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REVIEW OF REGRESSION RATE ENHANCEMENT TECHNIQUES IN HYBRID ROCKET ENGINES

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Abstract: Hybrid rocket engines (HREs) present a compelling alternative to traditional solid and liquid propulsion systems due to their inherent safety, throttle ability, and reduced environmental impact. Despite these advantages, HREs are fundamentally limited by low fuel regression rates, which often necessitate excessively long combustion chambers and lead to reduced volumetric efficiency. This paper reviews contemporary strategies for enhancing the regression rate in solid fuel grains, with a specific focus on paraffin-based systems. We evaluate various modification techniques identified in recent literature, including the implementation of advanced internal geometries such as helical, star, and multi-port designs, as well as the use of high-energy additives and swirl injection methods. Analysis shows that while paraffin-based fuels significantly boost regression rates, they suffer from poor structural integrity. This synthesis establishes a framework for the design and fabrication of modified fuel grains utilizing grid structures and precise casting processes to optimize hybrid rocket performance.

***Keywords* -** Hybrid Rocket Engines (HREs), Regression Rate, Paraffin Wax, Geometric Optimization, Droplet Entrainment, Structural Integrity, Numerical Simulation, CFD, O/F Ratio Shift.

I. INTRODUCTION

Hybrid rocket engines (HREs) represent a unique class of propulsion that combines the features of both solid and liquid systems [20]. In a typical HRE configuration, a solid fuel grain, such as Hydroxyl-terminated polybutadiene (HTPB) or paraffin wax, is reacted with a liquid or gaseous oxidizer, such as nitrous oxide or liquid oxygen. This separation of propellants provides a safer alternative to solid rockets and allows for critical operational capabilities including throttle control, engine shutdown, and re-ignition [30]. Furthermore, hybrids require simpler plumbing than liquid engines and offer a lower environmental impact compared to many conventional chemical rockets [6].

Despite these advantages, the commercial and academic application of hybrid propulsion is significantly hindered by the low fuel regression rate, which refers to the speed at which the solid fuel burns away during combustion [10]. Because the fuel burns slowly, engines often require very long combustion chambers or complex multi-port designs to achieve necessary thrust, which negatively impacts the overall size and mass efficiency of the vehicle [9]. Additionally,

HREs suffer from an Oxidizer-to-Fuel (O/F) ratio shift; as the fuel port widens during the burn, the ratio of propellants changes, leading to off-peak performance [26].

Overcoming these hurdles is vital for the growth of the hybrid propulsion market, particularly for emerging applications like reusable launch systems and space tourism [20]. Current research focuses on technological advancements such as the use of bio-derived waxes and advanced manufacturing techniques, including 3D printing, to create complex internal geometries [8]. By modifying the internal structure of the fuel grain—such as implementing helical, star, or grid-based geometries—researchers aim to increase the burning surface area and induce turbulence, thereby enhancing the regression rate [6], [9].

II. GEOMETRIC OPTIMIZATION AND PORT CONFIGURATION

The literature consistently identifies internal port geometry as a primary factor in determining the regression rate. Traditional cylindrical ports often suffer from low surface area, leading to insufficient thrust.

A. Star and Multi-Port Geometries

Research into complex configurations, such as star and rotated star geometries, demonstrates that increasing the initial burning surface area leads to higher instantaneous performance [9]. According to the surveyed data, star-shaped grains can provide a 20.6% increase in regression rate compared to standard cylindrical ports [6]. Furthermore, multi-port designs, such as 8-port configurations, have been shown to maximize fuel utilization [21]. However, these introduce complexities regarding the shifting O/F ratio as the port widens during combustion. Adaptation of fuel grain configurations is essential to tailor these designs for high-regression-rate applications [25].

B. Advanced Mold and Modular Designs

The use of 3D-printing technology has revolutionized the fabrication of complex grain shapes. Researchers have successfully designed and evaluated 3D-printed mold geometries to create intricate internal structures [8]. Furthermore, the development of composite hybrid rocket grains based on modular fuel units offers a way to enhance both regression rate and combustion efficiency by ensuring more uniform fuel consumption [21].

III. FLUID DYNAMIC ENHANCEMENTS: HELICAL AND SWIRL FLOW

Beyond static surface area, the manipulation of oxidizer flow is a critical enhancement strategy.

A. Helical Fuel Grains

Helical fuel grains are particularly effective, with experimental data indicating a regression rate increase of approximately 40.2% [6]. This is attributed to the induction of centrifugal forces and increased turbulence, which thins the thermal boundary layer and promotes heat transfer to the fuel surface. The interaction of multiple steps and geometric transitions within the grain can further influence these local regression rate profiles [7].

B. Swirl Injection and Recirculation Zones

The introduction of swirl injection is another powerful method to increase fuel consumption rates [4]. Swirl injectors create recirculation zones, often enhanced by Forward-Facing Steps (FFS) or Backward Facing Steps (BFS) within the grain [6]. These zones increase the residence time of propellants and trap heat near the fuel surface, significantly boosting combustion efficiency [11].

IV. ADVANCED FUEL FORMULATIONS AND ADDITIVES

A significant portion of recent research focuses on "liquefying fuels," primarily paraffin wax [24].

A. The Droplet Entrainment Effect

Unlike traditional HTPB, paraffin forms a thin liquid layer on the fuel surface, allowing for a "droplet entrainment" effect where liquid fuel is mechanically stripped into the gas stream [30]. This allows paraffin to achieve regression rates 3 to 4 times higher than conventional fuels [24]. Extensive testing, including scale-up tests at NASA Ames, has confirmed the high performance of these paraffin-based fuels when used with gaseous oxygen oxidizers [24].

B. Energetic and Nano-Additives

To further enhance performance, the literature suggests the inclusion of energetic additives. Magnesium-Aluminum (Mg-Al) additives can increase regression rates by up to 35% [6]. Carbon Black is utilized to improve the fuel's opacity and radiative heat absorption [24]. Additionally, the characterization of paraffin-based fuels loaded with nano-additives has shown significant improvements in thermal properties and burn rates [23].

V. NUMERICAL SIMULATION AND COMPUTATIONAL ANALYSIS

Numerical investigations are essential for predicting engine behavior and optimizing designs before physical testing [5].

A. Modeling Regression and Shape Change

Numerical simulations are used to analyze the fuel regression rate in lab-scale engines, particularly those utilizing swirl injection [4]. These simulations track the fuel shape change during the burn, which is critical for understanding how the engine's performance evolves over time [5]. Ballistic reconstruction of small-scale tests helps validate these numerical models against experimental data [3], [28]

B. Classical and Advanced Models

While classical diffusion-limited regression rate models provide a foundational understanding [10], [27], modern CFD techniques allow for more detailed analysis of the swirling flows and their impact on the thermal boundary layer [5]. Numerical investigations into star-segmented rotation grains have also been performed to evaluate their potential for high performance [16] [26].

C. Optimization through Genetic Algorithms

To achieve optimal engine performance, advanced computational tools like Genetic Algorithms (GA) are employed [19]. These are used in combination with adaptive basis function construction for the design of complex "Finocyl" grain geometries [18] [19]. Such optimization strategies help in designing motors that maintain stable thrust and efficiency throughout the flight envelope [2].

VI. STRUCTURAL INTEGRITY AND THE ARMORED GRAIN

While paraffin-based fuels significantly boost regression rates, they suffer from poor structural integrity due to their inherent brittleness [1].

To address this, researchers have explored "armored grain" strategies, such as the use of 3D-printed ABS grid structures to provide a mechanical skeleton [1]. This reinforcement balances the fuel's high-speed combustion with the necessary structural reliability. Modern manufacturing tools like CATIA V5 are utilized for precise modeling of these reinforced grains to ensure the "O/F ratio shift" is minimized while maintaining robustness [26]. Performance analysis of additively manufactured fuels confirms that these integrated skeletons can withstand the stresses of high-regression-rate combustion [22].

VII. PERFORMANCE PARAMETERS

The primary performance parameters for HREs categorize how effectively the system converts chemical energy into thrust.

Table 1 – Performance Parameters

Parameter	Unit	Definition	Importance in Hybrids
Regression Rate	*mm/s*	Linear rate at which the solid fuel surface recedes [10]	Determines engine length and thrust; typically diffusion-limited.
Specific Impulse	*s*	Measure of propellant efficiency (typically 280-350s) [30]	Determines the rocket's payload capacity.
O/F Ratio	-	Mass ratio of oxidizer to fuel [26]	Shifts as port diameter increases, affecting performance and stability.
Combustion Efficiency	-	Efficiency of mixing (C-Star) [11]	Evaluates how well the fuel and oxidizer mix.
Thrust	*N*	Total pushing force [30]	Controlled by oxidizer mass flow throttling.

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