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Evaluation of Solid Rocket Propellants for Low Earth Orbit

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Abstract

In contemporary aerospace technology, solid rocket propellants are commonly employed in the thriller and boost of space cargoes to LEO. These are reliable, uncomplicated, and high in thrust; and thus, can be used in both military as well as civil space ventures. This paper provides a comprehensive evaluation of five prominent solid rocket propellants: Five categories namely Ammonium Perchlorate Composite Propellant (APCP), Double-Base Propellant, Composite Modified Double Base (CMDB) Propellant, Hydroxyl-terminated polybutadiene (HTPB)-Based Propellant, and Ammonium Nitrate Composite Propellant (ANCP) have been identified. This also falls under the evaluation and includes aspects such as historical bases to see how the formulation of the propellant has changed over time regarding the development of propellant technology. In the case of each propellant, the chemical properties of the mix and reactions that its fundamental are analyzed. It also shares details regarding the changes and advancements made in the little while to enhance capability, safety, and environmental compatibility of these fuels, such as synthesizing fuels for liquid bipropellants. Some of the modern applications of technologies within the active spectrum of aerospace operations are explained in more detail to provide clients with the most versatile and essential information. Among the essentials of this work, the complex calculation of thrusts developed by the specific propellant with corresponding graphics has significant importance. These estimations afford chances of comparing the efficiency of the propellant in terms of producing thrusts as well as achieving the indicated optimal performance. Thus, the main objective of this study is to identify which of the solid rocket propellants to use in LEO missions and if any, what modifications could be made to improve them. Thus, the purpose of this paper is to contribute to the development of the constantly evolving branch of rocket propulsion by discussing the benefits and shortcomings of each propellant. These findings and recommendations could be useful in perfecting the recipes for the propellants and improving the efficiency of the subsequent missions to planets.

Keywords: Aerospace, Solid rocket propellants, Thrust, Low earth orbit.

1. INTRODUCTION

This development can only mean that as there is a need for improvement on the propulsion system in space, the aspect of solid rocket propellant increases. The following are some of the reasons why solid propellants are still important in the modern world, for example, they can easily provide high thrust, are relatively simple and very reliable, and therefore are even more important components in today's military and civil space activities. This paper focuses on evaluating five prominent solid rocket propellants: These are APCP, Double Base Propellants, CMDB Propellants, HTPB Based Propellants as well as ANCP. It is, therefore, rather impossible not to mention the fact that such kinds of propellants have been adjusted and enhanced from time to time. The new propellants of today chiefly derivate from old propellants and of these, nearly all those propellants have been produced from black power which has been coming from China for several centuries now. Probably there were little changes that were made to propellants probably because it is volatile up to the 20th century with double base propellants including nitroglycerin and nitrocellulose used in World War II. APCP's were developed by mid of the 20th century and had more relativistic specified impulse and better storage characteristics than APCP. In the last few decades, a significant proportion of research activity has been directed towards producing even better composite propellants. HTPB based and CMDB propellants are more contemporary propellants in which higher energy additives have been absorbed and variable formulation is added to get extra thrust moreover mechanical requirement is also fulfilled. This led to the development of ANCP as a substance that was harmless on the consumers since it had detrimental effects on them and the environment, it was safe to use the substance since it was not affecting the life of any living organism. To establish the chemical nature of each of the propellants, this paper will try to look at the parts that makes these propellants work or the reactions involved for these propellants to work. It also factors in modifications that have been done over the year to increase its usefulness, safety and effects brought about to the physical setting as well as the current working practices where it is being employed in space related activities. Therefore, a restricted comparison is made utilizing specific impulse together with the effective exhaust velocity. Besides, the current paper contains an analysis and numeric values as well as the plot of the force created by each propellant to give an additional assessment. These concepts shall strive to discern where to locate the pushing decisions for LEO missions and where progress might be manufactured in terms of enhanced performance and dependability. Concerning the conclusion, it is with the purpose of sharing ideas and findings on how successful or how far from the mark each one of the propellant types studied can go in furthering the rocket propulsion system, for the selection of the right constituents that could improve the viability of the subsequent space explorations.

2. LITERATURE REVIEW

There have been many advancements that has been made in rocket propulsion technology and these have led to enhanced efficiency of solid rocket propellants. In this section, Sutton and Biblarz discuss the components of rocket propulsion and provide an account of the theories as well as several types of propellants used in the rocket science [1]. Humble, Henry, and Larson delve into space propulsion analysis and design, offering detailed insights into the design considerations and performance metrics of different propulsion systems [2]. Huzel and Huang focus on modern engineering approaches for designing liquid-propellant rocket engines, highlighting the intricacies of propellant chemistry and combustion dynamics [3].

The chemistry and physics of solid propellants are thoroughly examined by Martin, who explores the chemical reactions and physical properties that influence propellant performance [4]. Summerfield discusses advances in solid propellant technology, providing an in-depth analysis of the materials and manufacturing processes that have improved propellant efficiency and stability [5]. Rocketdyne offers practical insights into the design and application of solid rocket motors, emphasizing the importance of material selection and structural integrity [6].

NASA provides a comprehensive handbook on space launch system propellants, detailing the characteristics and performance of various propellants used in space missions [7]. Zhang, Yang and Brill's paper is a study of the chemical behavior, flame propagation and reaction, and internal ballistic of solid propellants. They present a detailed account of the different factors that determine the effectiveness and productivity of these propellants [8]. Jain and Chaturvedi survey ammonium perchlorate-based composite propellants, discussing their advantages, limitations, and potential applications [9].

Parr and Sullivan address the environmental impact of solid rocket propellants, highlighting the need for environmentally friendly alternatives [10]. Knott traces the evolution of double-base propellants, exploring their historical development and modern applications [11]. Wernimont and Kennedy discuss improvements in CMDB propellant performance, focusing on the incorporation of high energy additives and advanced manufacturing techniques [12].

Kuo and Summerfield provide a fundamental understanding of solid propellant combustion, discussing the combustion mechanisms and factors that influence burn rate and efficiency [13]. Miller examines the development of HTPB-based propellants, highlighting their advantages and applications in modern rocketry [14]. Venkataramani discusses advances in ANCP propellant technology, focusing on improvements in performance and environmental impact [15].

SpaceX and Aerojet Rocketdyne provide insights into the innovations in rocket propulsion systems, discussing the latest advancements in propellant technology and their applications in space missions [16][17]. The European Space Agency (ESA) offers a comprehensive overview of solid propellant rocket motors, discussing their design, performance, and applications in space exploration [18]. The U.S. Department of Defense highlights the military applications of solid propellants, discussing their performance, reliability, and safety considerations [19]. Kumar and Singh discuss the environmental and performance considerations of rocket propellants, emphasizing the need for sustainable and efficient propellant solutions [20].

3. Solid Rocket Propellants

3.1. History

Solid rocket propellants have a long and storied history, dating back to ancient China where black powder rockets were first used. The development of solid propellants progressed significantly in the 20th century, particularly during World War I and II. During these wars, double-base propellants, which combined nitroglycerin and nitrocellulose, were developed, and widely used in military applications such as artillery shells and small rockets [11]. The mid-20th century saw the introduction of Ammonium Perchlorate Composite Propellant (APCP), marking a significant advancement in propellant technology. APCP was first used in military applications and later adapted for space exploration, offering improved performance and storage stability [1]. Composite Modified Double Base (CMDB) propellants were developed later in the twentieth century by addition of high energy ingredients to the composition to receive further enhancements [12]. Hydroxyl-terminated polybutadiene (HTPB) based propellants appeared in the modern epoch because they can be designed according to need and possess superior mechanical properties [14]. Ammonium Nitrate Composite Propellants (ANCP) were developed as environmentally friendly alternatives to traditional composite propellants, focusing on reducing toxicity and environmental impact [15].

3.2. Chemical Properties

The chemical properties of solid rocket propellants determine their performance, stability, and handling characteristics. Ammonium Perchlorate Composite Propellant (APCP) is composed of ammonium perchlorate ($NH4ClO4$) as the oxidizer, aluminum powder (Al) as the fuel, and hydroxyl terminated polybutadiene (HTPB) as the binder [1][9]. This combination results in a propellant with a density ranging from 1.7 to 1.9 g/cm³, a specific impulse of 250 to 300 seconds, and an effective exhaust velocity between 2,452.5 and 2,943 m/s [8][14]. Double-base propellants consist of nitroglycerine (NG) and nitrocellulose (NC), serving as both fuel and oxidizer [11]. These propellants have a density of approximately 1.6 g/cm³, a specific impulse of 220 to 250 seconds, and an effective exhaust velocity between 2,158.2 and 2,452.5 m/s [13]. Composite Modified Double Base (CMDB) propellants combine nitroglycerin (NG), nitrocellulose (NC), and high-energy additives like RDX (Cyclotrimethylenetrinitramine) [12]. These propellants exhibit a density of 1.6 to 1.8 g/cm³, a specific impulse of 240 to 270 seconds, and an effective exhaust velocity between 2,354.4 and 2,650.7 m/s [13]. HTPB-based propellants use ammonium perchlorate ($NH4ClO4$) or ammonium nitrate ($NH4NO3$) as the oxidizer, aluminum powder as the fuel, and hydroxyl-terminated polybutadiene as the binder [14]. These propellants have a density of 1.8 to 1.9 g/cm³, a specific impulse of 250 to 290 seconds, and an effective exhaust velocity between 2,452.5 and 2,843.9 m/s [8]. Ammonium Nitrate Composite Propellant (ANCP) is composed of ammonium nitrate ($NH4NO3$) as the oxidizer, aluminum powder or other metal powders as the fuel, and hydroxyl-terminated polybutadiene or other polymers as the binder [15]. ANCP has a density of 1.6 to 1.8 g/cm³, a specific impulse of 200 to 250 seconds, and an effective exhaust velocity between 1,962 and 2,452.5 m/s [15].

3.3. Upgradations

The evolution of solid rocket propellants has been marked by continuous improvements and refinements. Ammonium Perchlorate Composite Propellant (APCP) has seen advancements in binder properties and particle size optimization to enhance performance and reduce environmental impact [1]. Double-base propellants have remained relatively unchanged in their basic formulation, but improvements have been made in stabilizers and plasticizers to enhance performance and shelf life [11]. Composite Modified Double Base (CMDB) propellants have incorporated high-energy additives and plasticizers to significantly improve performance and make them more versatile for various applications [12]. HTPB-based propellants have benefited from continuous improvements in binder technology and particle size optimization, enhancing their performance and mechanical properties [14]. Ammonium Nitrate Composite Propellants (ANCP) have focused on enhancing the moisture resistance of ammonium nitrate and optimizing the binder system to improve performance and reduce environmental impact [15].

3.4. Current Use

Ammonium Perchlorate Composite Propellant (APCP) is widely used in space launch vehicles, military missiles, and commercial launch vehicles. Its high performance and good storage stability make it a preferred choice for many applications [1][8]. Double-base propellants are used in small rockets, artillery shells, and various military applications due to their simplicity and reliable performance [11]. Composite Modified Double Base (CMDB) propellants are used in tactical missiles, space launch vehicles, and specialized military applications, offering a good balance between performance and complexity [12]. HTPB based propellants.

3.5. Efficiency

The effectiveness of solid rocket propellants is normally measured using specific impulse and the effective exhaust velocity. The solid-propellant type is Ammonium Perchlorate Composite Propellant (APCP); it has the highest specific impulse hence is considered efficient. Once again, double-base propellants have a lesser specific impulse than the composite rocket propellants. The appropriate richness has Composite Modified Double Base (CMDB) types that offer good propellant performance without much difficulty in design. HTPB based propellants exhibit high performance and the specific formulation can be designed in a very flexible manner. Ammonium Nitrate Composite Propellants (ANCP) have desirable features in terms of environmental factors although they are less effective than APCP.

4. Estimation of Thrust Production

4.1. History of Thrust Production Estimation

As for the evaluation of the thrust production in rocket propulsion, it is noteworthy that the process has undergone a great evolution. The initial approaches to analyze the thrust production were mainly qualitative and by relying on the observations and experiments. Later, with the help of the principles of modern physics and engineering the more precise theoretical models appeared. The principles set down by Sir Isaac Newton early in the 18th century concerning the laws of motion are clearly involved in the apprehension of the connection between mass, acceleration, and force on which thrust computations are based. Since the mid-1900's rocket propulsion theory was further enhanced in terms of the mathematical and computational efficacies incorporated in its advancement. These enabled the establishing of better estimates of the thrusts determined by the specific impulse and mass flow rate of the propellant.

4.2. Revised Derivation

The thrust (F) produced by a rocket engine can be derived from Newton's second law of motion. The thrust produced by the exhaust gases is proportional to the change in momentum of the gases. This can be expressed as:

$$F = \dot{m} \cdot v_e$$

where:

- $\dot{m}$ is the propellant's mass flow rate,
- v_e is the effective exhaust velocity.

The effective exhaust velocity (v_e) can be related to the specific impulse (I_{sp}) by the equation:

$$v_e = I_{sp} \cdot g_0$$

Substituting this into the thrust equation gives:

$$F = \dot{m} \cdot I_{sp} \cdot g_0$$

This formula allows for the calculation of thrust based on the specific impulse and the propellant's mass flow rate.

4.3. Calculations for All Five Propellants

The values of the thrust force (F) and effective exhaust velocity (v_e) are obtained through assessments of two important values i.e., the propellant's mass flow rate ($\dot{m}$) and the specific impulse (I_{sp}) of each propellant. For simplicity it is assumed that the mass flow rate is 100 kg/s for all calculations. The specific impulse, measured in seconds, represents standardized performance for each propellant, typically derived from experimental results. The gravitational acceleration (g_0) is as 9.81 m/s^2, which is the standard value used in these calculations.

I. Ammonium Perchlorate Composite Propellant (APCP):

- Specific Impulse (I_{sp}): 275 $secs$
- Thrust Calculation (F):
- $F = 100\ kg/s \cdot 275\ s \cdot 9.81\ m/s^2 = 269{,}775$ N
- Effective Exhaust Velocity (v_e):
- $v_e = 275\ s \cdot 9.81\ m/s^2 = 2{,}697.75\ m/s$

II. Double-Base Propellant:

- Specific Impulse (I_{sp}): 235 $secs$
- Thrust Calculation (F):
- $F = 100\ kg/s \cdot 235\ s \cdot 9.81\ m/s^2 = 230{,}535$ N
- Effective Exhaust Velocity (v_e):
- $v_e = 235\ s \cdot 9.81\ m/s^2 = 2{,}304.35\ m/s$

III. Composite Modified Double Base (CMDB) Propellant:

- Specific Impulse (I_{sp}): 255 $secs$
- Thrust Calculation (F):
- $F = 100\ kg/s \cdot 275\ s \cdot 9.81\ m/s^2 = 250{,}155$ N
- Effective Exhaust Velocity (v_e):
- $v_e = 275\ s \cdot 9.81\ m/s^2 = 2{,}500.55\ m/s$

IV. HTPB-Based Propellant:

- Specific Impulse (I_{sp}): 270 $secs$
- Thrust Calculation (F):
- F = 100 kg/s · 270 s · 9.81 m/s^2 = 264,870 N
- Effective Exhaust Velocity (v_e):
- v_e = 275 s · 9.81 m/s^2 = 2,646.7 m/s

V. Ammonium Nitrate Composite Propellant (ANCP):

- Specific Impulse (I_{sp}): 225 $secs$
- Thrust Calculation (F):
- F = 100 kg/s · 225 s · 9.81 m/s^2 = 220,725 N
- Effective Exhaust Velocity (v_e):
- v_e = 275 s · 9.81 m/s^2 = 2,207.25 m/s

5. RESULT AND DISCUSSION

I. Comparison of Thrust Production

From the analysis of thrust production and the effective exhaust velocities, it can be understood that in terms of performance among the solid propellants, the Ammonium Perchlorate Composite Propellant (APCP) and HTPB based propellants have the best numbers. APCP has attracted much attention because of its high specific impulse and effective exhaust velocity, thus it can be widely applied to space launch vehicles and military vehicles. HTPB also provides adequate thrust and compatibility with customization with respect to facility requirements and primary uses.

II. Significant Point for Thrust Production Hikes

When it comes to the production of thrust, the aluminum powder used in APCP as well as in HTPB based propellants is a major factor. Aluminum powder has a high energy of mixture and combustion ratio, which in turn improves the performance of the propellant.

III. Significant Weakness in Propellants with Low Thrust

Double-base propellants have lesser thrust than the other solid propellants that were discussed here. The only disadvantage that can be noted regarding it is their specific impulse that is lower in comparison to other types of rocket engines and thus, the efficiency and efficacy of the system is relatively low. Also, uncontrolled combustion results into emission of hazardous fumes, which is environmentally and safety wise hazardous.

IV. Upgrades to Improve Thrust Production

Regarding the advancement of the lesser thrust-providing propellants such as the double-base propellant, one can opt to use high energetic additives and fine-tune the binder system. For example, incorporating RDX or other rapidly burning chemicals raises the specific impulse and thrust generation.

V. Relationship Between Thrust Production and Exhaust Velocity

Closely related with the exhaust velocities is the thrust production in other words the formula $F = \dot{m} \cdot v_e$. Thus, with higher exhaust velocities, there is more thrust and hence, a better propulsion system efficiency.

VI. Justification

The application of the hypotheses as well as the results obtained in this study underscore the importance of impulse and exhaust velocity of solid rocket propellants. So, it is easy to understand that the enhancement in the noted parameters through further developments in formulation of chemicals used in propulsion system and its manufacturing can lead to tremendous boost in thrust and performance.

VII. Graph of Thrust and Exhaust Velocity

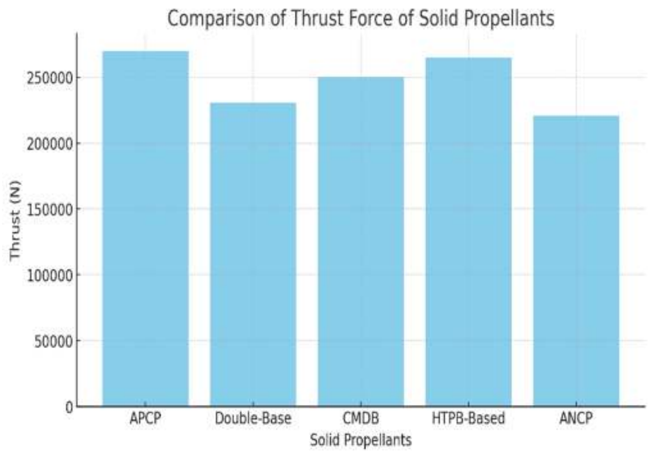

Figure 1: Thrust Force Comparison of Solid Rocket Propellants

The following graph shows the comparison of thrust and the effective exhaust velocity of the five types of solid rocket propellants. Thus, it can be claimed that propellant based on APCP and HTPB gives the highest indexes of performance and can be used for high-demanded operations.

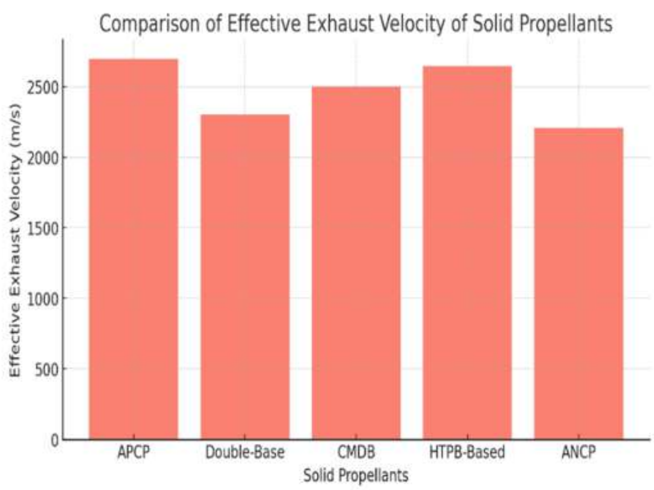

Figure 2: Effective Exhaust Velocity Comparison of Solid Rocket Propellants

The following graph shows the effective exhaust velocities of five solid rocket propellants. From the obtained results, it can be concluded that the APCP and HTPB based propellants achieved the highest velocities, which indicates the effectiveness from the perspective of the aspect of propelling.

SL NO.	*Solid Propellant*	*Thrust (kN)*	*Exhaust Effective Velocity (m/s)*
1.	*APCP*	*269.775*	*2,697.75*
2.	*Double Base*	*230.535*	*2,304.35*
3.	*CMDB*	*250.155*	*2,500.55*
4.	*HTPB-Based*	*264.870*	*2,646.70*
5.	*ANCP*	*220.725*	*2,207.25*

Table 1: Comparative Analysis of Solid Rocket Propellants

The following table reveals that the Ammonium Perchlorate Composite Propellant (APCP), and HTPB based propellant have given the maximum thrust values, which indicates that among the identified solid rocket propellants, these two kinds of propellants have outperformed others.

6. SCOPE OF FUTURE WORK

For the solid rocket propellants, the future will also entail the search for new materials which will result in higher performance but at lesser emission to environment. Further studies on nanotechnology and particularly, it's possible use in developing new propellant recipes could possibly result in improvements to certain impulse and combustion ratio. Also, the creation of clean propulsion systems including green oxidizers and fuel systems will be significant in meeting the future societal regulation and influence on sustainable technologies. It is also important to note that incorporation of technology like 3D printing, specifically in the production of Additive Manufacturing for solid rocket propellants can still bring about a major change in how the solid rocket propellant grains that are produced.

7. CONCLUSION

In sum, based on this detailed analysis of the solid rocket propellants options for LEO mission, the strengths, and the drawback of each have been outlined. Among the propellants, the ones based on APCP and HTPB exhibit the best performance and are used in high-performance models. Double-base propellants are easier and safer for small scale use while CMDB propellants are relatively better in effectiveness but comparatively complex in construction. In general, ANCP is safer and has lesser negative impact on the environment, though it offers lower efficiency than VANET. In fact, the use of solid propellants remains to this date due to steady upgrades that seek to optimize the functionality of rocket using solid propellants as power source today and in the future through research.

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