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DEVELOPMENT AND SIMULATION OF A LOW-COMPLEXITY EPOXY-KNO_3 SOLID PROPELLANT FOR MODEL ROCKETS

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ABSTRACT:

The present study is aiming to optimize solid rocket engine performance by using epoxy as fuel and potassium nitrate as the oxidizer to understand rocket dynamics through model rocketry. The propellant mixture is being prepared based on a weight-to-weight ratio to achieve optimum output parameters, namely exit velocity, static pressure, specific impulse, and nozzle temperature. The proposed mixture is offering less mechanical complexity compared to the existing rocket motor. Simulation is being carried out using the PROPEP main software. The results are showing that the lower performance of solid propellants (as compared to liquids) is not favoring their use as the primary propulsion system in modern medium-to-large launch vehicles typically used to orbit commercial satellites and launch major space probes. However, solids are frequently being used as strap-on boosters to increase payload capacity or as spin-stabilized add-on upper stages when higher-than-normal velocities are required. Solid rockets are also being used as light launch vehicles for low Earth orbit (LEO) payloads under 2 tons or escape payloads up to 1100 pounds.

KEYWORDS: Solid rocket engine, Epoxy fuel, Potassium nitrate oxidizer, Propellant performance optimization, PROPEP simulation

INTRODUCTION:

The progression from early, small-scale rockets to the powerful space launch vehicles used today reflects centuries of technological advancement. Historically, rockets were relatively small and primarily used for military applications, maritime rescue, signaling, and fireworks. While solid propellants played a foundational role in early rocketry, their inherently lower performance compared to liquid propellants limits their use as primary propulsion systems in modern medium-to-large launch vehicles. However, solid rockets remain essential in many roles — commonly used as strap-on boosters to increase payload capacity, or as spin-stabilized upper stages where additional velocity is required. They also serve as light launch vehicles capable of delivering payloads under 2 tons into low Earth orbit (LEO) or escape payloads up to 1100 pounds. Solid rocket propellants are mixtures of fuel and oxidizer in solid form, typically cast into a cylindrical rocket motor. Among emerging formulations, epoxy–potassium nitrate-based propellants have attracted growing research interest. These systems offer a promising balance of performance, structural simplicity, and environmental friendliness. The potential for safer handling and reduced mechanical complexity makes them particularly appealing for model rocketry, educational research, and small-scale aerospace applications. This study focuses on optimizing the performance of such solid propellants to better understand their dynamics and practical viability in contemporary rocketry.

The development of solid propellants based on epoxy and potassium nitrate has attracted significant research interest due to their potential advantages in performance, simplicity, and environmental compatibility. Han et al. [1] investigated the development of an epoxy-cured potassium nitrate-based solid propellant. They highlighted that energetic materials, whether intrinsically explosive or formulated from oxidizer-fuel mixtures, possess self-sustaining reactions capable of releasing substantial energy, with wide-ranging military and civilian applications. Zhang et al. [2] examined the thermal decomposition and combustion behavior of a novel composite propellant based on ammonium nitrate and potassium nitrate. Their analysis provided insight into the combustion characteristics critical for improving propellant efficiency. Liu et al. [3] analyzed the impact of various catalysts on the curing behavior and mechanical properties of epoxy resin binders used in solid propellants. Their findings are relevant for optimizing the structural and thermal stability of epoxy-based propellant formulations. Ornellas and Kumar [4], reviewed the use of thermoplastic elastomers as binders in composite solid propellants. Their work explored the processing techniques and structural benefits of such binders, offering alternatives to traditional thermosetting resins like epoxy. Li et al. [5] also investigated a composite propellant incorporating both ammonium perchlorate (AP) and potassium nitrate (PN). They employed a freeze-drying technique to prepare AP/PN particles, aiming to enhance the burning characteristics and performance of composite solid propellants. Fang et al. [6] prepared and characterized an epoxy resin/potassium nitrate nanocomposite propellant. They determined the thermal degradation mechanisms and kinetic parameters, contributing to the understanding of cured epoxy-KNO_3 systems. Singh et al. [7]

studied the effect of oxidizer particle size on KNSB (potassium nitrate-sorbitol) propellant properties. They demonstrated that smaller oxidizer particles significantly increase the burn rate, highlighting the critical role of particle size in combustion behavior. Ornellas and Kumar [8] further expanded on their review of thermoplastic elastomer-based composite propellants, discussing structural features and their implications for explosive and gas-generating formulations. Zhang et al. [9], reported on research progress in epoxy/sorbitol composite propellants. Their work bridges the transition from sugar-based fuels to more stable epoxy-based systems, offering improved mechanical and combustion properties. Wei et al. [10] presented research on the evolution of KNSB propellant as a replacement for traditional KN-sucrose (KNSU) formulations. Their historical and technical perspectives underscore the rationale for using sorbitol to overcome the brittleness issues of KNSU. Song et al. [11] detailed the formulation and characterization of high-performance KNSB propellants. They provided extensive data on composition, performance, and sensitivity, crucial for material selection and safety evaluation in energetic systems. Bhandarkar et al. [12] developed an environmentally friendly KNSB propellant for aerospace applications. Their study emphasized the reduced environmental impact of using potassium nitrate and sorbitol, especially in amateur and small-scale rocketry. Richard [13] contributed practical insights into the burn characteristics of KNSB, noting its moderate burn rate relative to other sugar-based fuels. His work serves as a valuable reference for amateur rocketry and experimental validation. Mabuse [14] provided a comprehensive guide to rocket motors, including KNSB propellants. The resource includes design principles, safety practices, and testing protocols relevant to both hobbyists and researchers. Ahles [15] reported on the mechanical properties of cast KNSB propellants, noting their rigidity and brittleness. His findings affirm that, with careful grain design and motor integration, KNSB grains can withstand significant flight loads.

Nevertheless, while numerous researchers have explored the development of new solid rocket propellants to enhance motor performance, studies specifically focusing on the optimization of model rocket motors using epoxy–potassium nitrate (Epoxy-KNO_3) propellants remain limited. The present study aims to address this gap by formulating a solid propellant using epoxy as the fuel and potassium nitrate as the oxidizer, with the objective of better understanding rocket dynamics through model rocketry. The propellant mixture is prepared based on a defined weight-to-weight ratio to achieve optimal performance metrics, including exit velocity, chamber pressure, specific impulse (ISP), and nozzle temperature. These parameters are being optimized through simulations conducted using the PROPEP main software.

METHODOLOGY:

Numerical methods are employed to estimate specific impulse, chamber pressure, and chamber temperature required to achieve a thrust of 50 N. Based on these calculations, the resulting parameters are determined and presented in Table 1. Additionally, the PROPEP simulation software is utilized to evaluate the variation of specific impulse with respect to the oxidizer-to-fuel (O/F) ratio for the Epoxy–KNO_3 propellant system, with the results presented in Table 2. The numerical calculations show good agreement with the simulation results, validating the accuracy of the computational approach.

Table 1: Numerical calculations for O/F.

O/F	Nozzle Temperature, K	ISP, sec	Chamber pressure C*, MPa	Expansion ratio
1	1186	139.3	2750.9	9.17
1.2	1259	142.2	2917.2	9.26
1.4	1393	146.6	2900.7	9.54
1.6	1556	150.6	2968.4	9.83
1.8	1690	152.9	3002.4	10.05
2	1794	154	3016.3	10.21
2.2	1878	154.5	3019.9	10.32
2.4	1949	154.7	3018.9	10.41
2.6	2011	154.7	3016	10.48
2.8	2067	154.7	3011.6	10.55
3	2029	154.8	2929.5	10.69

Table 2: O/F vs ISP from PROPEP main software.

O/F	ISP
1.00	148.5
1.14	149
1.31	149.4
1.50	149.8
1.73	150.2
2.00	150.6
2.33	151
2.75	152.4
3.29	155.2
3.65	156
4.38	155.6
5.36	154.5
6.78	141.5

Based on numerical and simulation results, the methodology involves formulating the Epoxy–KNO_3 solid propellant by selecting an optimal oxidizer-to-fuel ratio and incorporating any necessary additives. The epoxy resin is heated and mixed with potassium nitrate using high-shear equipment to ensure a homogeneous blend. The mixture is then cast into molds or extruded, followed by curing at controlled temperatures to achieve the desired mechanical properties. Post-curing, the propellant is machined to precise dimensions, including features for ignition and thrust control. Finally, the propellant grain is assembled with the rocket motor components such as the casing, nozzle, and igniter. CFD analysis was conducted using ANSYS FLUENT (version 21 R2) to simulate combustion dynamics and validate design parameters under specified boundary conditions.

The solid rocket motor was designed using SOLIDWORKS and subsequently imported into ANSYS FLUENT for computational fluid dynamics (CFD) analysis. An orthogonal, high-smooth, unstructured mesh was generated, with an element size of 1.7 mm, resulting in 24,321 nodes and 287,614 elements. The mesh model is illustrated in Figure 1. For the CFD simulation, the k–ε turbulence model was employed to accurately capture the flow characteristics within the combustion chamber and nozzle.

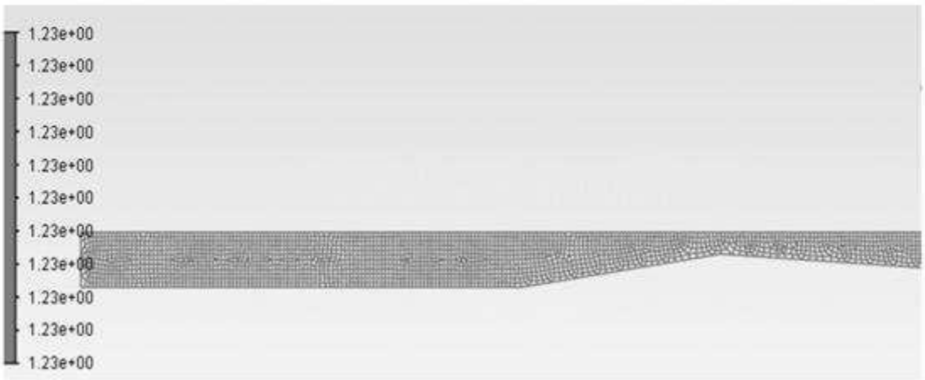

Figure 1: Meshmodel of solid rocket motor.

RESULTS AND DISCUSSIONS:

Pressure Flow-Field:

The pressure flow-field analysis reveals that the combustion reaction within the solid rocket engine proceeds efficiently under the defined boundary conditions. The reaction achieves optimal excitation, indicating complete combustion which directly enhances engine efficiency. As shown in Figure 2, the static pressure contour illustrates the pressure distribution within the combustion chamber. An over-pressure is observed in the pre-combustion zone, followed by a steady pressure drop along the combustion chamber. Figure 3 presents the static pressure profile along the axial direction, confirming a linear pressure decline as the gases expand and move toward the nozzle.

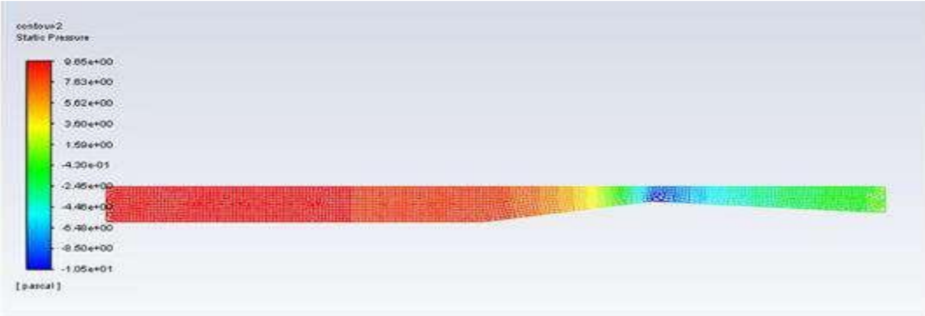

Figure 2: Static pressure contour of Solid Rocket Engine.

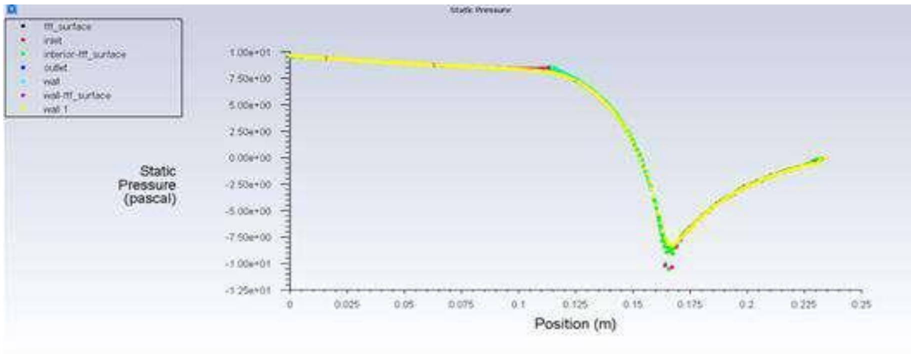

Figure 3: Static pressure plot of Solid Rocket Engine.

Velocity Flow-Field

Velocity flow-field results indicate a significant increase in gas velocity after combustion, with the exit velocity exceeding theoretical values. This suggests efficient thermal-to-kinetic energy conversion. The velocity magnitude contour shown in Figure 4 highlights the acceleration of gases through the nozzle. Figure 5 provides the corresponding velocity plot along the axial direction, clearly depicting a smooth and continuous rise in flow speed from the combustion chamber to the nozzle exit.

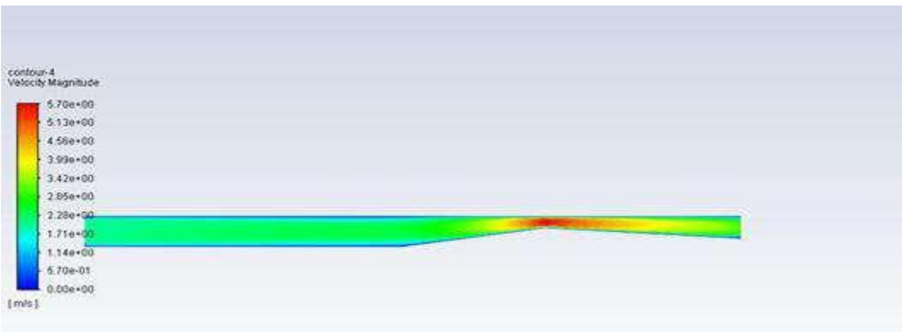

Figure 4: Contour Velocity Magnitude of Solid Rocket Engine.

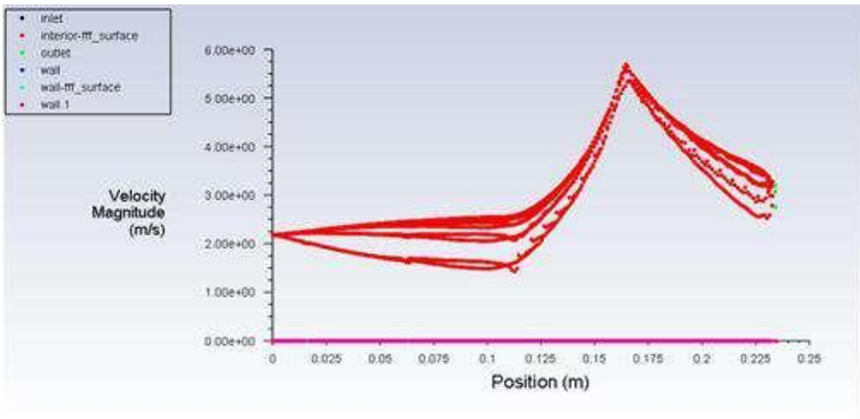

Figure 5: Contour velocity magnitude plot of Solid Rocket Engine.

Turbulent Kinetic Energy

The turbulent kinetic energy (TKE) distribution provides insights into the intensity of turbulence and mixing efficiency within the combustion chamber. Figure 6 shows the TKE contour during the combustion process, indicating areas of strong turbulence caused by flow recirculation and eddies. Figure 7 illustrates the turbulent energy variation along the axial direction. These results are crucial for understanding flow stability and combustion uniformity, which directly impact the performance of the solid rocket engine.

Strain Rate Flow-Field

Strain rate analysis gives an understanding of the deformation rate within the fluid flow during combustion. As shown in Figure 8, the strain rate contour highlights regions of intense shear and deformation, particularly around the nozzle throat and chamber walls. Figure 9 presents the plot of the strain rate, reflecting how the internal stresses evolve throughout the engine geometry. High strain zones correlate with rapid changes in velocity and pressure, typical in high-performance rocket motors.

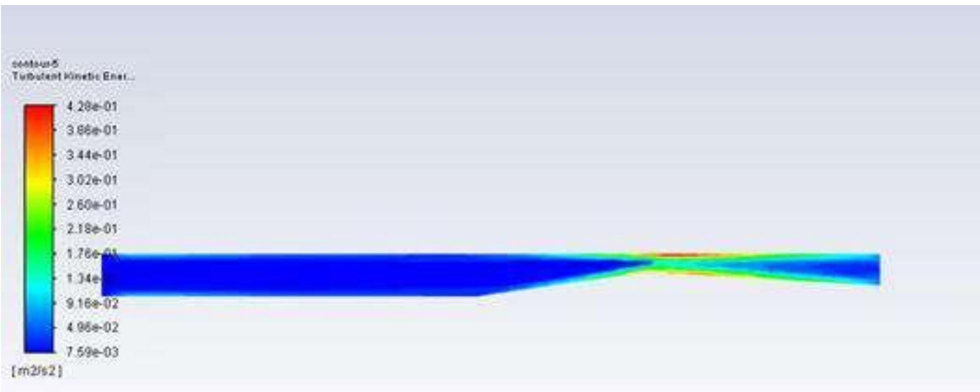

Figure 6: Turbulent Kinetic-Energy flow contours of Solid Rocket Engine.

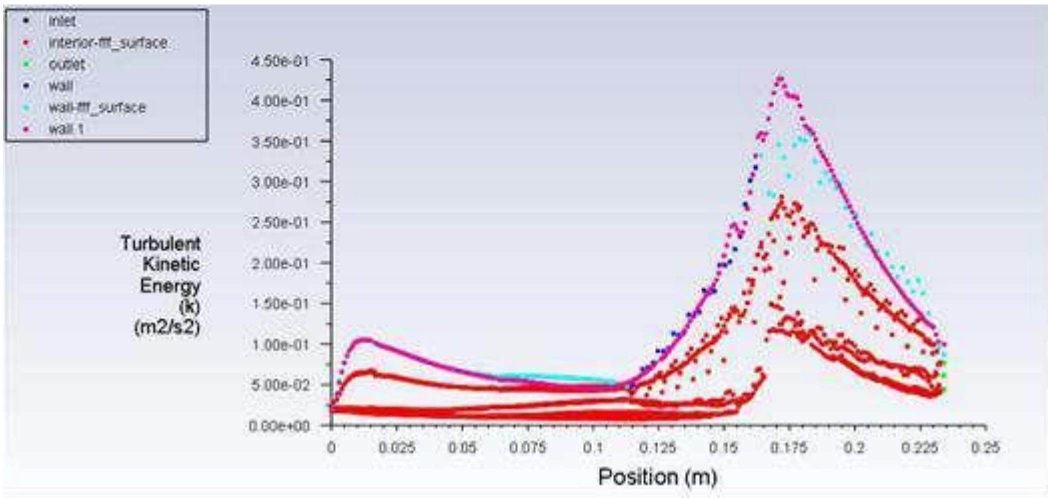

Figure 7: Plot of Turbulent Kinetic Energy flow contour of Solid Rocket Engine.

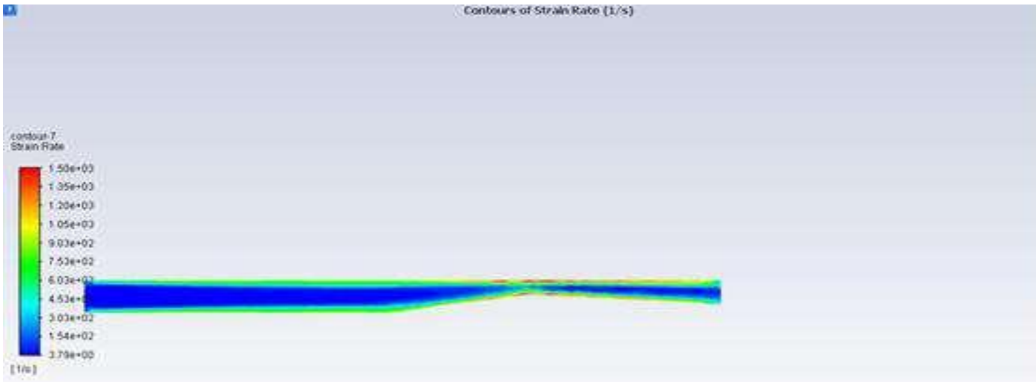

Figure 8: Contour Strain Rate of Solid Rocket Engine.

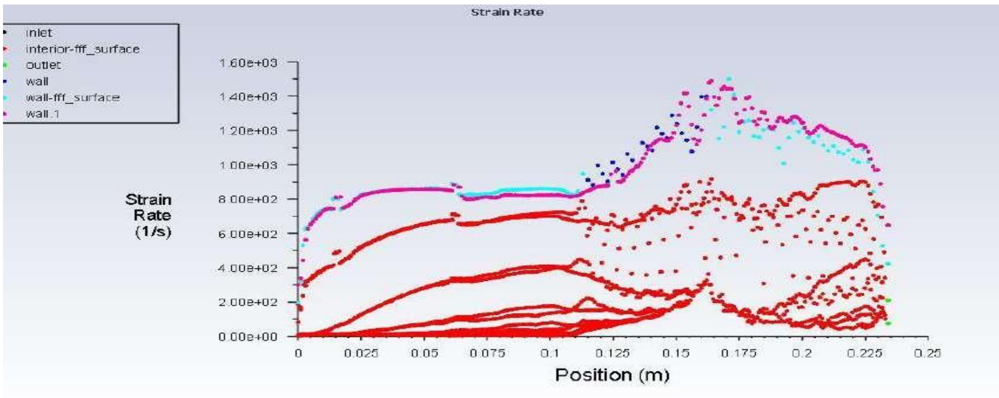

Figure 9: Plot of Contour Strain Energy of Solid Rocket Engine.

Mass Imbalance

Mass imbalance contours and plots provide insights into asymmetries in combustion and flow distribution, which can influence thrust vector stability. Figure 10 shows the mass imbalance contour along the combustion and post-combustion zones, indicating a relatively uniform burn pattern with slight asymmetries on the lateral surfaces of the propellant grain. Figure 10 further illustrates this behavior through a detailed contour plot, while Figure 11 presents the average mass imbalance along the axial direction. Mass imbalance in solid rocket motors can arise from variations in propellant casting, density, or insulation thickness, potentially leading to thrust asymmetry. To mitigate this, careful design, precision in manufacturing, and predictive simulations are essential.

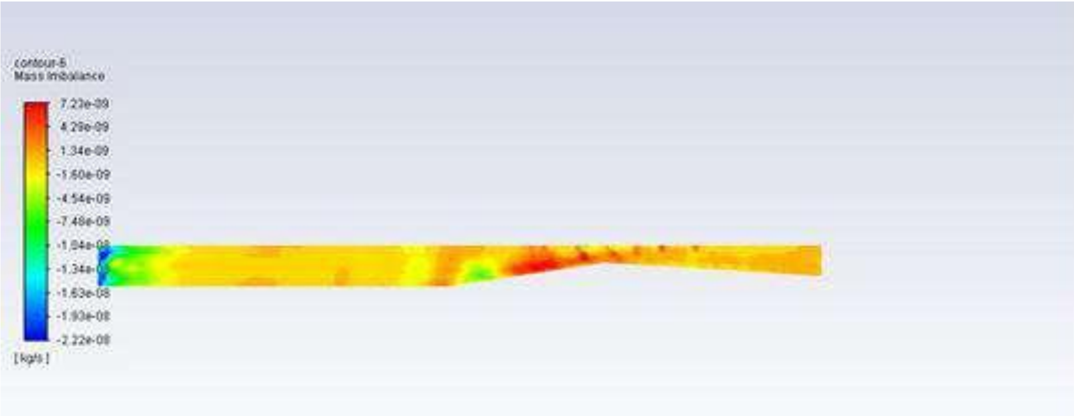

Figure 10: Contour Mass imbalace of Solid Rocket Engine.

CFD simulations of the Epoxy–KNO_3 solid rocket motor revealed efficient combustion with high pre-chamber pressure and smooth pressure drop through the nozzle. Exit velocities exceeded theoretical values, indicating effective energy conversion. Turbulent kinetic energy and strain rate results confirmed strong mixing and shear during combustion. Minor mass imbalances were observed, highlighting the need for precise propellant casting. The simulation results validate the propellant's suitability for high-performance model rocketry.

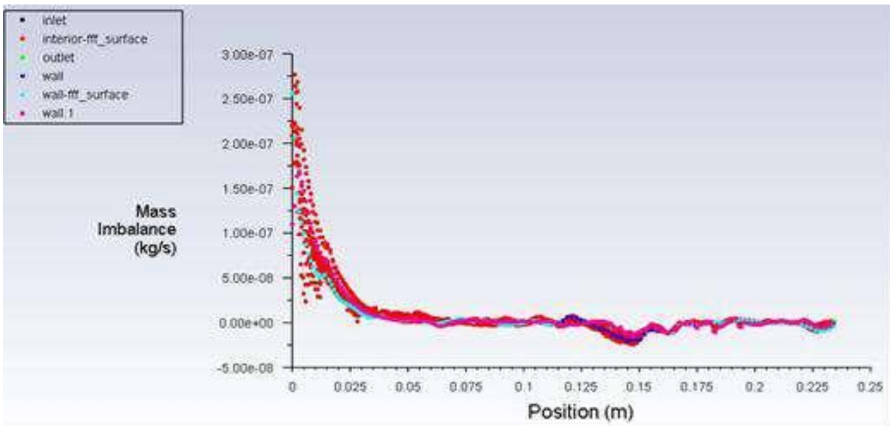

Figure 11: Plot of Mass imbalace contour of Solid Rocket Engine.

CONLCUIONS:

The preset work showws the feasibility and performance potential of an Epoxy–KNO_3-based solid propellant for model rocketry. Numerical calculations and PROPEP simulations guided the optimal formulation, focusing on maximizing specific impulse, chamber pressure, and nozzle temperature. The designed rocket motor was analyzed using ANSYS FLUENT, where CFD results confirmed efficient combustion behavior and validated the propellant formulation. Key findings include a high-pressure region in the pre-combustion chamber, a consistent pressure drop along the flow path, and an exit velocity exceeding theoretical expectations. Turbulent kinetic energy and strain rate distributions revealed effective mixing and stable combustion, while the mass imbalance analysis indicated minor asymmetries that can be addressed through improved manufacturing control. The integration of numerical modeling, simulation, and CFD analysis provides a robust methodology for solid propellant optimization. The results affirm that the Epoxy–KNO_3 system offers a promising balance of performance, simplicity, and manufacturability for small-scale and educational aerospace applications.

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CONFLICT OF INTEREST:

All authors declare that they have no conflicts of interest.

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15. Denneth Ahles (2020) in Denneth.nl website did First test launch of a Sorbitol based Sugar rocket and describes the procedure used to make it.
16. Georgia Korompili, Gunter Muhbach, Christos Rizotis (2024) in MDPI (Multidisciplinary Digital Publishing Institute) website under the Publication STRUCTURAL HEALTH MONITORING OF SOLID ROCKET MOTORS , I have taken the figure.