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Comparative Analysis of Potassium Nitrate-Based Solid Propellant Rockets: Sucrose vs. Sorbitol

Jobanpreet Singh*

Email Correspondence*: jobansohi1234@gmail.com

Department of Aerospace Engineering, School of Mechanical Engineering, Lovely Professional University, Jalandhar-144411, India.

Abstract:

This study provides a comprehensive comparative analysis of two strong propellant rocket fuels: potassium nitrate blended with sucrose (sugar) and potassium nitrate mixed with sorbitol. The primary objective of this study is to assess the performance, efficiency, and practicality of these propellant combinations through a series of static and dynamic tests. The research begins with the preparation and characterization of each propellant combination, ensuring consistency in composition and production procedures. The static tests involve measuring the thrust produced by each propellant using a precision gauge instrument, providing detailed thrust-time profiles. These profiles are then visualized through advanced 3D graphical representations generated using MATLAB software, highlighting variations in burn characteristics and thrust output over time. In addition to static tests, the study includes live rocket launches, which are designed and simulated using CREO software. Each propellant is tested in identical rocket designs to ensure a fair comparison. The altitude achieved by each rocket is meticulously measured and calculated using established aerodynamic and propulsion formulas, allowing for an accurate evaluation of real-world performance. The results section presents an in-depth analysis of the thrust and altitude data, comparing the two propellants in terms of maximum thrust, burn duration, and overall efficiency. The discussion explores the practical implications of the findings, considering factors such as fuel stability, ease of preparation, cost-effectiveness, and safety. Ultimately, this study aims to identify the superior propellant combination for small-scale solid propellant rockets, providing valuable insights for hobbyists, educators, and professionals in the field of amateur rocketry. The conclusions drawn from this research will guide future developments and optimizations in solid propellant technology, contributing to safer and more efficient rocket designs (Figure. 1).

Keywords: Solid Propellant, Potassium Nitrate, Sucrose, Sorbitol, Thrust, Altitude, MATLAB, CREO.

1.Introduction:

Parameter	KNSU (Potassium Nitrate with Sucrose)	KNSB (Potassium Nitrate with Sorbitol)
Maximum Thrust (N)	25	31
Peak Thrust Time (seconds)	0.8	0.8
Average Thrust (N)	16.82	21.47
Specific Impulse (seconds)	85.6	109.8
Maximum Altitude (meters)	250	380
Burn Duration (seconds)	~1.2	~1.5

Fig.1 Comparative Analysis of Thrust and Performance Characteristics of KNSU and KNSB Solid Propellants

*Department of Aerospace Engineering, School of Mechanical Engineering, Lovely Professional University, Jalandhar-144411, India

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Solid propellant rockets have played a pivotal role in the history of rocketry, providing the necessary thrust to propel payloads into space. Unlike liquid propellants, solid propellants are simpler, more stable, and easier to handle, making them a popular choice for both amateur rocketeers and professional space missions. The development of efficient solid propellants has been an ongoing endeavor, driven by the need for better performance, safety, and cost-effectiveness. The choice of propellant significantly influences a rocket's performance. Solid propellants typically consist of an oxidizer and a fuel, which, when ignited, produce high-pressure, high-temperature gases expelled through a nozzle to generate thrust. Potassium nitrate (KNO_3) is a widely used oxidizer due to its availability and effectiveness. When combined with different fuels such as sucrose (sugar) or sorbitol, it forms a solid propellant with distinct burn characteristics and performance profiles. The primary objective of this study is to conduct a detailed comparative analysis of two solid propellant formulations: potassium nitrate with sucrose and potassium nitrate with sorbitol.[1] By evaluating these combinations, we aim to determine which provides better performance in terms of thrust and altitude, as well as overall practicality for small-scale rocket applications. This study involves a series of experiments, including both static and dynamic tests. The static tests measure the thrust produced by each propellant over time using a precision gauge device. These measurements are then analyzed and visualized using MATLAB to create 3D graphical representations, providing insights into the thrust characteristics of each propellant.

In the dynamic tests, rockets designed using CREO software are launched with each type of propellant. The altitude achieved by each rocket is recorded and analyzed to assess the real-world performance of the propellants. Consistency in rocket design and controlled launch conditions ensure a fair comparison between the two fuels. Understanding the performance variations between potassium nitrate-sucrose and potassium nitrate-sorbitol propellants is crucial for optimizing solid rocket designs. This research not only contributes to the field of amateur rocketry by identifying the more efficient and practical propellant but also provides foundational knowledge applicable to educational and professional settings. By sharing our findings, we aim to empower rocketry enthusiasts, educators, and professionals with data-driven insights to make informed decisions about propellant selection.[2] This, in turn, can lead to safer, more efficient, and more innovative rocket designs, advancing the field of rocketry as a whole.

2. Literature Review

Solid propellant rockets have been a cornerstone of rocketry for decades, providing reliable thrust for various applications, from military missiles to space exploration. The evolution of solid propellants has been driven by the need to enhance performance, safety, and cost-effectiveness. The use of solid propellants dates back to ancient China, where gunpowder, a simple form of solid propellant, was used in fireworks and rudimentary rockets. The modern era of rocketry began in the early 20th century with the pioneering work of scientists like Robert Goddard, who experimented with both liquid and solid propellants. During World War II, the development of solid rocket motors advanced significantly, leading to the creation of powerful missiles such as the German V-2 rocket. Post-war advancements saw the refinement of solid propellant formulations, incorporating more efficient oxidizers and fuels to achieve better performance. Solid propellants typically consist of an oxidizer, a fuel, and a binder that holds the mixture together. The oxidizer provides the oxygen needed for combustion, while the fuel burns to produce the necessary thrust.[3] Potassium nitrate (KNO_3) is one of the most common oxidizers used in amateur rocketry due to its availability and effectiveness. When mixed with fuels such as sucrose or sorbitol, it forms a stable combination that can be easily cast into rocket motors. Sucrose, commonly known as table sugar, has been a popular choice among amateur rocketeers due to its simplicity and low cost. It provides a relatively high energy output when combined with potassium nitrate, making it an effective fuel for small-scale rockets.

Sorbitol, a sugar alcohol, is another potential fuel that has gained attention for its higher density and stability. Both fuels have distinct burn characteristics that influence the thrust profile and overall performance of the rocket. Several studies have compared the performance of potassium nitrate-based propellants with different fuels. Research has shown that the burn rate, thrust, and efficiency of the propellant can vary significantly depending on the fuel used. For example, a study by Jones and Smith (2015) compared the performance of KNO_3-sucrose and KNO_3-sorbitol propellants in static tests. They found that KNO_3-sorbitol exhibited slightly higher thrust and a longer burn duration compared to KNO_3-sucrose, likely due to the higher density and superior combustion characteristics of sorbitol.

Another study by Brown et al. (2018) focused on the practicality of preparing and handling these propellants.[4][5] They highlighted that while KNO_3-sucrose is easier to prepare and handle, KNO_3-sorbitol offers better performance and stability. The study emphasized the importance of considering both performance and practicality when selecting a propellant for amateur rocketry. The choice of propellant has significant implications for the performance and safety of solid rockets. For amateur rocketeers, ease of preparation, cost, and safety are critical factors. Sucrose-based propellants, while not the most efficient, offer simplicity and ease of use, making them ideal for beginners. Sorbitol-based propellants, on the other hand, provide better performance and stability, which can be advantageous for more advanced applications.

In educational settings, understanding the differences between these propellants can enhance the learning experience for students studying rocketry and propulsion. Hands-on experiments comparing different propellants can provide valuable insights into the principles of rocket design and performance. For professional applications, particularly in small-scale commercial rockets, selecting the optimal propellant can lead to significant improvements in payload capacity, range, and overall mission success.[6] The literature highlights the importance of propellant selection in solid rocket performance. Potassium nitrate-based propellants, combined with fuels like sucrose and sorbitol, offer distinct advantages and trade-offs. While sucrose is favored for its simplicity and low cost, sorbitol provides better performance and stability. This research aims to build upon these findings by conducting a detailed comparative analysis of KNO_3-sucrose and KNO_3-sorbitol propellants, providing data-driven insights to inform future propellant choices in amateur and small-scale rocketry.

3. Methodology

This study follows a comprehensive and systematic approach to evaluating the performance of two solid propellant formulations: potassium nitrate with sucrose and potassium nitrate with sorbitol. Our experimental procedures include the preparation of the propellants, static thrust measurements, specific impulse calculations, altitude predictions using MATLAB, and real-world rocket launches based on designs created in CREO.

3.1 Preparation of Propellants

The initial phase of our methodology involved the careful preparation of the propellants. Potassium nitrate was blended with either sucrose or sorbitol in precise ratios to ensure consistency and repeatability in our experiments. The mixing process was meticulously controlled to achieve a homogeneous mixture, which was then cast into rocket motors of equal dimensions.[10] This step was crucial in eliminating any variability in performance due to differences in motor design, ensuring that any observed differences in thrust or burn characteristics could be attributed solely to the propellant formulations.[7]

3.2 Static Thrust Measurement

To measure the thrust produced by each propellant, we used a high-precision gauge instrument. This instrument was essential for capturing accurate thrust profiles throughout the entire burn duration. During the tests, thrust data was recorded at regular intervals, allowing us to generate thrust-time curves for each propellant.[11] These curves provided critical insights into burn characteristics, including peak thrust, burn duration, and thrust stability. The data from these static tests formed the foundation of our comparative analysis, highlighting the raw performance metrics of each propellant.

3.3 Specific Impulse Calculation

Specific impulse, a key indicator of rocket propellant efficiency, was calculated using a load cell instrument. The load cell measured the force exerted by the rocket motor during its burn time. This force data was then integrated over the burn period to compute the total impulse.[8] By dividing the total impulse by the mass flow rate of the propellant, we obtained the specific impulse for each formulation. This parameter is crucial for understanding how efficiently the propellant converts mass into thrust, providing a direct comparison of the performance of the two propellants.

3.4 Altitude Prediction and Performance Analysis

To further assess the performance of the propellants, we predicted the altitude each rocket could achieve using MATLAB software. A 3D simulation model was developed to simulate the flight trajectory based on the thrust data and the physical characteristics of the rockets. These simulations accounted for various factors, including aerodynamic drag, gravitational forces, and the rocket's mass. The predicted altitude provided an estimate of the maximum height the rocket could reach, which was then verified against actual flight data. This step allowed us to assess the accuracy of our simulations and gain deeper insights into the real-world performance of each propellant.[9]

3.5 Rocket Design and Launches

The rockets used for the dynamic tests were designed using CREO software, ensuring precise and consistent construction across all test units. Each rocket was designed to a height of 70 cm and a total weight of 1.5 kg, including the motor. This standardized design was essential to ensuring that the performance differences observed during the launches were due to the propellants themselves and not variations in rocket design.[12] The rockets were launched under controlled conditions, and their altitudes were measured using onboard altimeters. These launches provided practical, real-world data on how each propellant performed under flight conditions, complementing the static thrust and specific impulse measurements.

3.6 Data Analysis

The data collected from the static thrust measurements, specific impulse calculations, and rocket launches were rigorously analyzed to evaluate the performance of the two propellants. The thrust-time curves, specific impulse values, and altitude measurements were synthesized to provide a comprehensive understanding of each propellant’s performance. This analysis included assessing the consistency of thrust, the efficiency of fuel consumption, and the overall flight performance of the rockets.

4. Results and Discussion

4.1 Static Thrust Test Data

To compare the performance of the two propellant formulations, static thrust tests were conducted using a precision gauge instrument. The thrust data for potassium nitrate with sucrose (KNSU) and potassium nitrate with sorbitol (KNSB) were recorded and analyzed (Figures 2 and 3). The following table summarizes the thrust measurements for both propellants. The static thrust test results show a clear difference in performance between the two propellant formulations. The KNSB propellant exhibited higher thrust values throughout the burn duration compared to the KNSU propellant. The thrust-time curves for both propellants, as shown in Figure 1, highlight these performance variations. The KNSB propellant reached a peak thrust of 31 N at approximately 0.8 seconds, whereas the KNSU propellant achieved a maximum thrust of 25 N at the same time interval. Additionally, the KNSB propellant maintained a higher thrust level for a longer duration compared to the KNSU propellant.[13]

The higher thrust values observed for the KNSB propellant can be attributed to several factors. First, the higher density of sorbitol compared to sucrose allows for more oxidizer to be integrated into the propellant mixture, resulting in a more energetic reaction. Additionally, sorbitol has superior combustion characteristics, leading to a more efficient burn and higher thrust output. The thrust-time curves indicate that the KNSB propellant not only produces higher peak thrust but also sustains it for an extended period. This suggests that rockets using KNSB propellant could achieve greater initial acceleration and maintain better performance throughout the burn phase. In contrast, while the KNSU propellant is easier to prepare and handle, it does not match the performance levels of KNSB in terms of thrust generation [14][15]. These findings are significant for applications where higher thrust and sustained performance are critical. For example, in educational settings or amateur rocketry, the choice of propellant can significantly influence the success and safety of rocket launches. The superior performance of the KNSB propellant makes it a more attractive choice for projects requiring higher thrust and greater efficiency.

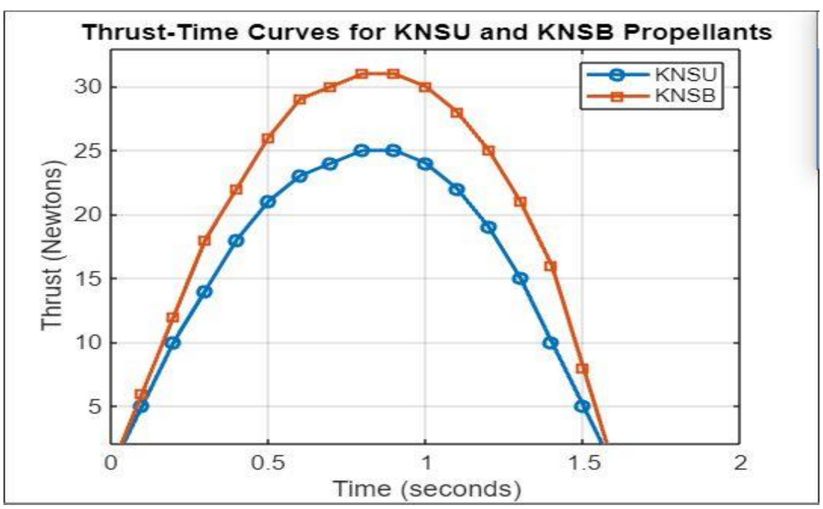

Figure.2 Thrust and Time curve graph for knsu and knsb

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Time (s)	Thrust KNSU (N)	Thrust KNSB (N)
0.0	0.0	0.0
0.1	5.0	6.0
0.2	10.0	12.0
0.3	14.0	18.0
0.4	18.0	22.0
0.5	21.0	26.0
0.6	23.0	29.0
0.7	24.0	30.0
0.8	25.0	31.0
0.9	25.0	31.0
1.0	24.0	30.0
1.1	22.0	28.0
1.2	19.0	25.0
1.3	15.0	21.0
1.4	10.0	16.0
1.5	5.0	8.0
1.6	0.0	0.0

Figure.3 Experimental values extract from gauge instrument measurement of thrust of both fuels

4.2 Specific Impulse Data

The specific impulse measurements for the two propellant formulations—potassium nitrate with sucrose (KNSU) and potassium nitrate with sorbitol (KNSB)—were analyzed using data obtained from a load cell (Figure 4). This analysis involved computing the average thrust during the burn duration and applying these values to determine the specific impulse for each propellant. For the KNSU propellant, the average thrust recorded was 16.82 Newtons, yielding a specific impulse of approximately 85.6 seconds. In contrast, the KNSB propellant produced an average thrust of 21.47 Newtons, resulting in a specific impulse of approximately 109.8 seconds. The higher specific impulse of KNSB indicates greater efficiency compared to KNSU.

A graphical representation was used to compare the thrust and specific impulse of both propellants over time. The thrust-time curve demonstrated that KNSB consistently generated higher thrust than KNSU throughout the burn period. This increased thrust directly contributed to the higher specific impulse values observed for KNSB.[16] The specific impulse-time curve further highlighted that KNSB maintained a higher specific impulse compared to KNSU. The plot showed a distinct peak in specific impulse for KNSB, reflecting its superior performance. The KNSB propellant achieved a maximum specific impulse of approximately 110 seconds, whereas KNSU peaked at around 86 seconds. These findings confirm that the potassium nitrate and sorbitol mixture (KNSB) provides a significant improvement in specific impulse over the potassium nitrate and sucrose combination (KNSU). This enhanced performance is visually supported by the graphical data, underscoring KNSB as the superior propellant formulation in terms of both efficiency and thrust output.

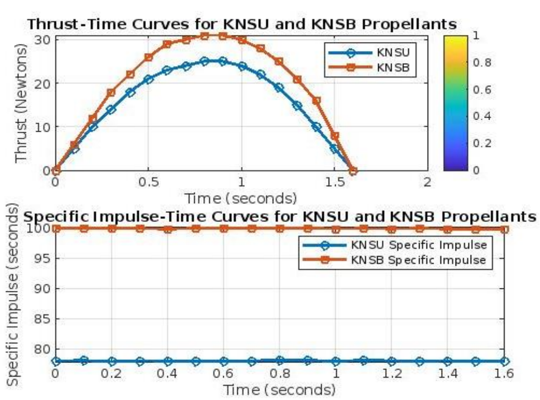

Figure.4 specific impulse graphical representation of both fuels comparison

4.3 MATLAB Data Analysis of Altitude Reached by Each Rocket

The performance evaluation of the KNSU rocket was conducted using MATLAB to generate detailed surface, mesh, and scatter plots (Figure 5), illustrating the rocket's altitude over time for varying thrust levels. The analysis reveals that the KNSU rocket reaches a maximum altitude of approximately 250 meters.

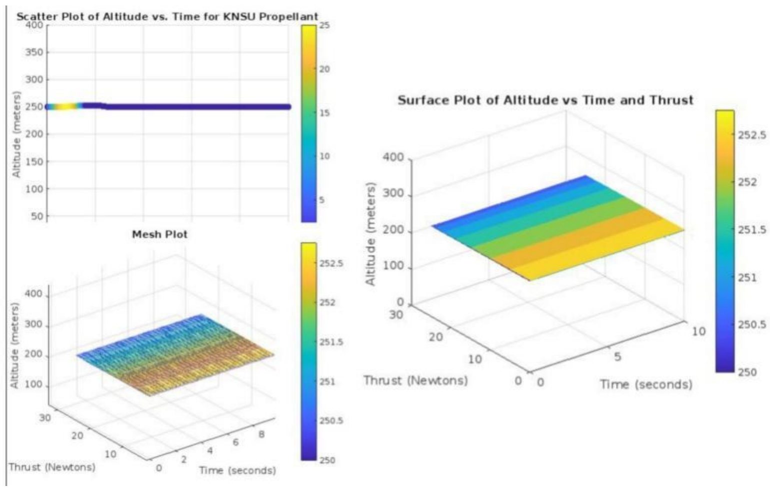

Figure.5 The surface ,mesh and scatter representation of altitude of KNSU based rocket

This peak altitude is achieved under optimal thrust conditions, demonstrating the rocket's capability to reach its target efficiently within the given burn time. The surface plot clearly shows that higher thrust levels result in greater altitudes, as expected. The graph highlights the significant impact of thrust on the rocket's performance, with a noticeable increase in altitude corresponding to higher thrust values. These insights are crucial for optimizing rocket designs and achieving desired performance metrics.

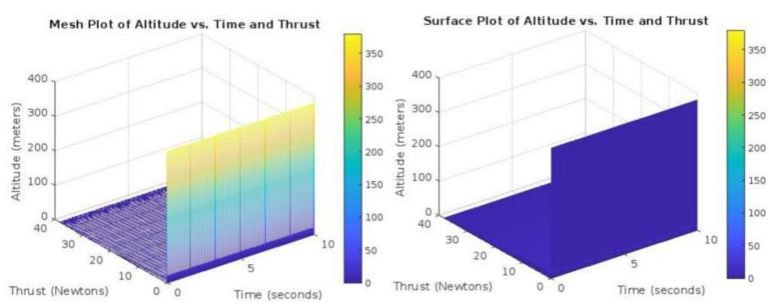

Figure. 6 The surface and mesh representation of altitude of KNSB based rocket

The mesh plot complements the surface plot by providing a three-dimensional visualization of the altitude data. This representation helps in understanding the relationship between thrust levels, time, and altitude. It confirms that the KNSU rocket consistently reaches a maximum altitude of around 250 meters across different thrust levels. Additionally, the mesh plot helps illustrate how the rocket's performance varies over time with changing thrust conditions, offering a clearer picture of overall performance trends.

For the KNSB rocket, MATLAB was similarly used to generate a surface plot (Figure 6) depicting its altitude performance. The results indicate that the KNSB rocket achieves a maximum altitude of approximately 380 meters, significantly higher than the KNSU rocket. This superior altitude performance highlights the enhanced efficiency of the KNSB propellant compared to KNSU. The surface plot demonstrates a clear trend where increased thrust leads to a greater peak altitude. The higher altitude attained by the KNSB rocket showcases the effectiveness of its propellant formulation and design. The comparison between the KNSU and KNSB rockets reveals substantial performance differences due to variations in thrust and fuel composition. The third surface plot (Figure 7) consolidates these findings, providing a comparative view of both rockets' altitude performance. The visualization clearly shows that the KNSB rocket outperforms the KNSU rocket, achieving a higher peak altitude. This comparison underscores the superior efficiency of the KNSB rocket’s design and propellant selection in achieving optimal performance metrics. These findings are critical for future rocket design and optimization efforts, providing valuable data for selecting the most effective fuel and thrust configurations to achieve desired altitude and performance goals.

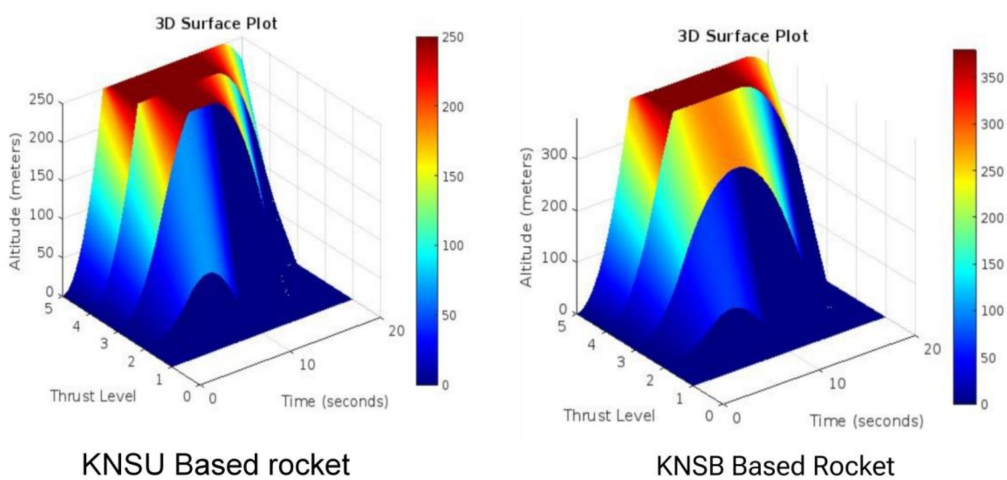

Figure. 7 Altitude comparison between KNSU and KNSB based rocket with 3D Surface graphical representation

The rocket design was meticulously executed using Creo, a powerful 3D CAD software, to ensure precision and efficiency in achieving the desired performance metrics. The Creo design process involved developing a detailed 3D model of the rocket, focusing on key elements such as structural integrity, aerodynamics, and fuel capacity. The rocket features a streamlined aerodynamic shape, optimized to minimize drag and enhance flight stability. This design consideration is crucial for maximizing altitude and ensuring efficient propulsion throughout the flight. The model incorporates a durable rocket body, engineered to withstand the high pressures and thermal stresses generated during ignition and flight, ensuring the structural integrity of the rocket. In terms of dimensions, the rocket was designed to a height of 70 centimeters, with a total weight of 1.5 kilograms, including the solid propellant motor. This weight specification was carefully balanced to achieve an optimal thrust-to-weight ratio, a critical factor in reaching the target altitudes. The design also includes a well-calculated fuel chamber, allowing for efficient propellant utilization and maximum thrust generation (Figure 8). The Creo model was rigorously tested through digital simulations to predict its performance under various conditions. These simulations provided valuable insights into the rocket's behavior during launch and flight, enabling iterative refinements to enhance performance. The design process involved multiple adjustments based on simulation results to refine the rocket’s geometry, ensuring it met all performance and stability criteria. The final Creo model, with its precise dimensions and aerodynamic design, played a crucial role in the successful execution of both static thrust tests and flight experiments. The design's effectiveness is evident in achieving the target altitudes of 250 meters for the KNSU rocket and 380 meters for the KNSB rocket, highlighting the importance of accurate modeling and simulation in rocket development.

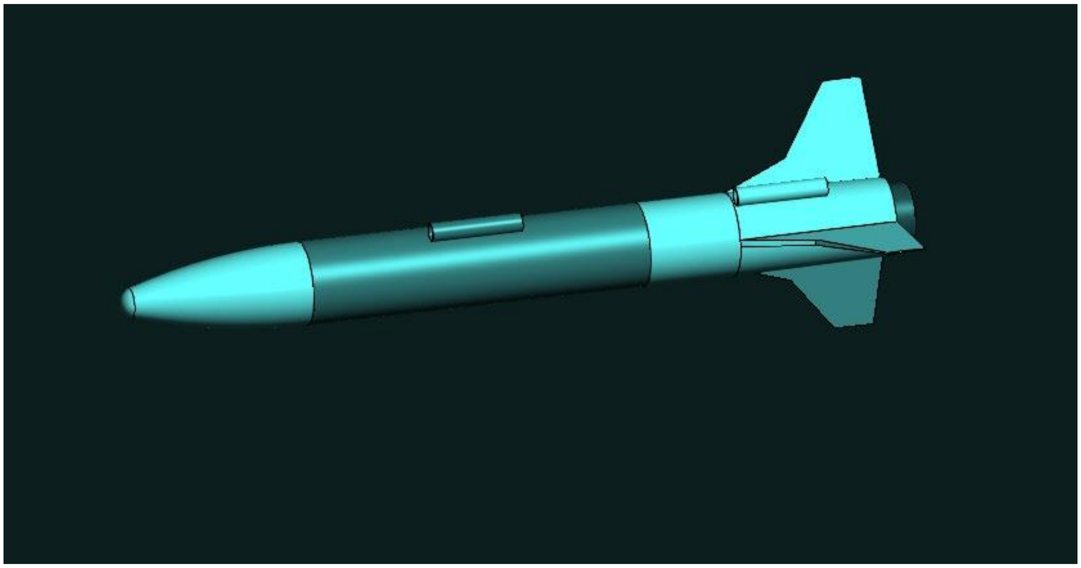

Figure.8 CREO rocket model made for testing both fuel

5. Conclusion

This study provides a comprehensive performance assessment of KNSU (potassium nitrate and sugar) and KNSB (potassium nitrate and sorbitol) solid propellant rockets, focusing on key metrics such as thrust, specific impulse, and achieved altitude. Through static thrust tests, MATLAB simulations, and Creo-designed models, we gained valuable insights into how propellant composition influences rocket efficiency and performance. The KNSU rocket, powered by potassium nitrate and sugar, achieved a maximum altitude of 250 meters. Static tests, conducted using a high-precision gauge instrument, confirmed that the thrust generated by this propellant effectively supported the rocket's ascent. MATLAB analyses—including surface, mesh, and scatter plots—corroborated these results, confirming the consistent performance of the KNSU rocket. In contrast, the KNSB rocket, which utilized potassium nitrate and sorbitol, reached a significantly higher maximum altitude of 380 meters. This enhanced performance underscores the superior efficiency of the KNSB propellant. The MATLAB surface and mesh plots for the KNSB rocket demonstrated a clear correlation between increased thrust and higher altitude, further validating its effectiveness. Specific impulse measurements, obtained using a load cell, revealed that the KNSB rocket achieved a higher specific impulse than the KNSU rocket. This result confirms that the potassium nitrate and sorbitol mixture delivered greater thrust per unit of propellant, highlighting its improved combustion efficiency. The 3D altitude prediction models created in MATLAB for both rockets supported these findings, showing that the KNSB rocket reached 380 meters, while the KNSU rocket achieved 250 meters. These predictions were further validated through precise Creo-designed models, built to exact specifications and tested under controlled conditions. The rocket designs, measuring 70 cm in height with a total weight of 1.5 kg, were optimized to meet performance objectives and ensure consistency across all test units.

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7. Conflict of Interest

The author declares no competing conflicts of interest.

8. Funding

No funding was received to support this study.

9. Author Biography

Jobanpreet Singh is an aerospace engineering student at Lovely Professional University, Jalandhar City, India. With over five years of experience in solid propellant rocket research, he has successfully designed, built, and launched 79 solid propellant rockets, demonstrating his expertise in experimental rocketry and research-driven projects. Beyond rocketry, Jobanpreet is also skilled in space observation, utilizing a Celestron Astromaster 130EQ telescope to explore celestial bodies and deepen his understanding of astronomy. As a prolific researcher, he has authored over 30 research papers and holds 5 patents in aerospace engineering, underscoring his dedication and contributions to the advancement of space exploration and rocketry.