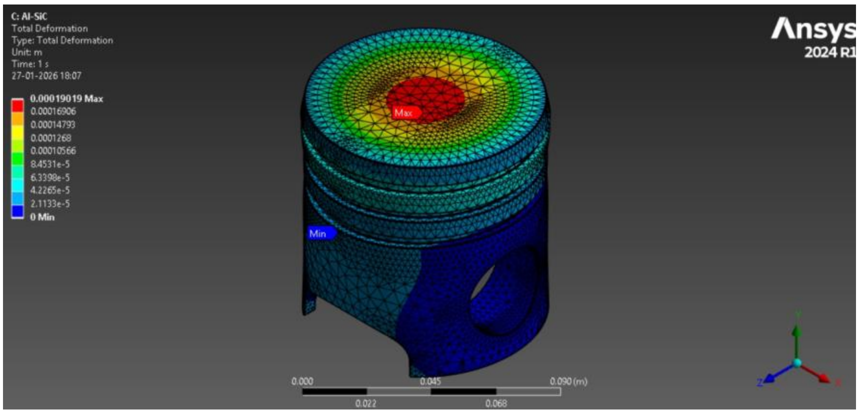


Figure 4. Total deformation of AlSiC

3.4 Results for Ti-6Al-4V

Among all the materials analysed, Ti-6Al-4V titanium alloy exhibited the best structural performance as shown in Figure 5. The total deformation was only 1.15 mm, which was the lowest among all the materials studied. The deformation was confined mainly to the piston crown surface, while the remaining piston body showed minimal displacement. The low deformation was attributed to the material's high elastic modulus, low thermal expansion coefficient, and excellent high-temperature strength.

The equivalent stress analysis showed a maximum stress value of approximately 170 MPa distributed uniformly across the piston crown and upper skirt regions. The stress level was significantly lower than the yield strength of Ti-6Al-4V, which is approximately 900 MPa. This provided a very high factor of safety and indicated excellent load-carrying capability under severe engine operating conditions.

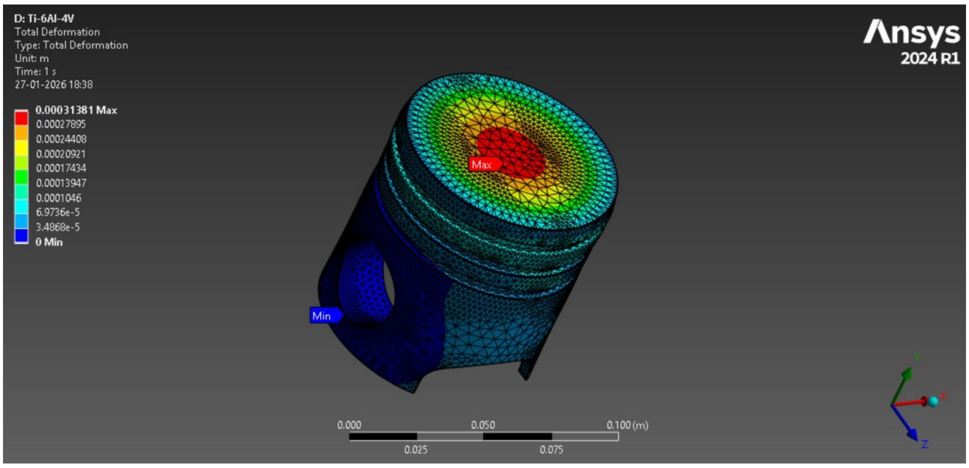


Figure 5. Total deformation of Ti-6Al-4V

The equivalent elastic strain reached only 0.7%, which was substantially lower than all the other materials. The strain remained within the elastic limit, indicating nearly complete elastic recovery after loading. The reduced strain level suggests excellent fatigue resistance and dimensional stability during cyclic engine operation.

The Ti-6Al-4V alloy demonstrated outstanding thermomechanical stability, making it highly suitable for racing engines, aerospace-derived engines, and high-performance automotive applications. However, its high material cost and lower thermal conductivity compared to aluminium alloys may require advanced cooling strategies and thermal barrier coatings for practical implementation.

3.5 Comparative Discussion

The comparative analysis of the four piston materials clearly showed that material selection plays a significant role in determining piston behaviour under combustion loading. Ti-6Al-4V exhibited the best overall performance with the least deformation and strain values, confirming its superior structural stability and fatigue resistance. Al-SiC composite emerged as the most balanced material because it provided low deformation, controlled stress distribution, improved wear resistance, and good thermal stability at comparatively lower cost than titanium alloys.

Al 6061, although widely used in commercial engines, showed comparatively higher deformation and stress concentration, limiting its suitability for high-load applications. Al-GHS-1300 demonstrated promising lightweight and stress-handling capabilities, but excessive deformation reduced its practical reliability under severe engine conditions.

The analysis also confirmed that the piston crown region is the most critical portion of the piston structure, as maximum stress, deformation, and strain were consistently concentrated in that area for all materials. Therefore, future piston design improvements should focus on crown geometry optimization, reinforcement techniques, and advanced material development to enhance piston durability and engine efficiency.

4. Conclusions

The present work examined the structural behaviour of a piston used in a 220 cc four-stroke petrol engine under pressure loading through finite element analysis. The study was carried out using a systematic methodology that involved material selection based on literature review, manual measurement of piston dimensions, three-dimensional modelling in ANSYS Discovery, mesh generation, and the application of loading and support conditions in ANSYS Workbench. This sequence ensured that the analysis was performed on a geometrically realistic piston model under a clearly defined loading condition of 13.65 MPa acting on the piston crown. A comparative evaluation of four candidate materials, namely Al 6061, Al-GHS-1300, Al-SiC, and Ti-6Al-4V, was undertaken to assess their suitability for piston applications under the selected pressure condition. The numerical results showed clear differences in deformation, equivalent stress, and equivalent strain among the materials, thereby demonstrating the strong influence of material properties on piston performance under loading. Al 6061 exhibited comparatively higher deformation and stress levels, indicating lower resistance to the applied loading when compared with the other selected materials. In contrast, the advanced materials showed improved structural behaviour, with Al-SiC and Ti-6Al-4V providing better dimensional stability and lower deformation under identical boundary conditions. Among the materials considered in the present investigation, Ti-6Al-4V exhibited the most favourable overall structural response, as it showed the least deformation and relatively lower strain values under the same pressure loading condition. Al-SiC also demonstrated strong performance and emerged as a promising alternative because of its improved stiffness and dimensional stability. Although Al-GHS-1300 showed advantages over conventional Al 6061 in certain response characteristics, the comparative results indicated that titanium alloy and aluminium matrix composite materials offered superior suitability for severe loading conditions. These findings established that the use of advanced materials can significantly improve the load-carrying capability and structural reliability of pistons intended for high-pressure engine applications. The study also confirmed that the piston crown region represented the most critical zone under the applied pressure load, as the highest response values were concentrated in that region across the analysed materials. This observation highlighted the importance of crown design, local geometry, and material strength in determining the overall structural integrity of the piston. Therefore, the present investigation demonstrated that accurate modelling, proper meshing, and realistic boundary condition definition are essential for obtaining meaningful finite element results and for supporting engineering decisions related to piston design and material selection. This can be concluded by following points.

- The study analysed the piston of a 220 cc four-stroke petrol engine under a pressure load of 13.65 MPa.
- A systematic methodology was followed, including material selection, manual measurement, modelling, meshing, and boundary condition setup.
- The analysis showed that piston response varied significantly with the selected material properties.
- Among the materials considered, Ti-6Al-4V gave the best overall structural performance with the least deformation and strain.
- The study confirmed that accurate modelling and proper material selection are essential for improving piston strength and reliability.

References

[1] B. K. S. Balahari Krishnan, M. S. A. Vallavi, M. Arunkumar, and A. Haripraveen, "Design and Analysis of an IC Engine Piston Using Composite Material," *European Journal of Advances in Engineering and Technology*, vol. 4, no. 3, pp. 209–215, 2017.

[2] N. Sengar, M. C. Patel, and K. A. Vyas, "Finite Element Based Static Structural Analysis of IC Engine Piston," *International Journal for Scientific Research and Development (IJSRD)*, vol. 4, no. 3, pp. 1642–1644, 2016.

[3] N. Dagar *et al*., "Design and Analysis of Piston Using Aluminum Alloy and Composites in SolidWorks and ANSYS," *Materials Today: Proceedings*, vol. 67, pp. 784–791, 2022.

[4] Y. Dhamecha, V. Saptarshi, S. Parikh, and T. Parnami, "Design and Analysis of Piston Using Different Materials," *International Research Journal of Engineering and Technology (IRJET)*, vol. 7, no. 12, pp. 1112–1117, 2020.

[5] S. Rajakumar and M. Karthiyaraj, "A Comparative Study of Structural and Thermal Analyses on Piston Materials," *International Journal of Scientific Development and Research (IJSDR)*, 2020.

[6] M. Viswanath *et al*., "Design and Analysis of Piston on Different Materials Using CAE Tools," *International Journal of Engineering Research and Technology (IJERT)*, 2021.

[7] A. N. Kumar *et al*., "Review Paper on Design and Analysis of IC Engine Piston with Different Material," *International Journal of Management Technology and Engineering*, 2019.

[8] R. Raveena *et al*., "Design, Modelling and Thermal Analysis of Hot Piston of IC Engine Using ANSYS Workbench 2021 R2," *International Journal of Engineering Trends and Technology (IJETT)*, 2021.

[9] H. N. Shah and S. Pandey, "A Review of Analysis and Performance of I.C. Engine Piston with Coating Material Using CATIA and ANSYS Software," *International Journal of Research Publication and Reviews*, 2023.

[10] G. Rabbani and Y. Yadav, "Comparative Study of the Use of Different Al Composites for Piston Material," *International Journal for Research Trends and Innovation (IJRTI)*, 2023.

[11] P. H. Sahare, N. K. Ade, M. A. Kumbhalkar, K. S. Rambhad, C. Giradkar, J. Gandate, S. Badkelwar, and S. Sondawale, "Comparison of alternative fuels in single cylinder diesel engine using CFD," in *AIP Conference Proceedings*, vol. 2839, no. 1, Art. no. 020034, 2023, doi: 10.1063/5.0167692.