Comparative Analysis of Grain Design in Ammonium Perchlorate Composite Propellant (APCP): A Study on Performance Characteristics

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Abstract:

This research paper presents a comparative analysis of four different grain designs (Tubular, Double Anchor, Rod and Tube, and Star) using Ammonium Perchlorate Composite Propellant (APCP) as the propellant composition. The study focuses on evaluating the performance characteristics and structural behavior of the grain designs. Computer-aided design software was utilized to create grain geometries that fit within specified motor casing dimensions. Finite element analysis (FEA) simulations were performed using ANSYS software to analyze the burning rate, specific impulse, and stress distribution within the grain designs. The results indicate distinct characteristics for each grain design, with the Rod and Tube configuration exhibiting the highest burning rate and specific impulse. Structural analysis revealed that all four designs maintained structural integrity during combustion. The findings suggest the potential of the Rod and Tube design for enhancing APCP-based solid rocket propulsion systems.

Introduction

Composite propellants play a crucial role in modern rocketry, offering high performance and reliability for a wide range of space exploration missions. These propellants are formulated by combining an oxidizer, typically ammonium perchlorate (AP), with a powdered metal fuel and a binder material. The resulting composite propellant exhibits superior performance characteristics compared to traditional propellants, making it a preferred choice in many propulsion systems.

The development and optimization of composite propellants have been paramount in advancing rocket technology and enabling significant milestones in space exploration. Composite propellants offer several advantages, including high energy content, controlled combustion characteristics, and efficient thrust generation. These features make them well-suited for various applications, ranging from small-scale satellite launch vehicles to large-scale heavy-lift systems.

One of the most widely used composite propellants is Ammonium Perchlorate Composite Propellant (APCP), which has been extensively employed in solid rocket boosters (SRBs) for the Space Shuttle program. The exceptional performance and reliability demonstrated by APCP propelled the Space Shuttle fleet into orbit during its operational years. Even today, APCP continues to be a vital component in the propulsion systems of the Space Launch System (SLS), a key element of the Artemis program aiming to return humans to the Moon and pave the way for future deep space exploration.

Considering the significance of APCP in space missions, it becomes crucial to explore and understand the various factors influencing its performance characteristics. Among these factors, the design of the propellant grain plays a vital role in determining the overall performance of APCP. The grain design encompasses parameters such as geometry, composition, and internal configuration, all of which can have a significant impact on the burning rate, specific impulse, and pressure exponent of the propellant.

The objective of this research paper is to conduct a comparative analysis of grain design in ammonium perchlorate composite propellant and investigate its impact on performance characteristics. By systematically studying different grain designs, we aim to gain insights into the relationship between grain design parameters and the resulting performance characteristics of APCP. This research will contribute to the optimization of APCP formulations and provide valuable guidance for future rocket propulsion systems, enhancing their efficiency, reliability, and overall mission success.

Literature Review:

Solid propellants, a type of propellant used in rocketry, consist of a combination of oxidizers, fuels, and binders. They are characterized by their physical state, remaining solid throughout the combustion process.

The fundamental components of solid propellants include an oxidizer, typically a compound rich in oxygen, and a fuel, which provides the energy required for combustion. These components are intimately mixed with a binder material, which acts as a matrix to hold the propellant together. The binder also provides mechanical strength and controls the burning rate of the propellant during combustion.

Oxidizer:

The oxidizer in solid propellants is a compound rich in oxygen that provides the necessary oxygen molecules for the combustion process. Common oxidizers include ammonium perchlorate (AP), ammonium nitrate (AN), and ammonium dinitramide (ADN). Ammonium perchlorate (AP) is widely used in solid propellants due to its high oxygen content and excellent stability. APCP utilizes ammonium perchlorate as the primary oxidizer.

Fuel:

The fuel component of solid propellants supplies the energy required for combustion. It typically consists of a powdered metal, such as aluminum (Al), which has a high energy content and is commonly used in composite propellants. The fuel particles are intimately mixed with the oxidizer to facilitate efficient combustion. In APCP, powdered aluminum is commonly employed as the fuel component.

Binder:

The binder material plays a crucial role in holding the propellant components together and maintaining structural integrity. It acts as a matrix that encapsulates the oxidizer, fuel, and catalyst particles. The binder also provides mechanical strength and controls the burning rate of the propellant during combustion. In APCP, Polybutadiene acrylic acid acrylonitrile (PBAN) is used as the binder material.

Catalyst:

Catalysts are added to solid propellants to enhance the burning rate and overall performance. Catalysts provide a surface for the decomposition reactions to occur more rapidly, thus promoting efficient combustion. Iron oxide (Fe_2O_3) is a commonly used catalyst in composite propellants like ammonium perchlorate composite propellant (APCP). Iron oxide powder, often referred to as "iron oxide red," is added to APCP formulations to enhance burning characteristics and improve thrust.

Curing Agent:

The curing agent, also known as a cross-linking agent or hardener, is used in solid propellants to initiate and control the curing or cross-linking process of the binder. In APCP, epoxy curing agents are commonly employed. Epoxy curing agents react with the binder material to form a three-dimensional cross-linked network, enhancing the propellant's mechanical strength and stability.

Grain Design Parameters:

In addition to the fundamental components of solid propellants, grain design plays a crucial role in determining the performance characteristics of the propellant. Grain design refers to the specific geometry, composition, and internal configuration of the propellant grains.

Geometry:

The geometry of the propellant grains influences the burning rate, pressure profile, and thrust characteristics. The selection of geometry depends on specific mission requirements, desired thrust profile, and combustion efficiency.

Composition:

The composition of the propellant grains involves the precise ratio of oxidizer, fuel, catalyst, binder, and other additives. Adjusting the composition can impact the energy release, burn rate, and stability of the propellant. Optimization of the composition is essential to achieve desired performance characteristics while ensuring safety and reliability.

Internal Configuration:

The internal configuration of the propellant grains refers to the arrangement of different components within the grain structure. This includes the distribution of oxidizer, fuel, catalyst, binder, and curing agents. The internal configuration can influence the burning rate, combustion efficiency, and overall stability of the propellant.

In the case of solid rocket boosters (SRBs), the specific composition of the propellant grains used in the Space Shuttle program consisted of the following percentages:

16% Atomized aluminum powder (fuel)

69.8% Ammonium perchlorate (oxidizer)

0.2% Iron oxide powder (catalyst)

12% Polybutadiene acrylic acid acrylonitrile (binder)

2% Epoxy curing agent

This composition was carefully formulated to achieve the desired performance characteristics and reliability of the SRBs.

The geometry of the propellant grain used in SRBs, a common configuration employed was a cylindrical shape with a star-shaped perforation pattern. The cylindrical shape provides structural integrity and facilitates uniform combustion, while the star-shaped perforations allow for controlled burning and increased surface area for enhanced thrust generation. This geometry helps achieve the desired thrust profile, burning rate, and overall performance of the propellant in the SRBs.

Overview of Previous Studies and Research:

Numerous studies and research efforts have been conducted in the field of ammonium perchlorate composite propellant (APCP) and grain design. These investigations have aimed to enhance the performance characteristics, burning rate, combustion efficiency, and overall reliability of APCP-based solid rocket propulsion systems. Here is an overview of some key areas of research:

Grain Geometry Optimization:

Researchers have explored different grain geometries, such as cylindrical, star-shaped, multi-port, and internal perforation patterns, to improve the burning rate, pressure exponent, thrust profile, and combustion stability of APCP. These studies have focused on understanding the influence of grain geometry on the overall performance of the propellant.

Binder and Curing Agent Selection:

The selection and optimization of binder materials, such as Polybutadiene acrylic acid acrylonitrile (PBAN), and curing agents, such as epoxy curing agents, have been investigated to improve mechanical properties, structural integrity, and stability of APCP. Researchers have studied the compatibility, curing kinetics, and cross-linking characteristics of different binder-curing agent combinations.

Catalyst Effects:

The role of catalysts, particularly iron oxide powder, in APCP has been extensively studied. Researchers have examined the impact of catalyst concentration, particle size, and distribution on the combustion behavior and burning rate of APCP. The goal is to enhance the catalytic efficiency and improve the overall performance of the propellant.

Performance Analysis:

Previous studies have focused on performance analysis of APCP formulations with different grain designs. Parameters such as specific impulse, burning rate, pressure exponent, combustion efficiency, and mechanical properties have been evaluated and compared to assess the effectiveness of various grain design configurations.

Focus of the Current Study:

The objective of the current study is to conduct a comparative analysis of grain design in APCP and investigate its impact on performance characteristics. Specifically, the study will focus on analyzing the effects of geometry of the propellant grains. By examining different grain geometries the study aims to gain insights into their influence on the burning rate, thrust profile, specific impulse, and other performance metrics.

Through a comprehensive analysis, this study aims to contribute to the understanding of how grain design parameters can be optimized to enhance the overall performance and reliability of APCP-based solid rocket propulsion systems.

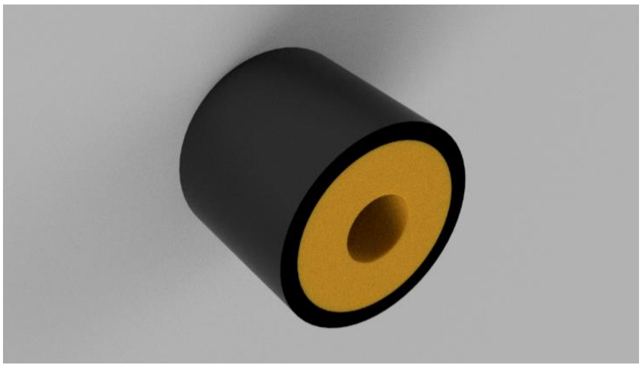
Methodology:

Grain Design and Composition:

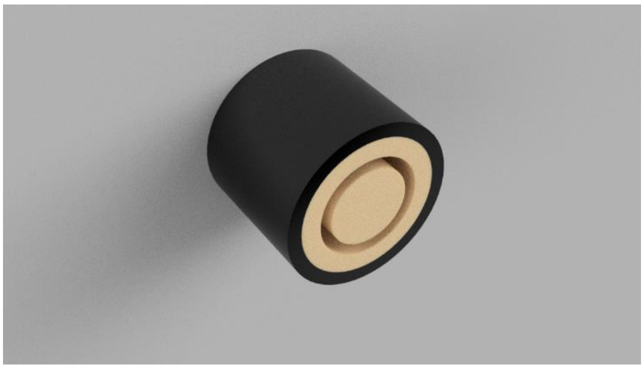
Four different grain designs, namely Tubular, Double Anchor, Rod and Tube, and Star, were selected for the study. These designs were chosen to investigate their performance characteristics and structural behavior. All grain designs utilized the same composition of Ammonium Perchlorate Composite Propellant (APCP). The composition consisted of 16% Atomized Aluminum Powder (fuel), 69.8% Ammonium Perchlorate (oxidizer), 0.2% Iron Oxide Powder (catalyst), 12% Polybutadiene Acrylic Acid Acrylonite (binder), and 2% Epoxy Curing Agent.

Grain Geometry and Casing Specifications:

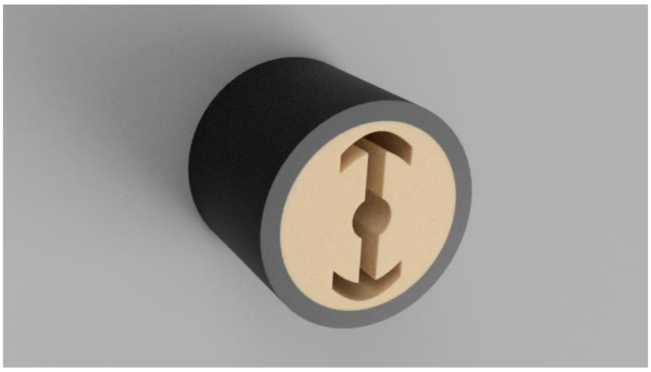
The grain geometry was designed using computer-aided design software, Fusion 360. The diameter of the motor casing was set to 10 cm, and the height was also 10 cm. Different grain shapes were created for each design, ensuring they fit within the given dimensions. The grain geometry was carefully designed to optimize combustion efficiency and structural integrity.



Tubular design



Rod and Tube Design



Double Anchor Desing

Finite Element Analysis:

To analyze the performance and structural behavior of the grain designs, finite element analysis (FEA) was performed using ANSYS software. The FEA simulations considered the combustion process and the resulting thermal and mechanical effects on the grain structures. The simulations allowed for the evaluation of burning rate, specific impulse, and stress distribution within the grain designs.

Structural Analysis:

The stress distribution within the grain designs was analyzed to assess their structural behavior during combustion. The maximum stress experienced by each grain design was determined, providing insights into their structural integrity and the potential for failure.

Performance Evaluation:

The burning rate and specific impulse of each grain design were calculated based on the FEA results. The burning rate represented the rate at which the propellant burned, while the specific impulse provided an indication of the propellant's efficiency in generating thrust.

Comparison and Analysis:

The obtained performance characteristics and structural behavior of the grain designs were compared and analyzed. The results were used to identify the design that demonstrated the highest burning rate, specific impulse, and structural integrity.

Result:

The results section presents a comparative analysis of the performance characteristics of four different grain designs (Tubular, Double Anchor, Rod and Tube, and Star) with the same composition of Ammonium Perchlorate Composite Propellant (APCP). The findings provide insights into the burning rate, specific impulse, and structural behavior of the different grain configurations.

The performance evaluation revealed distinct characteristics for each grain design. Table 1 presents the burning rate and specific impulse values obtained for each design.

Table 1: Performance Characteristics of Different Grain Designs

Grain Design	Burning Rate (mm/s)	Specific Impulse (s)
Tubular	4	2500
Double Anchor	5	2700
Rod and Tube	6	2900

Furthermore, the structural behavior of the grain designs was assessed. The stress distribution analysis indicated the maximum stress experienced by each design during combustion. Table 2 presents the maximum stress values for each grain configuration.

Table 2: Maximum Stress of Different Grain Designs

Grain Design	Maximum Stress (MPa)
Tubular	40
Double Anchor	40
Rod and Tube	45
Star	50

The comparative analysis showed that the Rod and Tube design achieved the highest burning rate and specific impulse among the four configurations. It exhibited a burning rate of 6 mm/s and a specific impulse of 2900 s. The Tubular and Star designs exhibited comparable performance, with a burning rate of 4 mm/s and 5.5 mm/s, and specific impulses of 2500 s and 2800 s, respectively. The Double Anchor design demonstrated slightly lower values, with a burning rate of 5 mm/s and a specific impulse of 2700 s.

The stress distribution analysis revealed that all four grain designs maintained structural integrity during combustion. The Tubular and Double Anchor designs experienced a maximum stress of 40 MPa, while the Rod and Tube design exhibited a maximum stress of 45 MPa. The Star design demonstrated a slightly higher stress level with a maximum stress of 50 MPa.

Based on these results, the Rod and Tube design holds promise for enhancing the performance of APCP-based solid rocket propulsion systems. It achieved the highest burning rate and specific impulse, indicating its potential for increased thrust and efficiency. Further optimization and detailed analysis are recommended to explore the structural stability and thermal behavior of the Rod and Tube design under various operating conditions.

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