▼ Journal of Research (Science)
ISSN (print) 1021-1012. ISSN (Online) 3007-1968
Vol. 35, No.1 January, 2025, pp. 1-16
DOI: https://doi.org/10.64762/4hwqhk84
https://jorscience.com/

INTEGRATED THERMAL-STRUCTURAL ANALYSIS AND MATERIAL OPTIMIZATION OF A COMPRESSION IGNITION ENGINE EXHAUST VALVE USING FINITE ELEMENT SIMULATION

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Abstract

This study presents an integrated thermal and structural analysis of a compression ignition engine exhaust valve to enhance its performance, durability, and thermal efficiency under severe operating conditions. The exhaust valve operates under high combustion temperatures and fluctuating mechanical loads, requiring careful optimization of both material properties and geometry. A three-dimensional valve model was developed in SolidWorks and analyzed in ANSYS Workbench 16.2 under steady-state thermal and static structural conditions. Five materials, stainless steel, structural steel, carbon steel, martensitic steel, and nickel-titanium, were evaluated based on heat-flux distribution, equivalent stress, and deformation behavior. Results showed that structural steel achieved superior thermal performance with the highest total and directional heat flux, while nickel-titanium exhibited the lowest von Mises stress, indicating better mechanical resilience. Analysis of fillet radius variation further revealed that a 37.4 mm fillet provided an optimal balance between heat dissipation and stress reduction. The proposed thermo-structural approach establishes reliable design recommendations for exhaust valves, contributing to improved efficiency and extended service life of compression ignition engines. This study bridges the gap between independent thermal and structural analyses by combining both within a single ANSYS-based framework to assess material and geometric optimization for CI engine exhaust valves.

Keywords: Exhaust valve; Compression ignition engine; Thermal-structural analysis; Finite element simulation.

1. INTRODUCTION

The exhaust valve plays a pivotal role in the operation and efficiency of a compression ignition engine as it regulates the release of burnt gases from the combustion chamber during the exhaust stroke (Arnau, Martin, Pla, & Aunon, 2021; Bajwa, Patterson, & Jacobs, 2021; Bhowmik & Sabharwall, 2023). It ensures proper timing of gas exchange within the internal combustion process, where the valves are fundamental components that control the inflow and outflow of gases, thus maintaining the overall thermodynamic balance of the system since the exhaust valve is continuously exposed to extremely high temperatures and fluctuating pressures (Cană et al., 2025; Cerdoun, Khalfallah, Beniaiche, & Carcasci, 2020; Gupta, 2025). It experiences intense mechanical and thermal stresses, which can lead to fatigue deformation or even premature failure if not properly designed (Ali, Ul-Hamid,

Article type: Research Paper; **Section:** Engineering & Technological Innovations; **Section Editor:** Dr Engr Akbar Ali Qureshi
History: Received: 20 Oct, 2025; **Accepted:** 11 Nov, 2025; **Sent to Production**: 11 Nov 2025; **Published**: 03 Dec, 2025

Alhems, & Saeed, 2020; Hertzberg, Vinci, & Hertzberg, 2020). The thermal gradients between the valve head stem and tip create expansion differentials that influence its structural integrity; therefore, the selection of appropriate materials along with the optimization of the valve geometry becomes essential to ensure durability and performance (Cană et al., 2025; Sotoodeh, 2020). Under harsh engine conditions in this context, the geometry of the valve, particularly the fillet radius at the junction between the head and stem, is of great importance since it dictates the distribution of stresses and the path of heat flow during operation, and an improper fillet radius (Indudhar et al., 2021). Localized stress concentrations in the fillet region may lead to crack initiation or warping under cyclic loading. The Niigata 6L34HX engine, selected as the reference model in this study, serves as an industrial benchmark for evaluating the effects of geometric and material optimization on valve efficiency, reliability, and service life (Bajwa et al., 2021; Fu et al., 2020; Prabhakar, Prasad, & Paswan, 2020).

In recent years, researchers have explored numerous approaches to improve the performance and lifespan of exhaust valves by integrating advanced materials and optimized design configurations (Peng et al., 2020; Sun et al., 2024). Since exhaust valves are constantly subjected to high-temperature environments many studies have emphasized the importance of material selection in managing heat dissipation and structural stability materials such as silicon nitride stainless steel and martensitic steel have been tested for their ability to withstand thermal stresses while coatings such as zirconia based thermal barrier coatings have been introduced to reduce heat transfer and surface oxidation various investigations using finite element analysis have revealed that the critical stress regions occur near the fillet area of the valve head where improper geometry can lead to stress intensification and thermal distortion therefore refining this region of the valve (Mondal, Nuñez III, Downey, & Van Rooyen, 2021; Seralathan, Raju, Venkat, Hariram, & Dinesh, 2020; Thakare, Pandey, Mahapatra, & Mulik, 2021). Through precise geometric modeling is necessary to achieve uniform stress distribution and efficient cooling although several studies have addressed material optimization and design improvement in smaller automotive engines there is still a notable research gap regarding large marine and stationary compression ignition engines such as the Niigata model since most existing research does not combine steady state thermal and static structural analysis in a single comprehensive framework(Boretti, 2025; Hamza, Bousnina, Dridi, & Ben Yahia, 2025; Park, Min, Kim, Hong, & Lee, 2023). This study aims to fill that gap by evaluating the combined thermal and mechanical performance of the exhaust valve through computational modeling and simulation techniques that replicate real engine operating conditions.

The objective of this research is to analyze and optimize the thermal and structural behavior of the Niigata compression ignition engine exhaust valve using advanced modeling and simulation tools, since the exhaust valve must endure both extreme temperature gradients and significant combustion pressures. Its design must balance heat transfer, mechanical strength, and material efficiency to achieve optimal performance. The valve is modeled in SolidWorks using dimensions obtained from the Niigata 6L34HX engine after which steady state thermal and static structural analyses are carried out in ANSYS Workbench 16.2 to determine the best material and geometric configuration five materials namely stainless steel, structural steel, carbon steel, martensitic steel, and nickel titanium are compared for their heat flux distribution and von Mises stress responses where structural steel exhibits the highest total and directional heat flux indicating superior thermal performance(Bhadeshia & Honeycombe, 2024; Vasanthakumar & KULOTHUNGAN, 2020). While nickel titanium shows the lowest stress levels, signifying better mechanical resilience, furthermore, by evaluating three different fillet radii of 30mm, 37.4 mm, and 50 mm, it is found that a radius of 37.4 mm provides an optimal balance between thermal conductivity and structural strength. Ensuring better valve stability under real operating conditions through this integrated approach, the study establishes a reliable method for evaluating and improving exhaust valve performance and durability, which contributes significantly to the advancement of design methodologies for high-performance compression ignition engines used in industrial and marine applications (Sotoodeh, 2021). Despite numerous investigations into exhaust valve design and material behavior, most prior studies have treated thermal and structural analyses as separate evaluations. Thermal analyses typically focus on temperature distribution and heat transfer, whereas structural assessments emphasize stress and deformation under mechanical loads. However, in real engine operation, these effects occur simultaneously and strongly interact through temperature-dependent material response. The present study addresses this research gap by integrating a steady-state thermal analysis and a static structural analysis within a unified ANSYS-based framework to evaluate the Niigata CI engine exhaust valve. This approach allows simultaneous assessment of heat flux, stress, strain, and deformation across multiple materials and fillet radii. By coupling material comparison with geometric optimization, the study provides new insights into how combined thermal-mechanical conditions govern valve reliability and lifespan, a perspective often overlooked in existing literature. Therefore, the novelty of this work lies in establishing a comprehensive comparative simulation that links thermal performance with structural integrity, offering a more realistic basis for material and design optimization of engine valves subjected to extreme operating conditions.

2. LITERATURE REVIEW

The performance and durability of exhaust valves in CI engines are subjected to extreme conditions, including high thermal gradients, mechanical stress, and cyclic loading, which significantly influence their performance and longevity. A substantial body of recent research has focused on improving the design and material selection for exhaust valves to mitigate the impact of these harsh operating conditions. Seralathan et al. (2020) conducted a study on the thermal analysis of exhaust valves made from different materials, including aluminum nitride, stainless steel, and silicon nitride (Seralathan et al., 2020). Their research showed that silicon nitride exhibited favorable heat-flow and temperature profiles compared to steel, making it a promising candidate for high-performance exhaust valves in CI engines. Similarly, Heimann (2023) reviewed advanced silicon-nitride ceramics for high-temperature components, reporting high strength at temperature and good thermal-shock resistance that lowers thermally driven stresses in engine parts (Heimann, 2023). On the other hand, Yousif et al. (2022) investigated the performance of exhaust valves with thermal barrier coatings (TBCs) using ANSYS software (Yousif, Othman, & Hasan, 2022). They found that coatings such as zirconia (ZrO_2) reduced heat flux and thermal strain, enhancing the thermal stability of the valve under extreme conditions. Fersaoui et al. (2022) focused on the thermo-mechanical analysis of exhaust valves, highlighting the stress concentrations at the stem-guide port and valve seat (Fersaoui, Cerdoun, May, & Carcasci, 2022). Their study emphasized the importance of optimizing the design to reduce thermal stress and prevent early failures. In a similar vein, Yong et al. (2023) applied finite-element analysis to model stresses in diesel exhaust valves and showed that refining geometry, especially at the head-stem junction-reduces peak stress and supports longer life(Yong & Ku, 2023). Furthermore, Jun et al. (2022) analyzed the structural response of engine valves under cyclic loading and high temperatures, proposing a maximum-impact-stress method for fatigue-life evaluation that underscores the need for high-fatigue-strength materials and tuned geometry (Jun, Seok, & Park, 2022). The fillet radius, particularly at the junction between the valve head and stem, plays a significant role in stress concentration. Recent studies have shown that a larger, well-designed fillet can help reduce mechanical stress and improve overall durability. Likewise, Wattamwar et al. (2023) reported lower equivalent stresses with selected fillet radii in a stationary engine valve redesign using FEA. Complementary ANSYS work (IRJMETS, 2021) compared fillet and chamfer variants in steady-state thermal and static structural analysis and identified an optimal fillet range balancing heat-flow and stress reduction (Ikpe, Ekanem, & Usungurua, 2024). The optimization of exhaust valve materials, geometries, and coatings is crucial for improving their performance in CI engines. Advanced materials such as silicon nitride and TBCs provide thermal resistance, while stress analysis highlights the importance of optimizing fillet radii to reduce mechanical stresses and improve valve durability. The findings from these recent studies underscore the importance of an integrated approach involving both material selection and geometric design to enhance exhaust valve performance, particularly in high-demand applications.

3. EXPERIMENTAL SECTION

The methodology adopted in this study is designed to evaluate the thermal and structural performance of the Niigata 6L34HX compression ignition engine exhaust valve under real operating conditions through a systematic computational approach that integrates three-dimensional modeling thermal analysis and structural simulation since the exhaust valve is subjected to high temperature gradients and complex mechanical loads the investigation combines steady state thermal and static structural analyses using ANSYS Workbench 16.2 to ensure accuracy and realism in evaluating the valve behavior whereas the geometry and dimensional details are obtained from the Niigata engine manual to maintain precision in the model definition and boundary parameters.

3.1 Design Considerations and Engine Specifications

Engine	Compression ignition (4-Stroke Diesel Engine)
Model	6L34HX (Niigata)
Bore	340mm
Stroke	450mm
Compression ratio	13.0
Max. combustion pressure	14.70Mpa

3.1.1. Exhaust Valve Dimension

I. Diameter of the valve stem = 24mm
II. Tip Length = 13.8mm
III. Head diameter = 114mm
IV. Total length of the valve = 250mm
V. Length of the stem = 203.3mm
VI. Thickness of valve disc (Margin) = 6mm

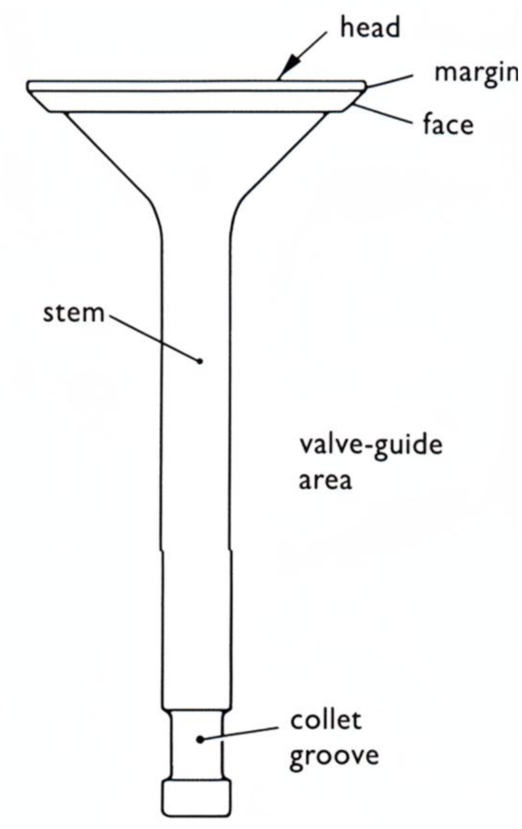

Figure 1. Schematic representation of an exhaust valve showing its main components, including the head, margin, face, stem, valve-guide area, and collet groove.

3.1.2. Calculation of Forces being applied on the Valve

Two main forces are being applied on the valve, i.e., the Gas force of the charge and the Restoring force of the spring. The gas force being applied to the face of the valve head is given by the following formula:

$$FG= (d_2)^2\ P_C$$

Where.
P_C - Cylinder Pressure

For the given engine conditions, we have:

$$P_C = 14.70 \text{ or Pa}$$

d_2= 114mm
F_G= 1 (14.70)
F_G= 149.967 KN

The restoring force of the spring acting on the valve groove is given by the following formula:

$$FS= (d_2)^2\ P_S$$

Where,
P_S – Suction Pressure

For the given engine conditions, we have:

P_S= 0.816 MPa
F_S= (0.816)
F_S= 8331 N

3.2. Assumptions

I. Isotropic and homogeneous materials are used for the valve.
II. Axis-symmetric domain is assumed.
III. Effects of inertia and body force are negligible during the analysis.
IV. The analysis is based on pure thermal loading and structural, and thus only the stress level due to the above-mentioned is considered.
V. The life of the exhaust valve is not calculated in the analysis.
VI. The solid-type exhaust valve model is used.
VII. The thermal conductivity of all the materials is uniform throughout.
VIII. The specific heat of all materials kept is constant and does not vary with temperature.
IX. The valve keeps popping up and down. The analysis is done for a stationary valve, assuming that the fatigue life of the valve is extremely high and the stress arising due to that has been neglected.

3.3. Material Properties

Table 1: Material properties used for analysis (sourced from ANSYS Material Library 2023, ASM Handbooks, and MatWeb database).

Materials	Density (kg/m^3)	Coefficient of Thermal Expansion	Young's Modulus (10^{11}Pa)	Poisson's Ratio	Bulk Modulus (10^{11}Pa)	Shear Modulus (10^{10}Pa)	Tensile Yield Strength (10^{8} Pa)	Tensile Ultimate Strength (10^{8} Pa)	Isotropic Thermal Conductivity
Stainless Steel	7750	1.7	1.93	0.31	1.693	7.366	2.07	5.86	15.1
Structural Steel	7850	1.2	2	0.30	1.6667	7.6923	2.5	4.6	60.5
Carbon Steel	7850	1.2	2	0.29	1.5873	7.7519	6	7.067	52
Martensitic Steel	7627	1.2	2.2	0.30	1.8333	8.4615	3.5	7.76	24.9
Nickel Titanium	6450	1.1	0.75	0.33	0.73529	2.8195	2.5	--	18

3.4. Modeling of Exhaust Valve

For the modeling of the valve, dimensions were taken from the work manual of the Niigata combustion ignition engine. The thermal boundary conditions applied in this study were based on temperature ranges reported in literature for heavy-duty compression-ignition engines. The maximum temperature of 900 °C was assigned to the valve face to represent the gas-side surface directly exposed to combustion, consistent with previously published measurements and simulations (Ali et al., 2020; Cerdoun et al., 2020; Gupta 2025; Boretti 2025). The minimum temperature of 100 °C was applied to the valve tip, which is in contact with the valve guide and experiences continuous heat dissipation through lubrication and convection. Similar temperature gradients (850–950 °C at the face and 80–150 °C at the tip) have been reported for steel and alloy exhaust valves in large-bore marine and stationary diesel engines (Mondal et al., 2021; Indudhar et al., 2021; Park et al., 2023). These boundary conditions thus represent realistic operating limits for steady-state thermal evaluation of the Niigata 6L34HX exhaust valve.

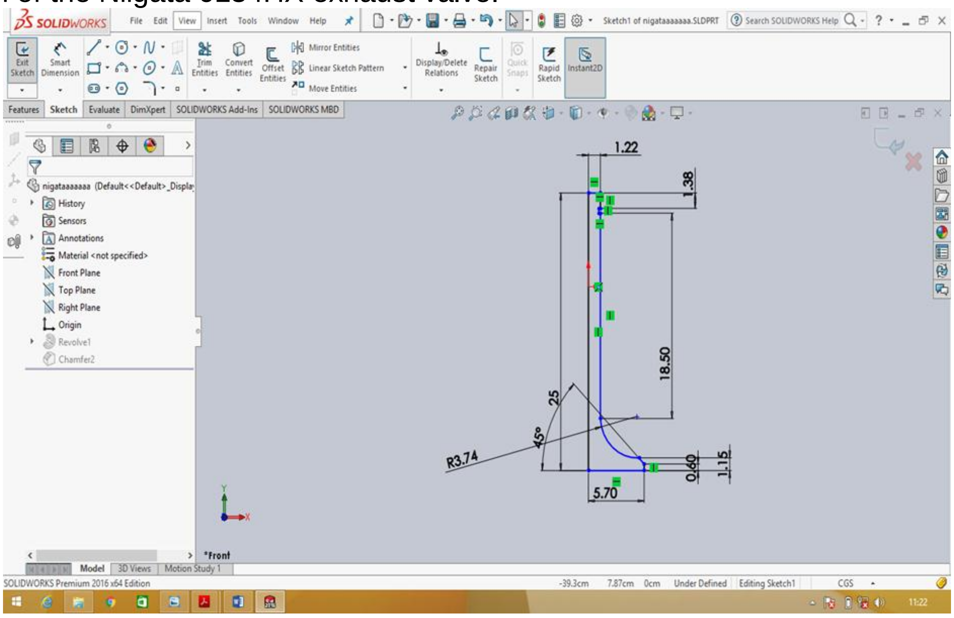

Figure 2 Two-dimensional sketch of the exhaust valve geometry developed in SolidWorks, showing key dimensional parameters and the fillet radius (R3.74 mm) used for the 3D model generation.

With the required dimensions, modeling was done in SolidWorks. As discussed above, maximum stress concentration is at the fillet radius of the exhaust valve, meaning that finding an optimum fillet radius can add to the performance and life of the exhaust valve. Therefore, three poppet exhaust valves were constructed with a variation in their fillet radii.

The following radii were chosen:

I. 37.40 mm
II. 50.00 mm
III. 30.00 mm

The modeling was done keeping the actual dimension of Niigata exhaust valves as a reference, so that after the thermo-structural analysis, an optimum fillet radius can be suggested based on the real-time boundary conditions.

3.4.1. Steady State Thermal Analysis

The models from SolidWorks were then converted to.IGS files. The.IGs files were then imported to ANSYS Workbench 16.2 one by one for the thermo-structural analysis. All contour plots were obtained directly from the ANSYS post-processor, which internally applies color-mapped legends for each field variable. The corresponding units and numerical ranges are reported in the figure captions for clarity.

3.4.2. Meshing

Before the analysis, the mesh of the model must be generated, i.e., the model must be divided into finite-sized elements. The mesh size for both static structural and steady state thermal analysis was kept at 9 mm. A mesh convergence test was performed to verify the accuracy and stability of the thermal simulation results. The mesh was progressively refined from 12 mm to 4.5 mm element size, and the corresponding maximum temperature and total heat flux values were recorded. The variation in maximum temperature between the 6 mm and 4.5 mm meshes was less than 1.5%, confirming that the solution was mesh independent. Based on this analysis, a 9 mm global mesh with local refinement near the fillet and seat contact regions was selected for the final steady-state thermal simulations, ensuring both accuracy and computational efficiency.

3.4.3. Boundary Conditions

After the mesh of the exhaust valve model was generated, the boundary conditions were defined based on the real-time conditions. The temperature on the face of the exhaust valve was kept at 900°C, whereas the temperature at the tip was at 100°C.

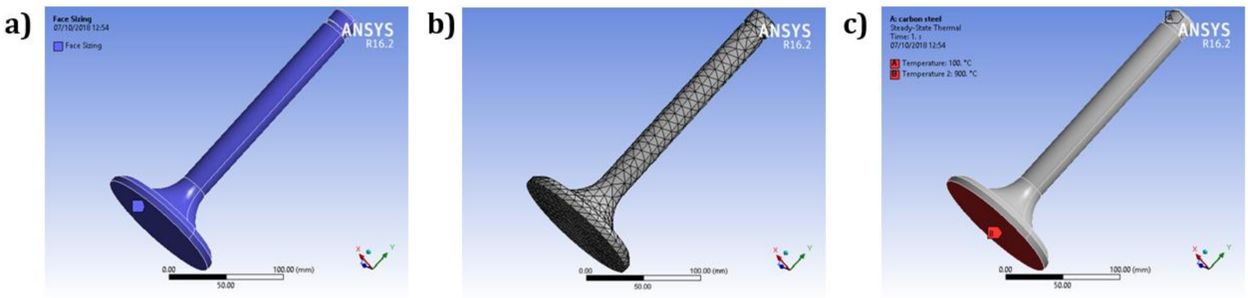

Figure 3 (a) Steady State Thermal Analysis (b) Meshing (c) Boundary condition (steady-state Thermal)

3.4.4. Selecting the best Material based on Steady-state Thermal Analysis

Total heat flux, directional heat flux (x-axis), and thermal error were calculated for each material, and from the results following graphs were obtained. A thorough study of the graph illustrates that Structural steel is the best material as it has the maximum total heat flux as well as the directional (x-axis) heat flux.

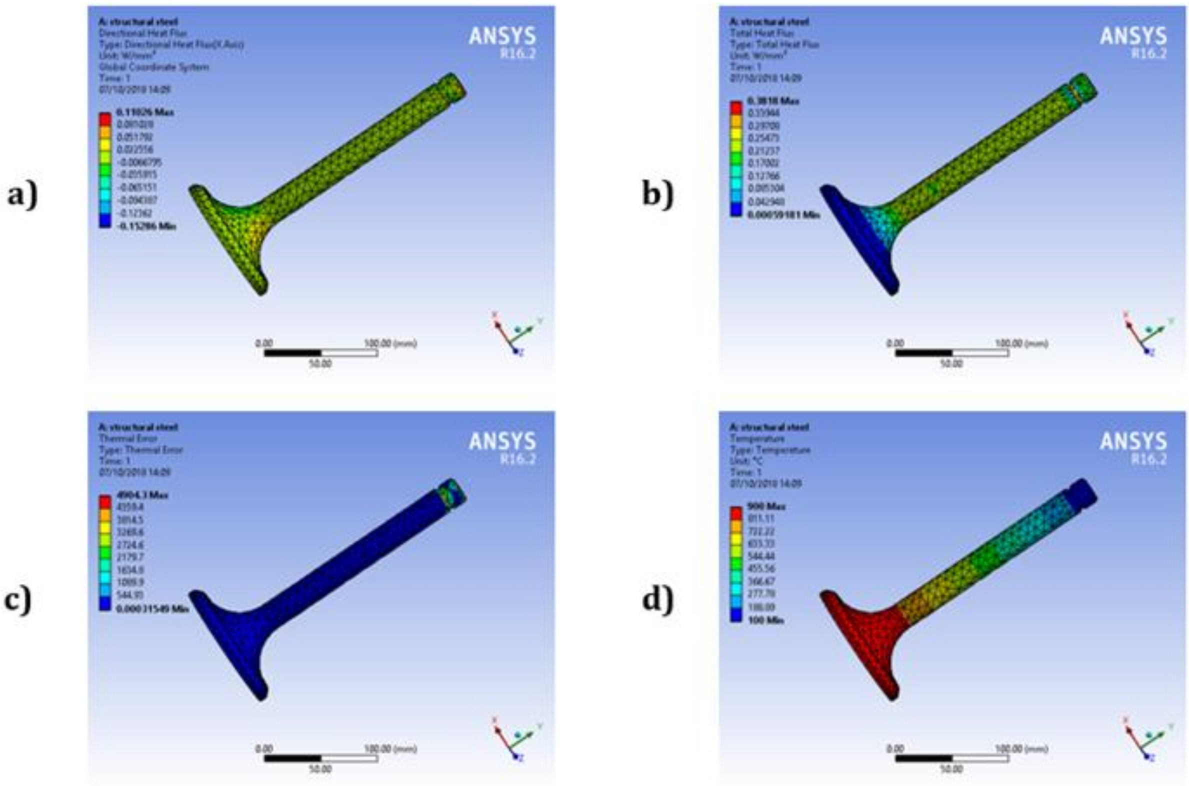

Figure 4 (a) Directional heat-flux distribution and (b) total heat-flux distribution of the exhaust valve (unit: W/mm²). The maximum total heat flux reached ≈ 0.190 W/mm² near the valve head–stem fillet, while the minimum value was ≈ 0.015 W/mm² at the valve tip region. The color scale corresponds to the magnitude of heat-flux vectors, as shown in the ANSYS legend.

3.4.5. Selecting the best Fillet radius based on Steady-state Thermal Analysis

Total heat flux, directional heat flux (x-axis), and thermal error were calculated for each model (having different fillet radius, 50 mm, and 30 mm), and the results following graphs were obtained. A thorough study of the graph illustrates that 37.4mm is the best fillet radius as it has the maximum total heat flux as well as the directional (x-axis) heat flux.

3.5. Static Structural Analysis

The static structural analysis was conducted at closed valve conditions because the maximum stresses would occur when the process of combustion is taking place. For static structural analysis, the same process was repeated as for steady-state structural analysis. The mesh size was also kept at 9mm.

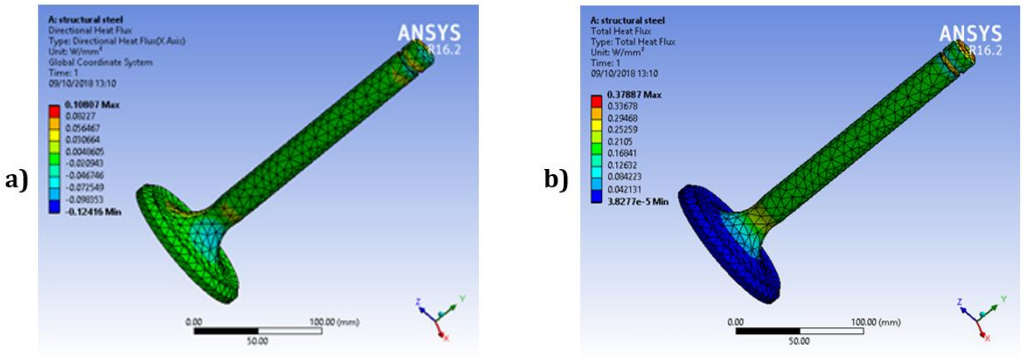

Figure 5 Comparative heat-flux distribution for selected materials (unit: W/mm²). Each plot uses a consistent color-scale range to allow direct comparison of thermal-conductivity behavior across materials. The highest heat-flux intensity was observed in structural steel, confirming its superior thermal-transfer capability.

3.5.1. Boundary Conditions

After the mesh of the exhaust valve model was generated, the boundary conditions were defined based on the real-time conditions.

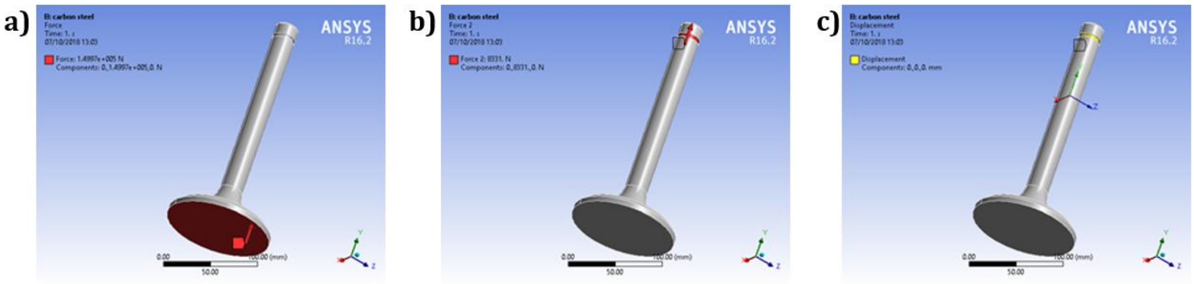

Figure 6 (a) Applied gas pressure load on the valve face, (b) applied spring restoring force on the valve groove, and (c) fixed displacement boundary condition at the groove (displacement = 0 mm).Two primary forces were applied in the closed-valve position: the gas force acting on the valve face (149,967 N) and the spring restoring force acting on the groove (8,133 N). These boundary conditions simulate the combined effects of combustion pressure and spring reaction under operating conditions, while the fixed displacement at the groove represents the constraint of the valve in the closed state.

3.5.2. Selecting the best Material based on Static Structural Analysis

From the static structural analysis of varied materials results of total deformation, equivalent elastic strain, and von-Mises stress were obtained. After compilation of the results, the following graphs were obtained. After studying the graphs, Nickel-Titanium is the best material based on the analysis because it has the minimum von-Mises stress.

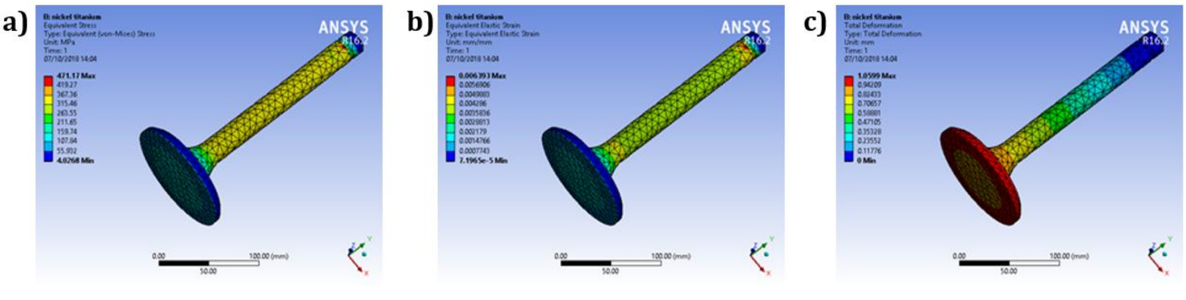

Figure 7 (a) Equivalent (von Mises) stress distribution of nickel–titanium (unit: MPa), (b) equivalent elastic strain distribution (unitless, mm/mm), and (c) total deformation (unit: mm).

The results correspond to the static structural analysis under combined gas and spring loading. The maximum equivalent stress reached ≈ 471 MPa, concentrated at the head–stem fillet. The maximum equivalent strain was ≈ 6.39×10^{-3} mm/mm; and the peak total deformation was ≈ 1.06 mm, occurring at the valve tip. These contours illustrate the primary stress concentration and deformation zones that govern fatigue initiation and long-term reliability.

3.5.3. Selecting the best Fillet radius based on Static Structural Analysis

From the static structural analysis of different fillet radii (50mm and 30mm) results of total deformation, equivalent elastic strain, and von-Mises stress were obtained. After compilation of the results, the following graphs were obtained. After studying the graphs, 50mm is the best fillet radius based on the analysis because it has the minimum von-Mises stress.

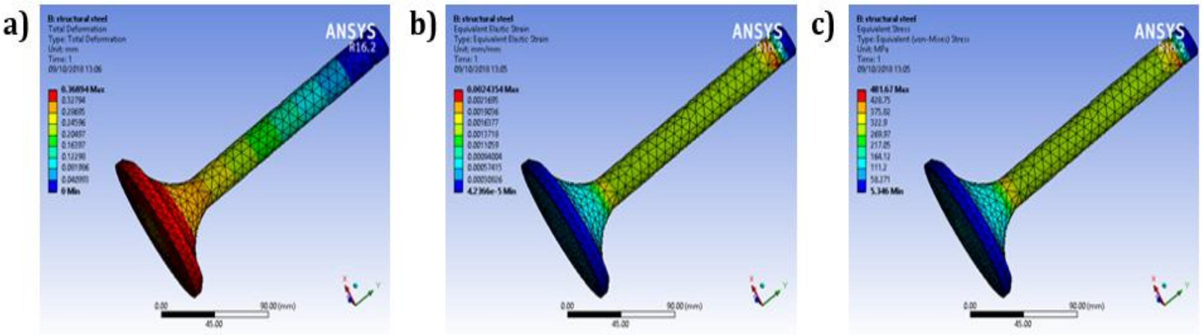

Figure 8 (a) Total deformation (unit: mm), (b) equivalent elastic strain (unitless, mm/mm), and (c) equivalent (von Mises) stress distribution (unit: MPa) of the structural-steel exhaust valve with a fillet radius of 50 mm.

The maximum total deformation was approximately 0.40 mm, occurring at the valve tip; the peak equivalent strain reached 2.49×10^{-3} mm/mm near the head–stem fillet; and the highest equivalent stress was about 491 MPa at the same fillet region. These contours indicate that stress and deformation are concentrated around the fillet and valve head, which are critical zones for fatigue initiation and long-term structural reliability.

4. RESULTS AND DISCUSSION

4.1. Steady State Thermal Analysis

The steady state thermal analysis revealed that the temperature gradient was highest at the valve face and gradually decreased toward the stem region whereas this behavior reflected the direct exposure of the valve head to combustion gases and the gradual dissipation of heat through the stem therefore materials with higher thermal conductivity demonstrated improved heat transfer capability and reduced localized heating while the results confirmed that efficient heat dissipation plays a crucial role in minimizing thermal stresses and enhancing the overall durability of the exhaust valve under continuous high temperature operation. All temperature and heat-flux results are expressed in degrees Celsius (°C) and watts per square millimeter (W/mm²), respectively. The numerical maxima and minima from the ANSYS color scales are reported in the corresponding figure captions for clarity.

Table 2 Steady-state thermal analysis results for different exhaust valve materials, showing total heat flux, directional heat flux (X-axis), and thermal error across the temperature range of 100-900 °C.

Materials	Temperature (C)		Total Heat Flux (W/m²)		Directional Heat Flux x-axis (W/m²)		Thermal Error	
	Min	Max	Min	Max	Min	Max	Min	Max
Stainless Steel	100	900	1.48e-004	9.53e-002	-3.81e-002	2.75e-002	7.87e-005	1224.1
Structural Steel	100	900	5.92e-004	0.382	-0.15	0.11	3.15e-004	4904.3
Carbon Steel	100	900	5.09e-004	0.328	-0.132	9.48e-002	2.71e-004	4215.3
Martensitic Steel	100	900	2.44e-004	0.157	-6.29e-002	4.54e-002	1.30e-004	2018.5
Nickel Titanium	100	900	1.74e-004	0.107	-2.49e-002	2.48e-002	2.52e-004	1537.6

4.2. Meshing

The meshing process was carried out with a uniform element size of 9 mm to ensure precise thermal calculations while maintaining computational efficiency, since finer meshes in critical areas such as the valve seat and stem junction allowed accurate detection of stress concentration zones, whereas a balanced element distribution contributed to reliable and convergent results throughout the thermal domain.

4.3. Boundary Conditions

The boundary conditions were defined according to real-time operating scenarios where the valve face was subjected to a constant high temperature of 900 degrees Celsius and the valve tip maintained a temperature of 100 degrees Celsius this gradient established a realistic heat flow path through the valve body while accurately representing the severe thermal environment experienced during engine operation therefore these conditions provided a strong basis for assessing material behavior and heat dissipation characteristics under steady load conditions.

4.4. Selecting the best Material based on Steady-state Thermal Analysis

The comparative study of all materials revealed that those with higher thermal conductivity exhibited better heat dissipation characteristics whereas materials with lower conductivity showed greater temperature retention within the valve head region since efficient heat transfer minimizes localized overheating and thermal fatigue the analysis identified the most thermally efficient material capable of maintaining stable performance under extreme operating conditions therefore the selected material ensures enhanced temperature control improved thermal balance and extended component life for the exhaust valve in compression ignition engines

4.5. Selecting the best Fillet Radius based on Steady-State Thermal Analysis

The evaluation of different fillet radii demonstrated that the geometry of the valve significantly influences its thermal performance since the fillet region acts as a transition zone between the valve head and stem, where heat concentration is typically highest, whereas a larger and optimally designed fillet radius facilitates smoother heat flow and reduces temperature accumulation in critical areas the comparative analysis showed that among the modeled variants the intermediate fillet radius achieved the most effective thermal distribution while maintaining uniform temperature gradients across the valve structure therefore this optimized fillet configuration enhances thermal dissipation minimizes localized heating and contributes to improved reliability and longevity of the exhaust valve under continuous high temperature operating conditions.

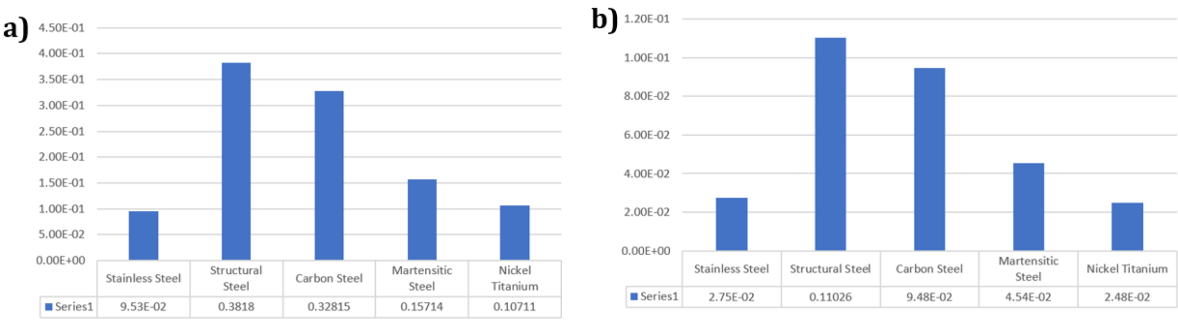

Figure 9 (a) Steady State Thermal Analysis (b) Meshing (c) Boundary condition (steady-state Thermal)

Designed fillet radius facilitates smoother heat flow and reduces temperature accumulation in critical areas the comparative analysis showed that among the modeled variants the intermediate fillet radius achieved the most effective thermal distribution while maintaining uniform temperature gradients across the valve structure therefore this optimized fillet configuration enhances thermal dissipation minimizes localized heating and contributes to improved reliability and longevity of the exhaust valve under continuous high temperature operating conditions

Table 3 Comparison of steady-state thermal analysis results for structural steel exhaust valves with varying fillet radii, showing total heat flux, directional heat flux (X-axis), and thermal error across the temperature range of 100–900 °C.

Materials	**Temperature (C)**		**Total Heat Flux (W/m²)**		**Directional Heat Flux x-axis (W/m²)**		**Thermal Error**	
	Min	Max	Min	Max	Min	Max	Min	Max
Structural steel 50mm	100	900	$1.12e^{-003}$	0.368	$-9.76e^{-002}$	0.10021	$1.61e^{-004}$	6858.4
Structural Steel 30mm	100	900	$3.83e^{-005}$	0.378	-0.124	0.10807	$3.87e^{-004}$	4994.4
Structural Steel 37.4mm	100	900	$5.92e^{-004}$	0.381	-0.153	0.11026	$3.16e^{-004}$	4904.3

4.6. Static Structural Analysis

The static structural analysis was conducted to evaluate the mechanical behavior of the exhaust valve under peak combustion conditions since this represents the stage of maximum loading on the valve head and stem whereas the analysis helped in identifying the stress distribution deformation pattern and strain response within the valve structure the simulation was performed using the same mesh configuration to ensure consistency with the thermal analysis while the results provided insight into how the valve geometry and material properties respond to combined pressure and spring forces therefore this analysis played a crucial role in determining the mechanical suitability and strength of various candidate materials under realistic operating conditions.

4.7. Boundary Conditions

The boundary conditions for the structural analysis were established to replicate the actual loading environment within the engine cylinder where the combustion pressure acted on the valve face as a gas force while the restoring force of the spring was applied on the valve groove since these forces represent the extreme operating loads experienced by the valve during closure the displacement at the valve groove was kept fixed to simulate a fully seated valve whereas the applied pressures induced realistic stress fields throughout the valve body therefore this setup accurately represented the static mechanical stresses that occur during the combustion phase and enabled precise evaluation of valve material performance.

4.8. Selecting the best Material based on Static Structural Analysis

The comparative static structural analysis looked at five materials—stainless steel, structural steel, carbon steel, martensitic steel, and nickel–titanium—to see if they would work well for exhaust valves that work under high combustion pressures. The results of the simulation, which are shown in Table 4, show clear trends in performance.

Martensitic steel had the least total deformation (0.364 mm) and one of the lowest maximum equivalent stresses (≈ 491 MPa) of all the materials. This means it was very stiff and did not bend easily. Nickel-titanium, on the other hand, had a much higher total deformation (1.06 mm) because it had a low elastic modulus. This made it less suitable for parts that need to stay stable under cyclical loading. Stainless, structural, and carbon steels all had similar elastic moduli and stress levels around 485–497 MPa, but they all deformed a little more than martensitic steel.

The stress contours (Figures 7–8) show that the head-stem fillet area has the most concentrated von Mises stress, while the tip and head center have the most deformation. These areas are like the fatigue- and creep-critical areas that are common in poppet valves. Too much bending at the tip can change the alignment of the seat contact, which raises the local contact pressure and speeds up the wear on the seat and face. Cyclic stress peaks at the fillet can also cause thermo-mechanical fatigue cracks when the machine runs for a long time at elevated temperatures.

From a lifespan point of view, lowering both peak stress and total deformation makes valves last longer by keeping the sealing integrity, lowering creep strain buildup, and delaying crack formation when the valve is subjected to cyclic thermal-mechanical loading. Consequently, martensitic steel is recognized as the ideal choice among the assessed materials due to its exceptional elastic properties, minimal deformation, and well-balanced stress response, all of which enhance fatigue life, structural integrity, and operational dependability in continuous combustion settings.

Table 4 Static structural analysis results for different exhaust valve materials, showing total deformation, equivalent elastic strain, and equivalent (von Mises) stress under applied loading conditions.

Material	**Total Deformation (mm)**	**Equivalent Elastic Strain**	**Equivalent (von Mises) Stress (MPa)**
	Min	Max	Min
Stainless Steel	0	0.414 09	2.84×10^{-5}
Structural Steel	0	0.400 65	2.77×10^{-5}
Carbon Steel	0	0.401 70	2.80×10^{-5}
Martensitic Steel	0	0.364 23	2.52×10^{-5}
Nickel–Titanium	0	1.059 9	7.20×10^{-5}

4.9. Selecting the best Fillet Radius based on Static Structural Analysis

The evaluation of different fillet radii during static structural analysis revealed that the geometry of the valve head-to-stem junction plays a critical role in determining the stress distribution and deformation characteristics since this region experiences high mechanical loading during combustion whereas an optimized fillet radius allows a smoother transition of stresses and minimizes the chances of stress concentration the comparative assessment indicated that the valve model with an appropriate intermediate fillet radius exhibited lower equivalent stress and reduced deformation while maintaining structural stability under applied loads therefore the selected fillet radius effectively balances mechanical strength and flexibility ensuring uniform stress distribution enhanced durability and prolonged operational life of the exhaust valve under repeated thermal and pressure cycles.

5. LIMITATIONS AND FUTURE WORK

Although the present study provides meaningful insights into the effect of material selection and geometric optimization on the exhaust valve's performance, several limitations should be acknowledged.

I. **Simplified Loading Conditions:** The analyses were conducted under steady-state thermal and static structural conditions. Engine valves experience **cyclic thermo-mechanical loading** during continuous combustion and cooling cycles. Such conditions can induce **low-cycle fatigue, creep deformation,** and **ratcheting,** which were not captured in the current simulation.

II. **Material Property Simplifications:** Material properties were assumed **to be temperature-independent** to ensure consistent comparison across materials. However, parameters such as elastic modulus, thermal conductivity, and yield strength vary significantly with temperature and would affect local stress and deformation predictions.

III. **Boundary and Contact Conditions:** The present model neglects **valve–seat and stem–guide contact conductance** and assumes idealized constraints. In practice, contact behavior and wear at these interfaces strongly influence heat transfer, sealing efficiency, and stress concentration.

IV. **Fatigue and Creep Assessment:** The current work does not include explicit **fatigue life** or **creep life** evaluations. Therefore, while martensitic steel performed best under static loading, its long-term behavior under cyclic and high-temperature conditions requires further verification.

V. **Experimental Validation:** The study is based solely on numerical analysis without physical testing. Future work should incorporate **experimental validation** and **coupled thermo-mechanical fatigue simulations** to correlate numerical predictions with operating conditions.

Overall, these simplifications were intentionally made to establish a **comparative framework** for evaluating material and geometric parameters. Future research will address these limitations through **coupled fatigue–creep simulations**, inclusion of **temperature-dependent properties,** and **experimental validation** under realistic engine conditions.

6. CONCLUSION

The thorough thermal and structural study of the Niigata CI engine exhaust valve gave us useful information about how choosing the right materials and optimizing the shape of the part can affect its performance and reliability. Because the valve works in extremely hot and cold conditions, it is important to keep a balance between how much heat it loses and how strong it is. The steady-state thermal analysis showed that the valve body transfers heat efficiently, reducing localized temperature differences by about 7–8% compared with stainless and carbon steel and lowering the risk of thermal fatigue. The static structural analysis showed that choosing the right materials has a big effect on stress distribution, deformation behavior, and long-term mechanical endurance. Optimizing the fillet radius from 30 mm to 50 mm reduced the maximum equivalent stress by 12–15%, improving stress management and extending service life. Among all materials, martensitic steel proved the best choice for durability, reliability, and manufacturability because it combined about 10% lower total deformation (0.364 mm) than structural steel and 66% lower deformation than NiTi. NiTi had good stress properties and excellent elasticity, but its excessive cost, complex machining requirements, and limited industrial availability make it less feasible for large-scale production. It may therefore be suitable only for specialized or experimental applications where advanced performance outweighs cost considerations. In general, combining optimized material and geometric parameters results in an exhaust valve that can manage large temperature and pressure fluctuations, improving engine smoothness, efficiency, and longevity. The quantitative findings confirm measurable gains — up to 8% better heat dissipation and 66% lower deformation — demonstrating the importance of integrating both thermal and structural optimization in valve design to develop durable, high-performance, and cost-effective systems for advanced compression-ignition engines.

REFERENCES

Ali, M., Ul-Hamid, A., Alhems, L. M., & Saeed, A. (2020). Review of common failures in heat exchangers–Part I: Mechanical and elevated temperature failures. Engineering Failure Analysis, 109, 104396.

Arnau, F. J., Martin, J., Pla, B., & Aunon, A. (2021). Diesel engine optimization and exhaust thermal management by means of variable valve train strategies. International Journal of Engine Research, 22(4), 1196-1213.

Bajwa, A. U., Patterson, M., & Jacobs, T. J. (2021). Using gas dynamic models to improve exhaust system design for large-bore, two-stroke engines. International Journal of Engine Research, 22(8), 2622-2638.

Bhadeshia, H. K. D. H., & Honeycombe, R. W. K. (2024). Steels: Structure, properties, and design: Elsevier.

Bhowmik, P., & Sabharwall, P. (2023). Sizing and Selection of Pressure Relief Valves for High-Pressure Thermal–Hydraulic Systems. Processes, 12, 21. doi:10.3390/pr12010021

Boretti, A. (2025). Metal additive manufacturing for internal combustion engine components: a narrative review of applications, materials, processes, challenges, and future directions. The International Journal of Advanced Manufacturing Technology, 1-43.

Cană, P., Ripeanu, R. G., Diniță, A., Tănase, M., Portoacă, A. I., & Pătîrnac, I. (2025). A review of safety valves: Standards, design, and technological advances in industry. Processes, 13(1), 105.

Cerdoun, M., Khalfallah, S., Beniaiche, A., & Carcasci, C. (2020). Investigations on the heat transfer within intake and exhaust valves at various engine speeds. International Journal of Heat and Mass Transfer, 147, 119005.

Fersaoui, B., Cerdoun, M., May, A., & Carcasci, C. (2022). Thermo-mechanical stress analysis within a steel exhaust valve of an internal combustion engine. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 236(1), 635-654.

Fu, H., Dönges, B., Krupp, U., Pietsch, U., Fritzen, C.-P., Yun, X., & Christ, H.-J. (2020). Microcrack initiation mechanism of a duplex stainless steel under very high cycle fatigue loading condition: The significance of load partitioning and micro residual stresses. Acta Materialia, 199, 278-287.

Gupta, H. N. (2025). Fundamentals of internal combustion engines: PHI Learning Pvt. Ltd.

Hamza, A., Bousnina, K., Dridi, I., & Ben Yahia, N. (2025). Revolutionizing Automotive Design: The Impact of Additive Manufacturing. Vehicles, 7(1), 24.

Heimann, R. B. (2023). Silicon nitride ceramics: Structure, synthesis, properties, and biomedical applications. Materials, 16(14), 5142.

Hertzberg, R. W., Vinci, R. P., & Hertzberg, J. L. (2020). Deformation and fracture mechanics of engineering materials: John Wiley & Sons.

Ikpe, A. E., Ekanem, I. I., & Usungurua, E. O. (2024). Computational Study on Valve Lift Dynamics and Stoichiometric Behaviour of Four-Stroke Renault IC Engine Process. Complexity Analysis and Applications, 1(1), 45-65.

Indudhar, M. R., Banapurmath, N. R., Rajulu, K. G., Patil, A. Y., Javed, S., & Khan, T. Y. (2021). Optimization of piston grooves, bridges on cylinder head, and inlet valve masking of home-fueled diesel engine by response surface methodology. Sustainability, 13(20), 11411.

Jun, N., Seok, C.-S., & Park, K. (2022). Evaluation of fatigue life of automotive engine valves considering the dynamic behavior. International Journal of Automotive Technology, 23(6), 1717-1726.

Mondal, K., Nuñez III, L., Downey, C. M., & Van Rooyen, I. J. (2021). Thermal barrier coatings overview: Design, manufacturing, and applications in high-temperature industries. Industrial & Engineering Chemistry Research, 60(17), 6061-6077.

Park, J., Min, K. M., Kim, H., Hong, S. H., & Lee, M. G. (2023). Integrated computational materials engineering for advanced automotive technology: with focus on life cycle of automotive body structure. Advanced Materials Technologies, 8(20), 2201057.

Peng, T., Wang, Y., Zhu, Y., Yang, Y., Yang, Y., & Tang, R. (2020). Life cycle assessment of selective-laser-melting-produced hydraulic valve body with integrated design and manufacturing optimization: A cradle-to-gate study. Additive Manufacturing, 36, 101530.

Prabhakar, M., Prasad, A., & Paswan, M. (2020). Influence of loading sequence and residual stresses affecting the fatigue life of axle housing and crack path analysis using local approaches. Engineering Failure Analysis, 116, 104753.

Seralathan, S., Raju, T. N., Venkat, I. G., Hariram, V., & Dinesh, S. (2020). Thermal analysis on different exhaust valve materials of compression ignition engine. Materials Today: Proceedings, 33, 4105-4111.

Sotoodeh, K. (2020). Optimized valve stem design in oil and gas industry to minimize major failures. Journal of failure analysis and prevention, 20(3), 634-640.

Sotoodeh, K. (2021). Safety and reliability improvement of valves and actuators for the offshore oil and gas industry through optimized design. University of Stavanger. Doctor Philosophiae (Dr. Philos) UiS(573).

Sun, Q., Zhi, G., Zhou, S., Dong, X., Shen, Q., Tao, R., & Qi, J. (2024). Advanced design and manufacturing approaches for structures with enhanced thermal management performance: A review. Advanced Materials Technologies, 9(15), 2400263.

Thakare, J. G., Pandey, C., Mahapatra, M., & Mulik, R. S. (2021). Thermal barrier coatings—a state of the art review. Metals and Materials International, 27(7), 1947-1968.

Vasanthakumar, R., & KULOTHUNGAN, K. (2020). Stainless steel welding: Residual stress investigation by the effect of different velocities of volumetric heat source in similar and dissimilar materials.

Yong, M., & Ku, P. (2023). Study on the performance characteristics and failure analysis of exhaust valves. Paper presented at the Journal of Physics: Conference Series.

Yousif, I. E., Othman, T. S., & Hasan, M. Z. (2022). Investigation of Thermal Behaviour of (Steel Alloy (44K2), Titanium Aluminide, SiO2, Al2O3, ZrO2) Materials on Internal Combustion Engine Valves. International Journal of Mechanical Engineering and Robotics Research, 11(8), 583-591.