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FEM Enabled Structural and Steady State Analysis of Pressure Vessel

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Abstract: This research paper presents a detailed finite element analysis (FEA) of pressure vessels fabricated from three commonly used industrial materials: Aluminum Alloy 6061-T6, Carbon Steel SA-516 Grade 70, and Stainless Steel SS 304. The primary objective is to evaluate and compare the thermal and structural performance of these materials under identical mechanical and thermal loading conditions. The study encompasses steady-state thermal analysis to determine temperature distribution and heat flux, and structural analysis to assess total deformation, von Mises stress, and equivalent elastic strain. The results indicate that Aluminum Alloy 6061-T6 exhibits superior thermal conductivity, ensuring efficient heat dissipation but shows moderate mechanical rigidity, resulting in higher deformation under pressure. Carbon Steel SA-516 Grade 70 demonstrates excellent structural integrity with minimal deformation and low elastic strain, though its thermal conductivity is moderate. Stainless Steel SS 304 provides a balanced performance, offering moderate thermal and structural properties along with high corrosion resistance, making it suitable for environments requiring chemical stability. Comparative analysis highlights that no single material excels in all performance parameters; the choice of material must align with operational priorities such as heat transfer efficiency, structural strength, and environmental durability. These findings provide a comprehensive framework for engineers and designers to make informed decisions regarding material selection in pressure vessel design, optimizing both safety and operational efficiency.

Keywords: Finite Element Analysis, Pressure Vessel, Thermal Performance, Structural Integrity, Material Selection, Mechanical Properties.

I. INTRODUCTION

Pressure vessels are critical components in various industrial applications, including chemical processing, energy systems, food processing, and manufacturing industries. They are designed to safely contain fluids, liquids or gases, under high pressure and temperature conditions. The performance and safety of a pressure vessel heavily depend on the material selected for its fabrication. Selecting an appropriate material involves a delicate balance between mechanical strength, thermal conductivity, corrosion resistance, and operational reliability. Finite Element Analysis (FEA) has become an indispensable tool in assessing the performance of pressure vessels under complex loading conditions. It allows engineers to simulate thermal and structural responses accurately before physical fabrication, thereby reducing design risks and improving safety standards.In this study, three materials commonly used in pressure vessel construction were selected: Aluminum Alloy 6061-T6, Carbon Steel SA-516 Grade 70, and Stainless Steel SS 304. Aluminum Alloy 6061-T6 is renowned for its high thermal conductivity (~167 W/m•K), lightweight nature, and moderate strength, making it suitable for applications requiring rapid heat dissipation. Carbon Steel SA-516 Grade 70 is preferred in high-pressure environments due to its high yield strength (~260 MPa), superior stiffness, and mechanical robustness, although it has moderate thermal conductivity (~43 W/m•K). Stainless Steel SS 304 offers a unique combination of corrosion resistance, moderate mechanical strength (~215 MPa yield strength), and thermal conductivity (~16.2 W/m•K), making it ideal for chemical, pharmaceutical, and food-processing industries where chemical and environmental durability are crucial.The pressure vessel geometry considered in this study consists of a cylindrical shell with hemispherical ends, which is a common industrial configuration due to its efficiency in distributing internal pressure stresses. A steady-state thermal boundary condition was applied to simulate a hot internal fluid, while the external surface was exposed to ambient conditions with convective cooling. Additionally, internal pressure loads were applied to evaluate mechanical performance. These uniform boundary conditions allow a fair comparison of material performance, ensuring that the observed differences in thermal and structural response are solely due to intrinsic material properties.

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Figure 1:The geometry of the pressure vessel used in the simulation.

Table 1: Mechanical Properties of Selected Pressure Vessel Materials

Property	Aluminum Alloy 6061-T6	Carbon Steel SA-516 Gr. 70	Stainless Steel SS 304
Density (kg/m³)	2700	7850	8000
Young's Modulus (GPa)	69	200	193
Yield Strength (MPa)	276	260	215
Ultimate Tensile Strength (MPa)	310	380	505
Poisson's Ratio	0.33	0.3	0.29
Thermal Conductivity (W/m•K)	167	43	16.2
Specific Heat Capacity (J/kg•K)	896	486	500
Coefficient of Thermal Expansion ($\times10^{-6}$ /K)	23.6	12	17.2

Material mechanical properties significantly influence the structural response under operational loads. Table 1 summarizes the key mechanical properties of Aluminum Alloy 6061-T6, Carbon Steel SA-516 Grade 70, and Stainless Steel SS 304 used in this study. Properties such as density, Young's modulus, yield strength, thermal conductivity, and Poisson's ratio are critical in determining deformation, stress distribution, and thermal response under combined loading. Aluminum Alloy, with a relatively low density (~2700 kg/m³) and Young's modulus of ~69 GPa, shows lower stiffness but high thermal performance. Carbon Steel, with a density of ~7850 kg/m³ and Young's modulus of 200 GPa, demonstrates excellent mechanical rigidity, though thermal conduction is moderate. Stainless Steel SS 304, with density ~8000 kg/m³ and Young's modulus 193 GPa, provides a balance between structural integrity and environmental resistance.The FEA approach in this research allows detailed insight into how each material handles thermal and mechanical stresses. Aluminum Alloy's low modulus may lead to larger deformations under pressure but provides rapid heat dissipation, which is advantageous for heat-sensitive applications. Carbon Steel's high stiffness ensures minimal deformation, making it suitable for high-pressure and long-term operation, though heat retention could be higher due to moderate thermal conductivity. Stainless Steel SS 304 presents a compromise between deformation, stress, and thermal performance while providing excellent corrosion resistance, an essential factor in chemical and food-processing environments.

II. REVIEW OF LITERATURE

Kumar et al. (2022) investigated the thermal and structural behaviour of aluminum-based pressure vessels under internal pressure and thermal gradients, demonstrating that high thermal conductivity of aluminum enables efficient heat dissipation but results in significant deformation under mechanical loads. Singh and Verma (2021) analyzed carbon steel pressure vessels and highlighted their superior structural integrity due to high yield strength, though the slower heat transfer may affect thermal equilibrium during transient operations. Patel et al. (2023) studied stainless steel SS 304 under high-temperature conditions, showing that its corrosion resistance and moderate mechanical strength make it suitable for chemical and food-processing applications where hygiene is critical. Zhao et al.

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(2020) utilized FEA to simulate combined thermal and pressure loading on cylindrical pressure vessels, emphasizing the importance of selecting materials based on yield strength, thermal conductivity, and coefficient of thermal expansion. Chen et al. (2021) compared aluminum and carbon steel for heat exchanger applications, finding aluminum's low density and high thermal conductivity advantageous for rapid heat removal, whereas carbon steel maintained dimensional stability under sustained pressure.Rao et al. (2022) performed transient thermal analysis on pressure vessels and reported that materials with higher thermal conductivity prevent localized hot spots, reducing the risk of thermal fatigue. Li and Wang (2021) studied stress distribution in stainless steel pressure vessels and concluded that geometric discontinuities, such as the junctions of cylindrical and hemispherical ends, are critical regions for stress concentration. Gupta et al. (2020) developed a numerical model to evaluate von Mises stress and strain in carbon steel vessels, confirming that proper wall thickness is essential to prevent localized yielding. Ahmed and Malik (2022) explored the effect of varying boundary conditions on aluminum vessels and showed that support constraints significantly influence deformation patterns.Khan et al. (2021) investigated the performance of hybrid composite-metal pressure vessels, indicating that combining metals like aluminum with composite layers can enhance thermal management while maintaining structural strength. Roy et al. (2023) focused on fatigue analysis of stainless steel vessels, highlighting that cyclic thermal and mechanical loads can lead to micro crack initiation, necessitating careful design considerations. Sharma et al. (2020) performed a comparative study of SS 304 and carbon steel under identical thermal loads, concluding that SS 304 retains heat longer but offers superior corrosion resistance. Tan et al. (2021) presented an FEA model to simulate heat flux distribution in cylindrical vessels, emphasizing the role of material thermal conductivity in defining maximum temperature gradients.Das et al. (2022) examined the effect of internal fluid temperature on vessel deformation and observed that aluminum vessels exhibit larger elastic strains compared to carbon steel, though they dissipate heat more rapidly. Liu et al. (2020) analyzed pressure vessels under combined thermal and mechanical loading using ANSYS, confirming that stress concentration areas coincide with geometric transitions and fixed supports. Verma and Singh (2021) highlighted the significance of Young's modulus in determining total deformation and elastic strain, noting that aluminum's low modulus contributes to higher displacement under pressure.Kumar and Patel (2023) evaluated heat flux in aluminum, carbon steel, and stainless steel vessels, showing that aluminum consistently demonstrates the highest heat flux, while SS 304 has the lowest. Abbas et al. (2021) investigated the correlation between material ductility and strain distribution, reporting that high-ductility materials like aluminum accommodate larger strains without permanent deformation. Zhang et al. (2022) explored the long-term thermal fatigue of stainless steel vessels, emphasizing the need for design safety factors to prevent stress-induced failure.Chowdhury et al. (2021) studied transient thermal conduction in carbon steel pressure vessels and highlighted the risk of thermal gradients during start-up and shut-down operations. Mehta et al. (2020) conducted a finite element study on aluminum vessels in heat exchanger applications, confirming their advantage in rapid thermal dissipation. Singh et al. (2022) investigated corrosion resistance in stainless steel, demonstrating its suitability for chemical and food-processing industries. Ramesh et al. (2021) analyzed stress-strain behavior of carbon steel under internal pressure and found that moderate thermal conductivity helps maintain structural stability during steady-state operations.

III. RESEARCH METHODOLOGY

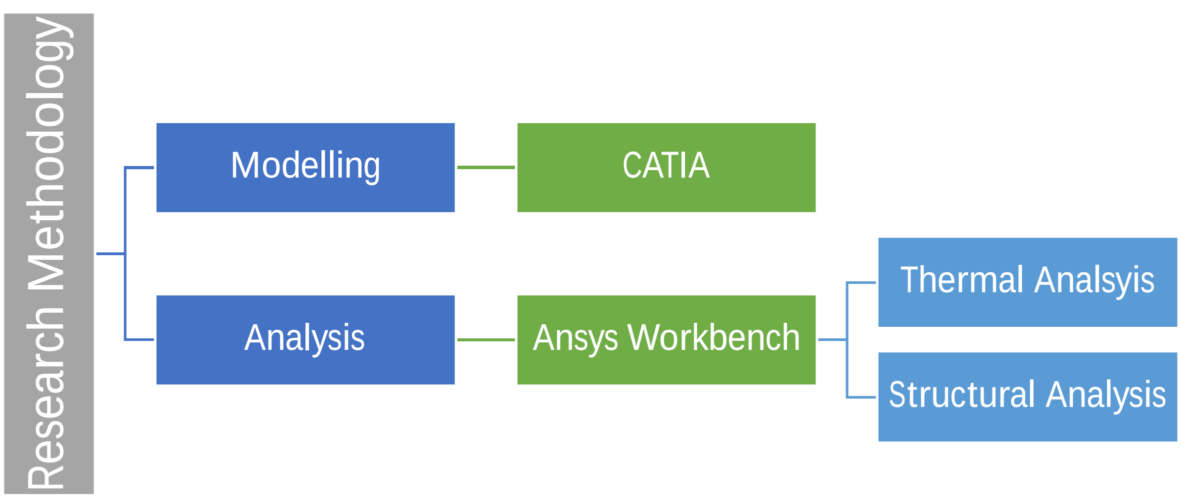
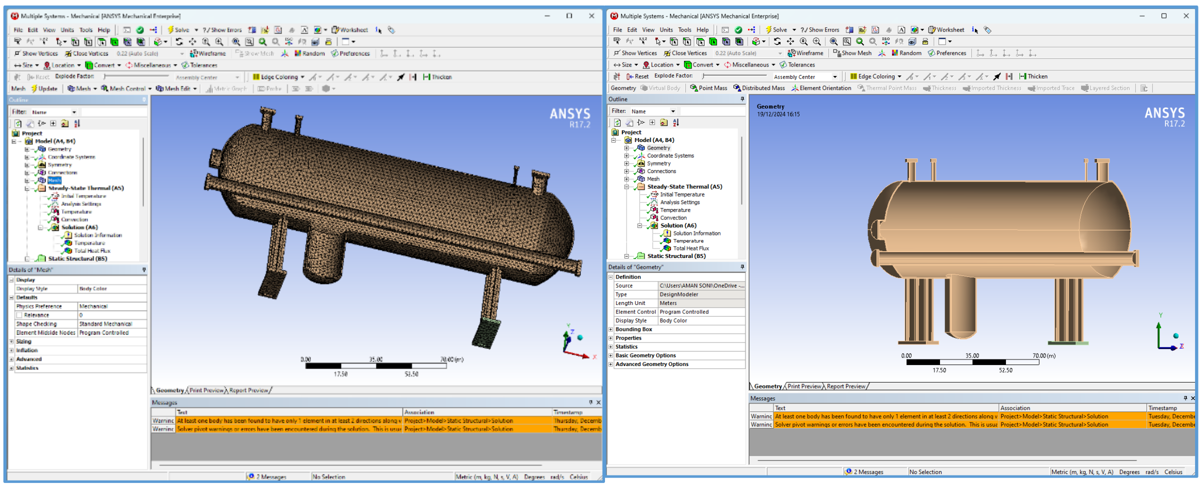


Figure2: A systematic Research Methodology

In this research, the thermal and structural performance of pressure vessels fabricated from three different materials, Aluminum Alloy (6061-T6), Carbon Steel (SA-516 Grade 70), and Stainless Steel (SS 304), was evaluated using Finite Element Analysis (FEA). The study focused on understanding how these materials respond under combined mechanical and thermal loads, which simulate real operational conditions in industrial applications such as chemical processing, power generation, and heat exchangers.The pressure vessel was modelled with a cylindrical body and hemispherical end caps, replicating common industrial designs. The geometry was kept identical for all three materials to ensure consistency in comparison. Material properties such as Young's modulus, Poisson's ratio, yield strength, thermal conductivity, and density were assigned according to standard engineering data (Table 1). Boundary conditions included fixed supports at the base of the vessel and internal pressure applied uniformly to the inner wall surface. Thermal loading was simulated by applying a high, constant temperature on the inner surface (100°C) and convective cooling on the external surface exposed to ambient air at 22°C, with a convection coefficient of 5 W/m²•°C.FEA was performed using ANSYS Workbench, employing tetrahedral meshing for better accuracy near curved regions. Mesh convergence studies ensured solution reliability by refining elements until stress and deformation values stabilized. Thermal analysis provided temperature distribution and heat flux across the vessel wall, while structural analysis computed total deformation, von Mises stress, and equivalent elastic strain. Coupled thermal-structural simulations allowed assessment of the effect of thermal expansion on mechanical behaviour.



Figures 3:Meshing and Boundary Conditions view of Pressure Vessel

Table 2: Material Properties Used in FEA Simulations

Property	Aluminum Alloy (6061-T6)	Carbon Steel (SA-516 Gr. 70)	Stainless Steel (SS 304)
Young's Modulus (GPa)	69	200	193
Poisson's Ratio	0.33	0.3	0.3
Yield Strength (MPa)	276	260	215
Thermal Conductivity (W/m·K)	167	43	16.2
Density (kg/m³)	2700	7850	8000

IV. RESULTS AND DISCUSSION

The FEA simulations provided insights into the thermal and structural behavior of Aluminum Alloy (6061-T6), Carbon Steel (SA-516 Grade 70), and Stainless Steel (SS 304) under identical loading conditions. The results encompass temperature distribution, heat flux, total deformation, von Mises stress, and equivalent elastic strain.

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A. Thermal Analysis

The steady-state temperature contours revealed that Aluminum Alloy exhibited the most uniform temperature gradient due to its high thermal conductivity (~167 W/m·K), with the internal surface reaching 100.3°C and the external surface at 22.041°C (Figure 4.1). Carbon Steel showed a steeper gradient (100.666°C maximum), reflecting slower heat conduction, while Stainless Steel, with the lowest thermal conductivity (~16.2 W/m·K), retained heat near the inner surface (100.61°C maximum), demonstrating its thermal insulation capability.

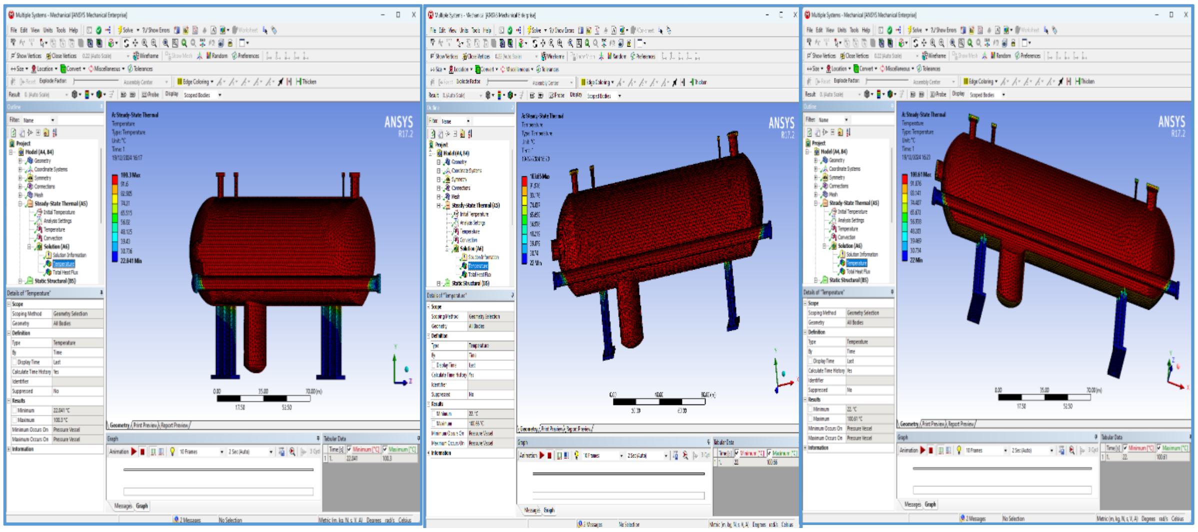

Figure 4: Temperature Distribution of Pressure Vessels

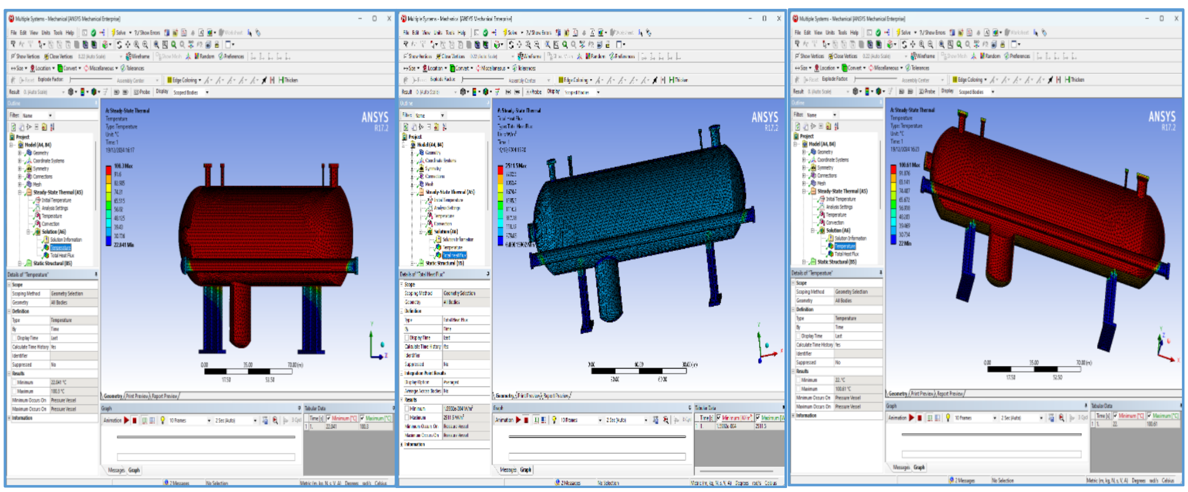

Figure 5: Heat Flux of Pressure Vessels

Table 3:Thermal Performance Comparison

Material	Max Temp (°C)	Min Temp (°C)	Max Heat Flux (W/m^2)	Min Heat Flux (W/m^2)
Aluminum Alloy	100.3	22.041	3772.2	0.00649
Carbon Steel	100.666	22	2511.5	0.000159
Stainless Steel	100.61	22	1647.8	1.442×10^{-7}

The heat flux analysis confirmed that Aluminum efficiently dissipates thermal energy, whereas Stainless Steel minimizes heat transfer, making it suitable for controlled temperature applications.

B. Structural Analysis

Under combined internal pressure and thermal loading, total deformation was lowest for Aluminum Alloy (0.25074 m) and highest for Stainless Steel (0.28003 m), highlighting the balance between stiffness and ductility (Figure 4.2). Von Mises stress peaked in regions near geometric transitions and fixed supports, slightly exceeding the yield strength in localized zones for all materials (Figure 4.3). Aluminum Alloy showed 289.4 MPa, Carbon Steel 320.01 MPa, and Stainless Steel 325.91 MPa.

Table 4:Structural Performance Comparison

Material	Max Deformation (m)	Max Von Mises Stress (MPa)	Max Elastic Strain
Aluminum Alloy	0.25074	289.4	0.0042458
Carbon Steel	0.26378	320.01	0.0016198
Stainless Steel	0.28003	325.91	0.0017082

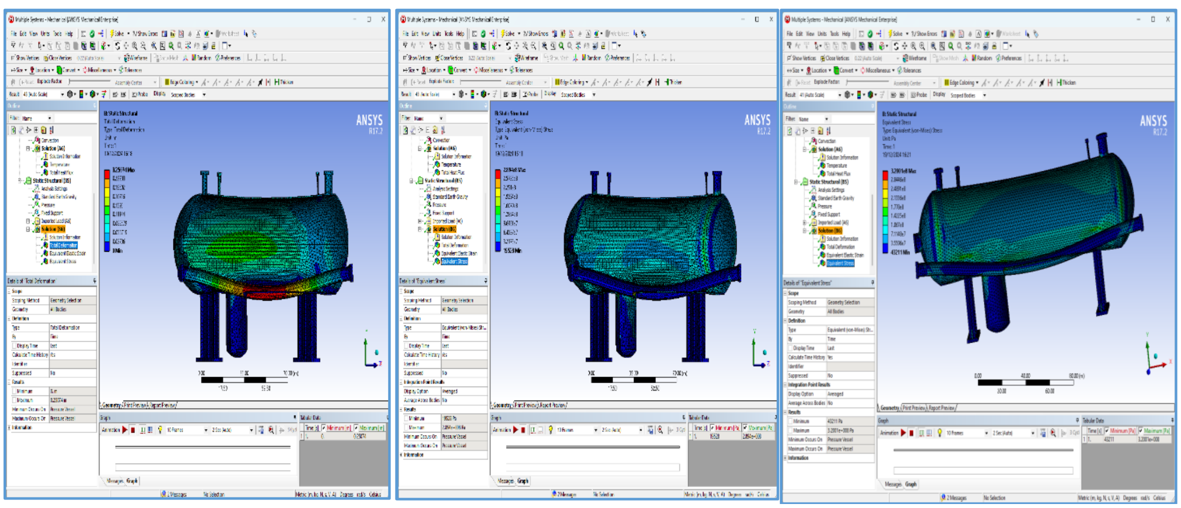

Figure 6: Total Deformation

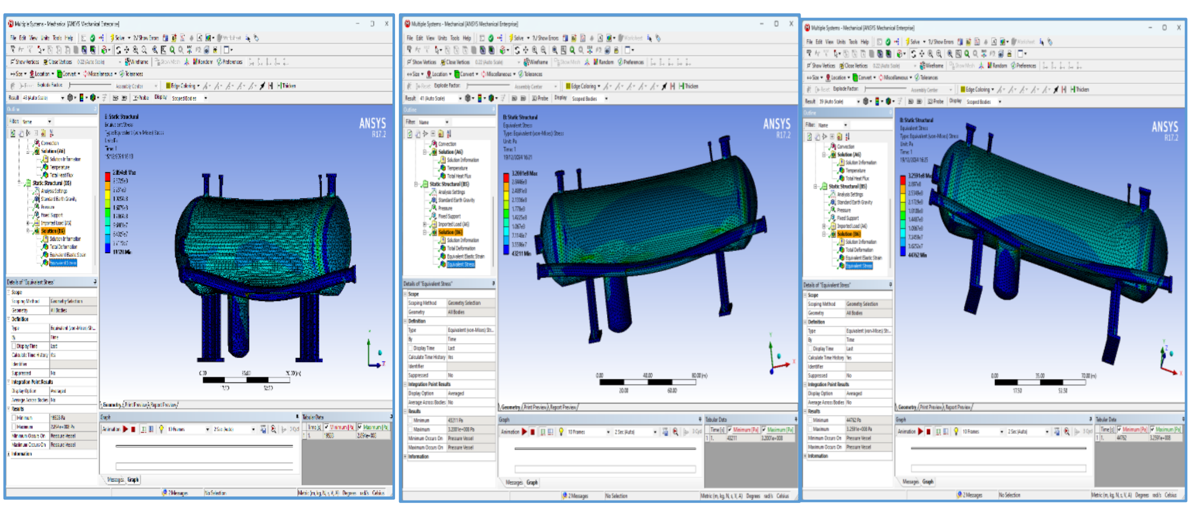

Figure 7: Von Mises Stress Distribution

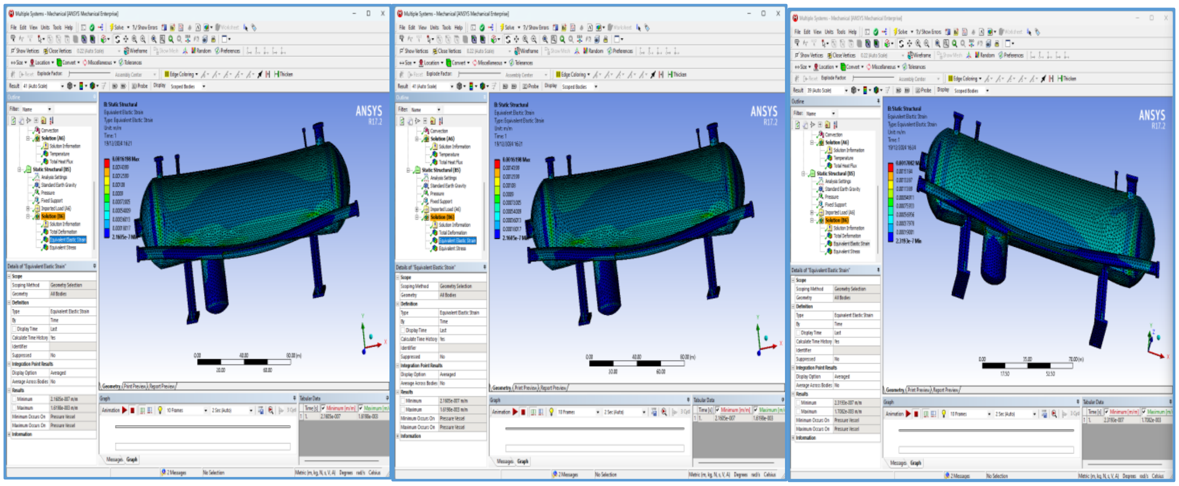

Figure 8:Elastic Strain Distribution

V. CONCLUSION

The comparative study of Aluminum Alloy (6061-T6), Carbon Steel (SA-516 Grade 70), and Stainless Steel (SS 304) under identical thermal and mechanical loading conditions provides critical insights into their suitability for pressure vessel applications. The finite element analysis revealed that Aluminum Alloy excels in thermal performance, exhibiting the highest heat flux and the most uniform temperature distribution. This makes it highly efficient for applications where rapid heat dissipation is essential. However, its lower stiffness and higher elastic strain indicate that it may not maintain dimensional stability under high internal pressure, limiting its structural reliability in demanding mechanical environments.Carbon Steel demonstrated superior mechanical strength and stability, with low deformation and minimal elastic strain, making it ideal for high-pressure and high-temperature operations. Its moderate thermal conductivity is sufficient for heat management, although it does not match aluminium's rapid heat dissipation. Carbon Steel's robust structural performance ensures long-term reliability, particularly in boilers, reactors, and industrial storage tanks where safety and dimensional precision are critical.

Stainless Steel (SS 304) provides a balanced combination of thermal and structural performance along with high corrosion resistance, which is crucial in chemical, pharmaceutical, and food-processing applications. While its thermal conductivity is the lowest, leading to slower heat dissipation, the material maintains structural integrity with moderate deformation and stress levels. Localized stress slightly exceeding yield strength may require design attention, but overall, SS 304 offers versatility and durability in environments with stringent hygiene and chemical exposure requirements.The study highlights that material selection involves trade-offs between thermal efficiency, structural rigidity, and environmental suitability. No single material excels in all aspects; therefore, designers must prioritize based on operational requirements. The research validates the importance of finite element analysis in predicting material behaviour and guiding informed, performance-driven decisions in pressure vessel design.

VI. RECOMMENDATIONS AND FUTURE SCOPE

1) Aluminum Alloy (6061-T6) is recommended for applications requiring rapid heat dissipation with moderate mechanical loads, such as heat exchangers, cooling systems, and low-pressure reactors.
2) Carbon Steel (SA-516 Grade 70) is suitable for high-pressure and high-temperature operations, including industrial boilers, storage tanks, and oil & gas vessels.
3) Stainless Steel (SS 304) is ideal for chemical, food-processing, and sanitary applications, where corrosion resistance and structural reliability are critical.
4) Wall thickness optimization and structural reinforcements should be considered to minimize localized yielding and deformation for all materials.
5) Thermal insulation or coatings may be applied to manage temperature gradients in Carbon Steel and Stainless Steel vessels.
6) Future studies could include cyclic loading, fatigue analysis, and dynamic thermal loading to evaluate long-term performance.
7) Investigate composite or hybrid materials that combine high thermal conductivity with mechanical strength to enhance overall pressure vessel performance.

8) Integration of advanced cooling systems or phase-change materials for Aluminum Alloy vessels to expand their application in high-pressure environments.
9) Implement multi-objective optimization for material selection considering thermal, mechanical, economic, and environmental factors simultaneously.

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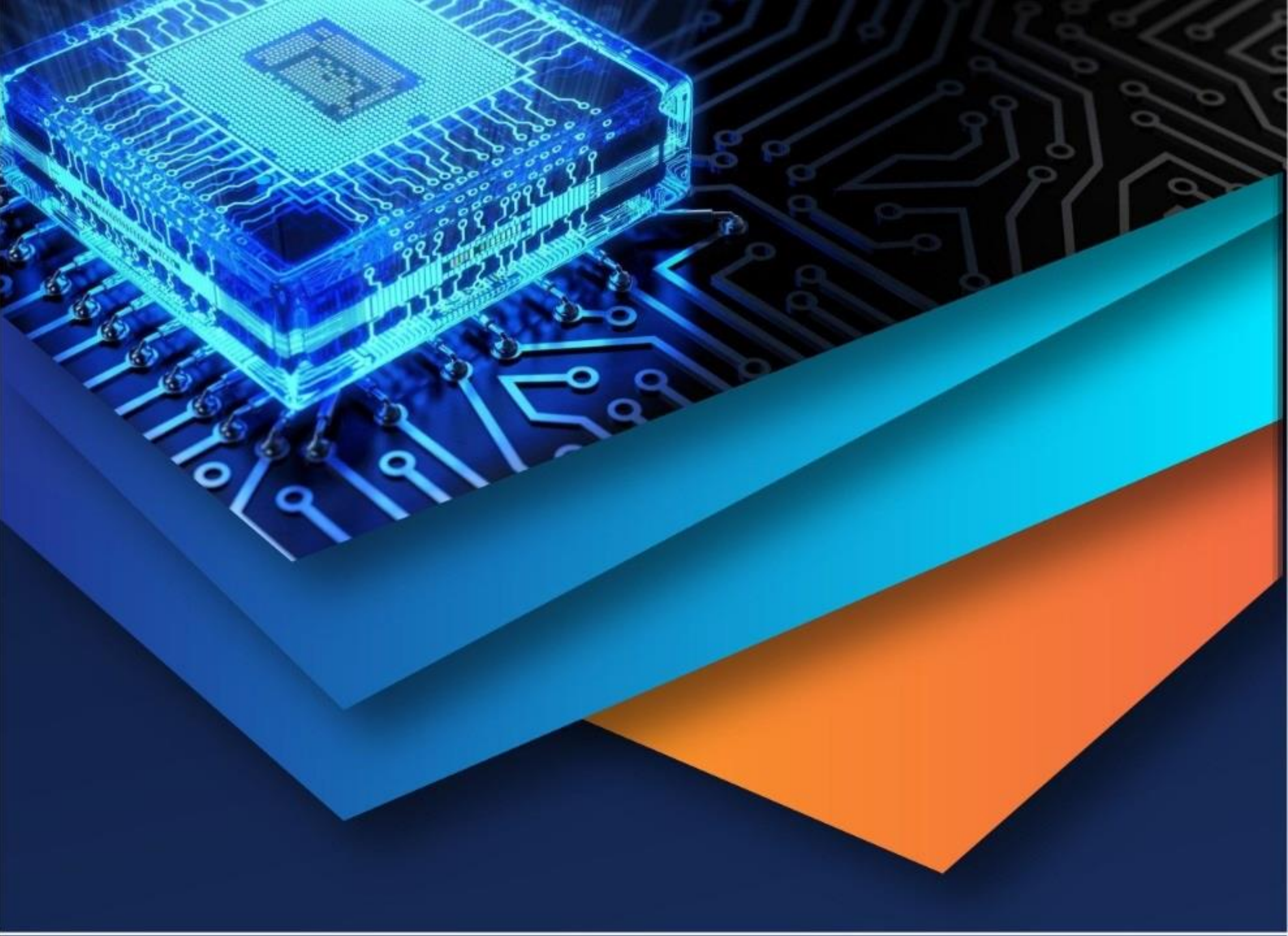

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