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Mass Optimization of Rocket Nozzles Using Ablative Materials: A Case Study on Indonesian Sounding Rockets

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Abstract

This study presents a comprehensive redesign of the RX450 sounding rocket nozzle aimed at reducing mass while maintaining thermal and structural integrity. The baseline design, characterized by heavy steel casing and monolithic graphite liners, imposes significant limitations on payload capacity and flight performance due to its weight and thermal management challenges. The proposed design replaces the divergent section's steel casing with a combination of ablative silica-phenolic composite liners and aluminum 6061 structural support, achieving a substantial mass reduction from approximately 59 kg to 14.5 kg in this critical region. Thermal simulations demonstrate that the addition of a glass-phenolic insulation layer effectively limits heat transfer to the metallic casing, allowing for thinner structural components without compromising safety. Structural analyses confirm that both steel and aluminum sections maintain high safety factors under operational loads. Comparative evaluations of alternative configurations further highlight the benefits of advanced composite materials and innovative structural concepts, with the lightest model reducing total nozzle mass by around 40% compared to the baseline. While these results are based on literature-derived properties and simplified assumptions, they underscore the potential of integrating ablative composites and lightweight metals to enhance rocket nozzle performance. Future work will focus on detailed thermochemical modeling, experimental validation, and full-scale testing to confirm thermal-structural behavior and erosion rates. Overall, this study supports Indonesia's strategic objective of advancing indigenous rocket technology through accessible, high-performance materials and design innovations.

Keywords: *nozzle, solid rocket, mass optimization, alternative materials, simulation, fabrication technology.*

1. Introduction

Since 1964, Indonesia has pursued strategic advancements in rocket technology, highlighted by the development of the RX-series sounding rockets. These vehicles, ranging from the RX1220 (122 mm caliber) to the RX450 (450 mm caliber), serve as critical platforms for technological experimentation and foundational propulsion studies (Sutrisno, 2006). Globally, comparable-class sounding rockets, such as Japan's SS-520 (520 mm caliber) and NASA's Black Brant IX (440 mm), demonstrate the viability of sub-500 mm platforms for high-altitude scientific missions (Burth et al., 2023)(Inatani, 2018). Similarly, India's RH-560 Mk-II (560 mm) and RH-300 Mk-II (300 mm) rockets have been utilized for upper atmospheric studies, reaching altitudes up to 548 km and 116 km respectively (Marar and Shyla, 1982). Additionally, the European Space Agency's TEXUS program employs sounding rockets with a diameter of 438 mm, capable of carrying payloads of approximately 260 kg to altitudes around 260 km (Bille, 2010). Sounding rocket missions depend on the optimal performance of all subsystems. Minimizing structural mass is essential for enhancing flight performance. One of the critical components, the nozzle, is subjected to high operational loads, and any design misinterpretation may result in unnecessarily heavy or redundant structures. Therefore, advancing nozzle technology is imperative. However, Indonesia's progress in nozzle technology lags behind these benchmarks, particularly in adopting mass-efficient ablative materials (Setiadi, 2013). While international peers employ phenolic-based composite nozzles with silica or carbon reinforcements (Sutton and Biblarz, 2001), Indonesian designs remain reliant on graphite as the monolithic throat insert, while thick steel serves as the structural casing of the nozzle, incurring significant mass constraints that limit flight performance, including maximum range (Dito Saputra and Andria, 2021).

Ablative phenolic composites reinforced with fibers such as glass, carbon, or silica are widely used in sounding rocket nozzles to achieve effective thermal protection while reducing mass (Silva, Pardini, and Bittencourt, 2016). These materials protect the nozzle by forming a char layer through pyrolysis during combustion, which dissipates heat and preserves structural integrity, a mechanism well suited to the short-duration, high-heat flux environment typical of sounding rocket motors (Sutton and Biblarz, 2001). Agencies like JAXA and NASA commonly employ silica-phenolic and carbon-phenolic composites in their solid rocket motor nozzles, benefiting from their lightweight and reliable ablative performance. The fabrication of these composites typically involves autoclave or hydroclave curing processes, which ensure uniform resin impregnation and fiber consolidation is critical for consistent thermal protection. Compared to more complex and costly manufacturing methods, such as chemical vapor infiltration (CVI) used for carbon-carbon composites, phenolic composites cured via autoclave represent a more accessible and scalable solution for sounding rocket nozzle applications (Arabab, 2015)(Sanoj and Kandasubramanian, 2014).

Indonesia's current nozzle architecture, using alloy steel housings and isotropic graphite throats (Yuda, 2016), is 4–5 times heavier than international phenolic-based counterparts for the similar caliber. This heavier design is attributed to monolithic graphite's properties, necessitating thicker throat sections and steel's high density (Sutton and Biblarz, 2001). Transitioning to ablative composites would align with global trends while leveraging Indonesia's existing capabilities in polymer composites processing. Although the domestic industry does not yet manufacture its own fiberglass or carbon fiber, these materials are readily available through imports for use in maritime and automotive applications, suggesting feasible adaptation to rocket-grade phenolic resin systems. However, challenges persist in fabrication technology and optimizing cure cycles for defect-free nozzle liners and ensuring interfacial adhesion between ablative layers and metallic housings under cyclic thermal loading (Grippi, 1967)(Mehdikhani et al., 2019) .

The urgency of advancing nozzle technology in Indonesia is underscored by the need to enhance the performance of its sounding rocket program, which faces limitations in payload capacity and flight stability due to outdated nozzle designs. This study conducts a thermal-structural analysis to assess and optimize the current nozzle design by incorporating phenolic-based ablative composite materials. By simulating the combined thermal and mechanical behavior under operational conditions, the analysis aims to reduce nozzle mass significantly without compromising structural integrity or thermal protection. This design improvement addresses key performance limitations and aligns with trends toward lightweight, high-performance ablative nozzles. Moreover, it supports Indonesia's strategic objectives of enhancing technological self-reliance by utilizing readily available composite materials and manufacturing techniques, contributing to the sustainable growth of its domestic rocket capabilities.

2. Methodology

The methods used in this study combine targeted design modifications with separate thermal and structural finite-element simulations to evaluate and optimize nozzle mass reduction without sacrificing performance. A state-of-the-art ablative composite liner was introduced in two critical regions of the nozzle: as a thin thermal barrier between the graphite liner and steel casing in the convergent–throat section and as a bonded liner on the divergent section. Three-dimensional CAD models of both the baseline and modified nozzle assemblies were created in CAD software, capturing all relevant geometry and material layering.

Thermal analysis was conducted exclusively on the convergent section to characterize how the insulator reduces heat transfer into the steel casing. MSC MARC was used to apply a realistic 12-second burn heat-flux profile, yielding detailed temperature distributions at the steel–insulator and insulator–graphite interfaces. Thermal simulation of the divergent section was not attempted, as modeling ablative composites in that region requires complex, temperature-dependent thermochemical properties and specialized solvers capable of capturing gas-blowing and surface erosion phenomena. The structural analysis then followed, applying internal pressure loads across the full nozzle geometry.

2.1. Nozzle Model and Boundary Conditions

The study adopts the RX450 sounding rocket nozzle as the baseline design platform. The original configuration (Figure 1) employs a thick steel casing (AISI 4340) as the primary structural component. Thermal protection is provided by isomolded graphite liners installed in the convergent section, throat, and the short forward segment of the divergent section. This design leverages graphite's high melting point (~3,600°C) to withstand combustion temperatures. However, graphite's high thermal conductivity (~120 W/m·K) accelerates heat transfer to the steel casing, necessitating excessive thickness in both materials to mitigate structural deformation and ablation. In the baseline design, the steel casing thickness reaches up to 17 mm, while the graphite liner measures up to 80 mm in the throat region to effectively manage thermal gradients.

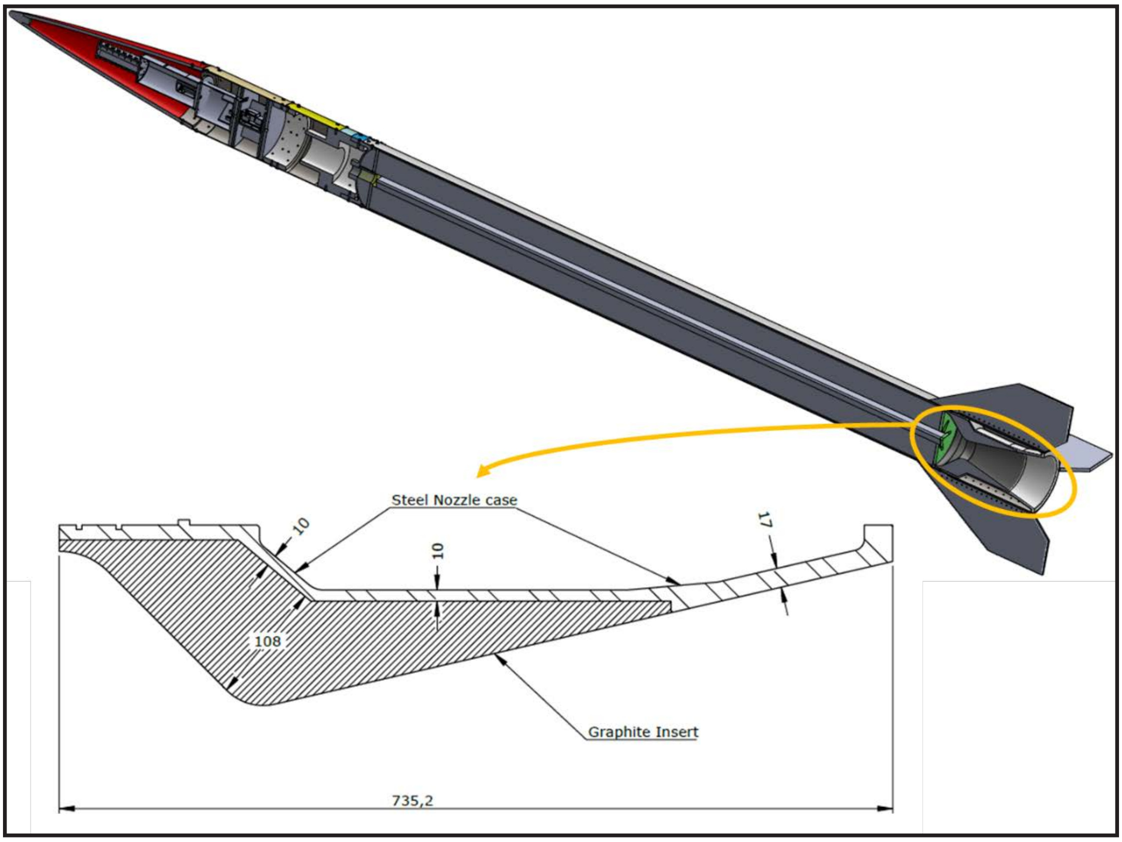

Figure 1: Baseline RX450 nozzle with steel casing and monolithic graphite thermal protection.

An alternative design approach introduces the use of ablative liners in the convergent area, with graphite components overwrapped by a similar ablative material. In this configuration, the nozzle casing is reimagined as a two-piece assembly: the section extending up to the throat remains steel, while the divergent section transitions to aluminum 6061, chosen for its favorable strength-to-weight ratio. The incorporation of ablative liners serves to insulate the structural components from extreme thermal loads, thereby allowing for a reduction in the thickness of both the graphite and steel elements. This not only decreases the overall weight but also ensures that the thermal exposure of the aluminum 6061 divergent section remains within safe operational limits, as this alloy's mechanical properties can degrade at temperatures exceeding 120 °C. This revised design is illustrated in Figure 2.

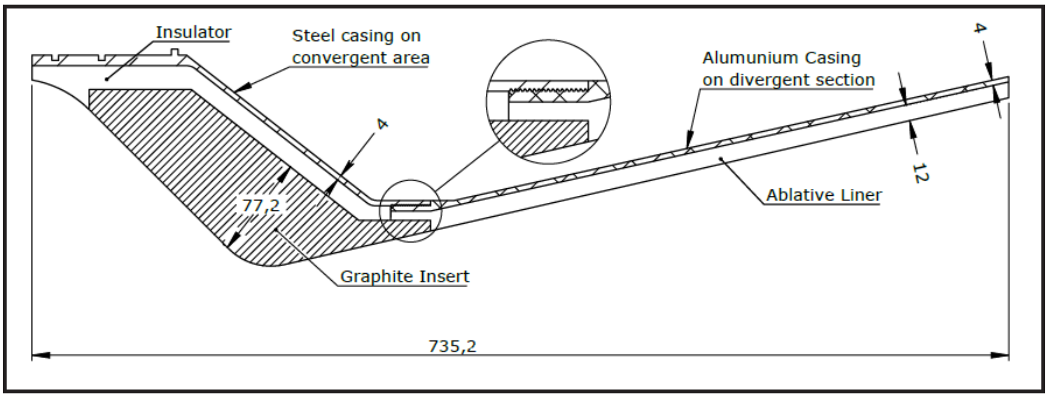

Figure 2: Proposed nozzle design with segmented casing, ablative liners, and optimized material distribution.

2.2. Material Properties and Boundary Conditions

The baseline RX450 sounding rocket nozzle employs AISI 4340 steel and graphite as its primary structural and thermal protection materials. AISI 4340 steel is used for the nozzle casing due to its high mechanical strength and toughness, making it a standard choice in aerospace, military, and nuclear applications. Graphite serves as the nozzle insert material because of its low density and excellent thermal properties, including high thermal conductivity and compressive strength, which make it well-suited for direct exposure to high-temperature combustion gases (Bianchi et al., 2011).

To accurately capture the behavior of AISI 4340 steel under operational conditions, temperature-dependent material properties are incorporated into the analysis. The elastic modulus and yield strength vary with temperature and are modeled using regression-based analytical expressions derived from established codes, as detailed in the NIST report (Seif et al., 2016) :

$$E(T) = E_0\, exp\left(-\frac{1}{2}\left(\frac{T^*}{e_3}\right)^{e_1} - \frac{1}{2}\left(\frac{T^*}{e_4}\right)^{e_2}\right) \quad (1)$$

$$yield(T) = \left(r_5 + (1 - r_5)\, exp\left(-\frac{1}{2}\left(\frac{T^*}{r_3}\right)^{r_1} - \frac{1}{2}\left(\frac{T^*}{r_4}\right)^{r_2}\right)\right)S_y \quad (2)$$

where E0 and Sy represent the elastic modulus and yield strength at ambient temperature (20 °C), and e1 through e4 and r1 through r5 are regression parameters (Seif et al., 2016). The thermal conductivity of AISI 4340 steel decreases from approximately 54 W/mK at room temperature to about 27.3 W/mK above 800 °C, remaining nearly constant up to 1200 °C, which is critical for thermal analysis.

The redesigned nozzle adopts a novel approach by introducing ablative liners in the convergent section, with graphite components overwrapped by similar ablative composite material. This configuration reimagines the nozzle casing as a two-piece assembly: the section extending up to the throat remains constructed from AISI 4340 steel, while the divergent section transitions to aluminum 6061. Aluminum 6061 is chosen for its optimum strength-to-weight ratio, making it suitable for reducing overall nozzle mass. Key properties of aluminum 6061 relevant to the analysis include an elastic modulus of approximately 69 GPa, ultimate tensile strength near 300 MPa, thermal conductivity around 167 W/mK, and a coefficient of thermal expansion (CTE) of about 23.6×10−6 /°C. It is important to note that aluminum's mechanical properties degrade at temperatures exceeding approximately 120 °C; therefore, the ablative liners serve as thermal insulation to maintain the aluminum divergent section within safe operational temperature limits. The room temperature thermo-mechanical properties for AISI 4340, graphite, and aluminum 6061 used in this study are summarized in Table 1. These values are based on standard references commonly used in industry, including ASTM specifications for AISI 4340 steel (Davis, 1998) and have also been reported in previous studies (Abrizal et al., 2024)(Dito Saputra and Andria, 2021).

Table 1: Summary of Nozzle Materials Thermo-Mechanical Properties

Properties	AISI 4340	Al 6061	Isomolded Graphite
Density (kg/m^3)	7850	2690	1810
Elastic modulus (GPa)	210	69	15
Ultimate Tensile strength (MPa)	745	300	34
Coefficient of thermal expansion (μm/m˚C)	12.3	23.6	5.59
Specific heat (J/kg-K)	387	945	707
Thermal conductivity (W/m-K)	44.5	167	80

Thermal protection in the redesigned nozzle is significantly enhanced by the integration of ablative composite materials, specifically glass-phenolic and silica-phenolic composites. These materials combine the insulating and char-forming properties of phenolic resins with reinforcing fibers that improve mechanical strength and thermal stability. Key material characteristics such as density, thermal conductivity, specific heat capacity, and mechanical properties are summarized in Table 2. The use of these composites allows for a substantial reduction in the thickness of traditional graphite and steel components, resulting in overall weight savings while maintaining effective thermal protection.

Designing and sizing ablative materials for nozzle liners is a critical yet challenging task due to limitations in current tools, laboratory apparatus, and software. Accurate characterization of thermal and ablation properties often requires temperature- and sometimes pressure-dependent data, which are difficult to obtain experimentally. Historically, during the early NASA era, most ablative material behaviors were studied through real rocket firings to capture realistic performance. To overcome these challenges, this study relies on carefully selected literature data that closely match the operating conditions of the RX450 rocket. For instance, reports by (Chen, Liu, and Du 2015)(Prescott and Macocha, 1996)(Schaefer and Dahm, 1966)(Shi et al., 2016)(Williams and Curry, 1992) provide relevant data such as a gas static temperature of 2255 °C and a steady-state surface recession rate of 0.22 mm/s for silica-phenolic composites. Table 2 presents a summary of the data collected from these and other referenced studies, forming the foundation for the thermal protection design in this work.

Table 2: Summary of Ablative Material Models and Their Properties

Properties	Glass-phenolic	Silica-phenolic	Ref.
Density (kg/m^3)	1940	1750	(Prescott and Macocha 1996)
Thermal conductivity (W/m-K)	0.27	0.52-0.66	(Prescott and Macocha 1996)
Specific heat (J/kg-K)	921	1005-1256	(Prescott and Macocha 1996)
Thermal expansion (μm/m˚C)	10	7.02	(Prescott and Macocha 1996)
Thermal diffusivity (m^2/s)	1.5×10^{7}	2.06×10^{7}	(Williams and Curry 1992)
Recession rate (mm/s)	-	0.22	(Chen et al. 2015; Williams and Curry 1992)

Based on the gathered data, the designed silica-phenolic on the nozzle divergent section liner thickness of 12 mm provides a substantial safety margin. Considering the erosion rate of approximately 0.22 mm/s and a burn time of 12 seconds, the minimum required thickness would be around 2.64 mm. The chosen 12 mm thickness thus incorporates a significant safety factor to account for uncertainties such as calculation errors, fabrication defects, variations in material properties, and other unforeseen conditions, ensuring reliable and safe operation of the nozzle liner.

For the determination of the operating loads on the nozzle, load data was derived from numerical simulations of the transient flow field using Computational Fluid Dynamics (CFD) analysis. The resulting datasets include distributions of heat flux and static pressure along the nozzle contour. These parameters were then employed as input for the transient coupled thermo-structural simulation. Figure 3 presents the heat flux in the first second of burning time and static pressure profiles along the longitudinal axis of the nozzle.

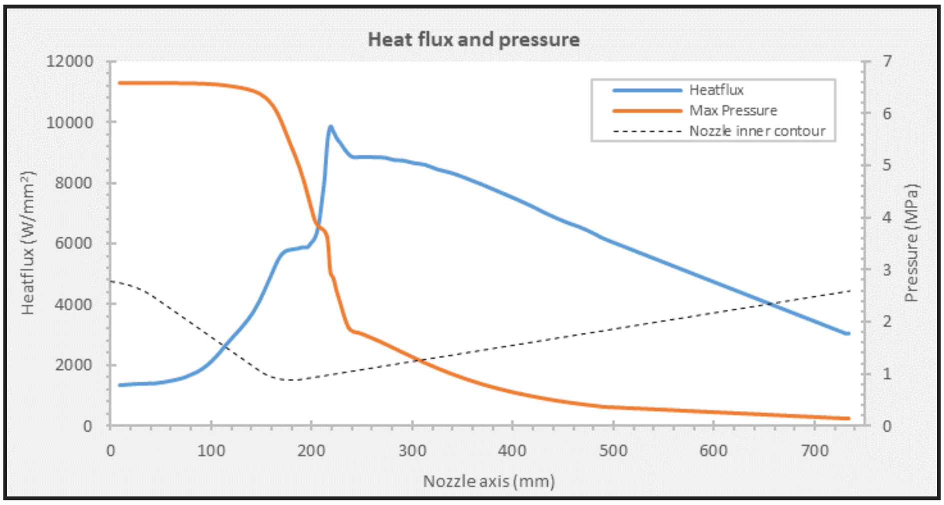

Figure 3: Heat flux and pressure distribution across the nozzle longitudinal axis

3. Discussion and Analysis

Based on the materials, models, and design considerations discussed previously, Figure 2 illustrates the proposed redesign of the nozzle. In this new design, the divergent section of the nozzle is separated from the convergent and throat sections and is later integrated using a threaded joint. In the previous configuration, the divergent section contributed the largest proportion of the nozzle casing mass accounting for approximately 60% of the total casing weight.

To optimize the design, the material used in this section was changed from AISI 4340 steel to a combination of ablative silica-phenolic composite as the liner and 6061 aluminium as the structural support at the divergent of nozzle case section. The ablative composite and case materials are bonded using epoxy adhesive, which is a common practice in the integration of metal structures and composite liners in solid rocket nozzles (Felix and McBride 1971). With this updated configuration, the mass of the divergent section has been reduced significantly from 59 kg down to only around 14,5 kg.

Further modifications were also made to the convergent and throat regions by introducing an additional insulating layer made of ablative glass-phenolic composite. Glass-phenolic was selected based on its low thermal conductivity and cost benefit, as referenced in (Schaefer and Dahm 1966), making it highly suitable for insulation purposes. The addition of this insulator allows for a reduction in both graphite and steel casing thickness, effectively lowering the overall mass of the nozzle casing and thermal protection system.

3.1 Heat Transfer Simulation Analysis

The simulation and thermal analysis results shown in Figure 4 demonstrate that adding a glass/phenolic insulation layer between the graphite liner and steel casing drastically reduces heat transfer to the outer steel surface while preventing a significant temperature rise at the steel–insulator interface. At such reduced thermal exposure, the structural casing is able to maintain its mechanical properties under operational loads, including internal pressure, inertial forces, and vibrational stresses.

However, the addition of thermal insulation also influences the heat distribution within the graphite liner. As indicated in Figure 4, the maximum temperature in the inner graphite surface can reach up to 3000°C. This occurs due to the restricted heat dissipation pathway, as conduction into the surrounding structure is inhibited by the low thermal conductivity of the insulating material. This thermal buildup may lead to surface erosion or ablation of the graphite liner, particularly in regions subjected to high thermal stress.

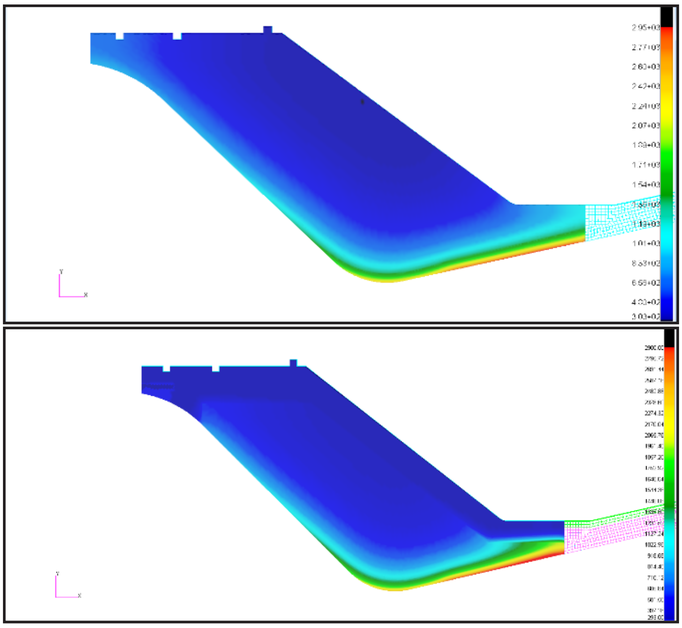

Figure 4: Temperature distribution Across Convergent Section

Notably, Figure 4 reveals that the location of maximum temperature within the graphite does not occur at the throat, but slightly downstream in the divergent section. This is attributed to the thinner graphite geometry in that region, which results in a steeper thermal gradient and faster heat penetration toward the insulator interface. In contrast, the graphite around the throat remains thicker, allowing more internal heat conduction within the graphite itself, thereby mitigating thermal accumulation on the inner surface. This observation aligns with findings by Fulan et al. [00], who reported that excessive graphite ablation near the throat can significantly impact rocket motor performance due to throat geometry changes and altered flow dynamics.

Figure 5 presents the temperature distribution along the insulator bond line at the end of the 12-second burn for both liner thicknesses. In each case, the steel–insulator interface remains essentially constant at around 300 K, indicating negligible heat penetration to the casing. The graphite–insulator interface for the 11 mm liner dips slightly to about 260 K before rising sharply past 250 mm and reaching a peak near 1850 K at the end of the convergent section. With the thinner 6.5 mm liner, the interface temperature stays near ambient for a longer portion of the axis but ultimately climbs to roughly 1300 K under the same conditions. At this condition, AISI 4340 steel remains well within its normal operating range, so its strength and stiffness are effectively unchanged by the reduced insulation thickness.

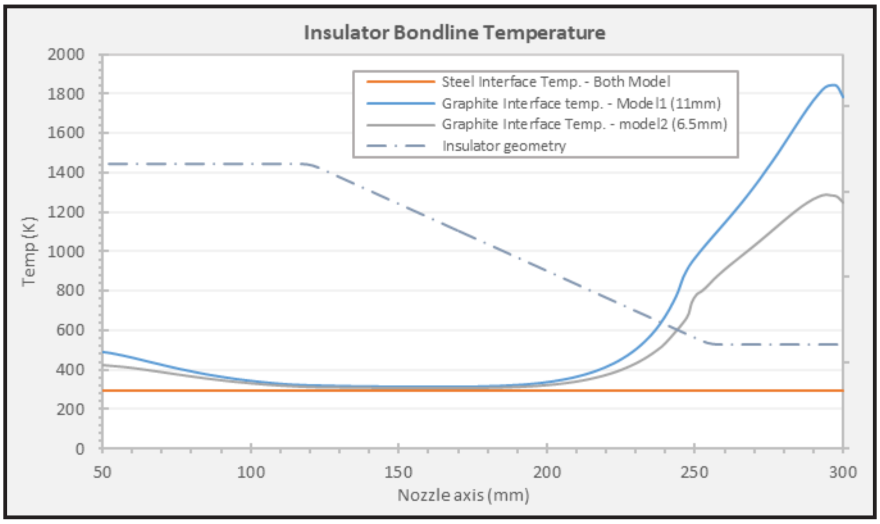

Figure 5: Insulator Bond line Temperature across Nozzle Axis

Figure 6 plots temperature histories at three critical points: outer surface, mid-thickness, and inner surface, each located at 290 mm along the nozzle bond line, over the 12 second burn. In both configurations, the outer surface temperature rises only modestly from ambient and remains under 350 K by burnout, while the mid-thickness temperature stays below 500 K. At the inner surface, the thinner 6.5 mm insulator (Model 2) exhibits a lower peak temperature around 1300 K compared to roughly 1 900 K for the thicker 11 mm insulator (Model 1). This occurs because the thinner insulator reaches its steady-state temperature more quickly, allowing heat to spread into the graphite earlier and preventing the higher peak at the interface. These results highlight that a thinner insulator can produce a more moderate thermal response, even though thicker insulation delays initial heating. Optimizing nozzle performance therefore requires balancing insulator thickness, total mass, and the risk of graphite erosion under the specific burn duration.

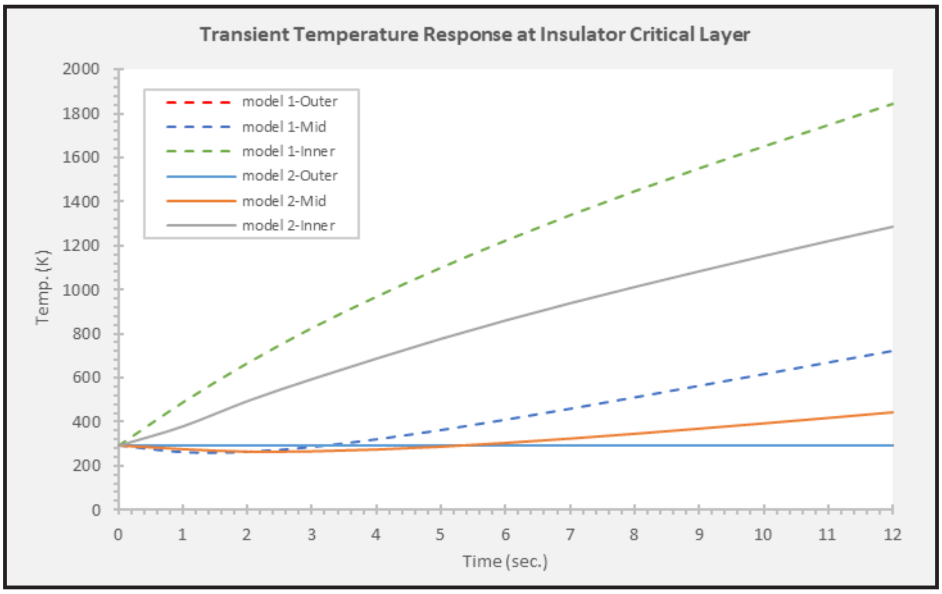

Figure 6: Transient Temperature Response at Insulator Critical Layer

3.2 Structural Analysis of Divergent Section

Figure 7 shows the Von Mises stress distribution along the nozzle axis under internal pressure, with both the convergent–throat and divergent sections originally built entirely from AISI 4340 steel. In the baseline configuration, the steel casing was 10 mm thick in the convergent section and increased to 17 mm in the divergent section where no graphite liner was present to prevent thermal failure or melting during operation. All stresses in this analysis arise purely from internal pressure, assuming the outer surface temperature remains low enough to preserve the materials mechanical properties.

In the redesigned nozzle, the steel casing thickness in the convergent–throat region has been reduced to 4 mm (from 10 mm), while the divergent section now uses 4 mm of 6061 aluminium (replacing the original 17 mm of steel). A graphite–ablative composite liner sits between these sections, absorbing and redistributing much of the mechanical load before it reaches the lighter aluminium casing. This hybrid approach maintains structural integrity under pressure while significantly reducing mass.

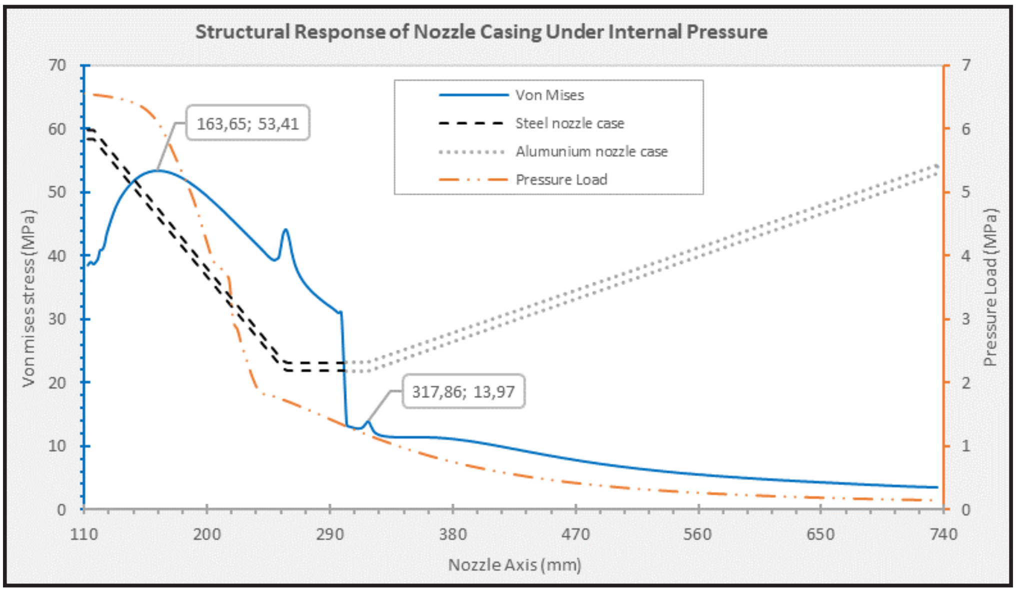

Figure 7: Stress distribution along nozzle axis

Stress peaks at 53.41 MPa in the steel section at 163.65 mm, where internal pressure reaches roughly 6.5 MPa, then drops sharply around 290 mm at the transition from the steel to the aluminum casing as the load transfers through the graphite/ablator liner into the aluminium. In the aluminium divergent section, the maximum stress is only 13.97 MPa at 317.86 mm and continues to fall as pressure decreases. Both materials remain well below their yield strengths 470 MPa for AISI 4340 steel and 276 MPa for aluminium 6061 resulting in safety factors of approximately 8.8 and 19.8, respectively. These generous margins ensure the nozzle casing stays firmly within the elastic regime throughout the burn.

Table 3: Von Mises Stress and Safety Factors at Two Nozzle Locations

Position (mm)	Material	Von Mises Stress (MPa)	Yield Strength (MPa)	Safety Factor
163.65 (Convergent section)	AISI 4340 Steel	53.41	470	8.8
317.86 (Divergent section)	Aluminium 6061	13.97	276	19.8

3.3 Comparative Mass Analysis of Proposed Design Models

In addition to the thermal and structural performance already presented, three alternative nozzle configurations were compared to quantify achievable mass savings. As summarized in Table 4, Model A (the baseline steel–aluminium configuration) achieves a total nozzle mass of 60.90 kg by combining a 16.75 kg AISI 4340 steel convergent case, a 5 kg 6061-T6 aluminium divergent case, a 9.2 kg silica-phenolic ablative liner, and standard thermal inserts in the throat and convergent section. Model B reduces the divergent casing mass by approximately 44 percent dropping the total assembly weight to 57.73 kg by substituting the aluminium with a 2.83 kg carbon–epoxy filament-wound structure while maintaining the same ablative liner and glass-phenolic insulator. Model C takes this concept further, entirely removing the structural casing in the divergent section and relying on an enhanced silica-phenolic composite to bear both thermal and mechanical loads, resulting in the lightest design at 56.70 kg.

Table 4: Comparison of Alternative Nozzle Configuration Mass Breakdown

Nozzle Sections	Model A		Model B		Model C	
	Material	Mass (kg)	Material	Mass (kg)	Material	Mass (kg)
Throat Insert	Graphite	21	Graphite	21	Graphite	21
Convergent Section Nozzle case	Steel 4340	16,75	Steel 4340	16,75	Steel 4340	16,75

Nozzle Sections	Model A		Model B		Model C	
	Material	Mass (kg)	Material	Mass (kg)	Material	Mass (kg)
Insert Insulator	Glass-phenolic	8,95	Glass-phenolic	8,95	Glass-phenolic	8,95
Divergent section nozzle case	Aluminum 6061	5	Carbon-epoxy	2,83	N/A	-
Divergent section liner	Silica-phenolic	9,2	Silica-phenolic	8,2	Enhanced Silica-phenolic	10
Total Mass		60,9		57,73		56,7

It must be noted that these mass predictions in Table 4 are grounded solely on literature-sourced component weights and simplified thermal–mechanical assumptions. Accurate modelling of the divergent section's ablative behaviour for all Model A, B and Model C will require specialized thermochemical solvers that account for temperature-dependent material reactions and gas–solid interactions during surface erosion. Future work should therefore focus on experimentally characterizing the ablative composite properties, extending thermal simulations with high fidelity ablative material solver code, and conducting full-scale tests to confirm both thermal–structural models and erosion rates. Such efforts will ensure that the most promising configuration not only minimizes mass but also meets the stringent reliability standards required for sounding-rocket applications.

4. Conclusions

Based on the comprehensive thermal, structural, and mass analyses presented, the proposed redesign of the RX450 sounding rocket nozzle demonstrates significant potential for performance improvement through strategic material substitution and design optimization. By replacing the heavy steel casing in the divergent section with a combination of ablative silica-phenolic composite liners and aluminium 6061 structural support, the nozzle mass in this critical region was reduced drastically from approximately 59 kg to around 14.5 kg without compromising structural integrity or thermal protection.

Thermal simulations confirm that the introduction of glass-phenolic insulation layers effectively limits heat transfer to the metallic casing, maintaining temperatures within safe operational limits and enabling reductions in casing thickness. Although this insulation leads to higher temperatures within the graphite liner, the design balances thermal protection with manageable erosion risk, highlighting the importance of optimizing insulator thickness for specific burn durations. Structural analyses reveal that both the steel and aluminium sections maintain substantial safety margins under internal pressure loads, ensuring reliable mechanical performance throughout the burn.

However, these findings are based on literature-derived material properties and simplified thermal–mechanical assumptions. To fully validate the proposed designs, future work must focus on detailed thermochemical modelling of ablative behaviour, experimental characterization of composite materials, and full-scale testing to confirm thermal-structural performance and erosion rates.

In summary, the study successfully demonstrates that integrating ablative composites and lightweight metals in the RX450 nozzle design can substantially reduce mass while preserving essential thermal and mechanical functions. This approach aligns with the strategic goal of enhancing Indonesia's sounding rocket capabilities through accessible, high-performance materials and design innovations, paving the way for more efficient and reliable rocket propulsion systems.

Acknowledgements

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