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Advancements in Hybrid Rocket Motor Technology: Safety, Performance, and Applications

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ABSTRACT

Hybrid rocket propulsion is a unique propulsion system that combines elements of both solid and liquid rocket engines. It offers several advantages over traditional rocket propulsion systems, such as increased safety, simplicity, and controllability. This abstract provides an overview of hybrid rockets, their working principles, and the current state of research and development in this field. The fundamental concept of a hybrid rocket involves using a solid fuel grain and a liquid or gaseous oxidizer. The solid fuel grain, typically composed of a rubber-like compound, is ignited and burns in the presence of the oxidizer, resulting in the generation of hot gases. These gases are expelled through a nozzle, creating thrust and propelling the rocket forward. Both liquid fuel and solid fuel rocket motor parts can be found in a hybrid rocket engine. The oxidising agent is typically liquid (hydrogen peroxide or liquid oxygen), although the fuel itself is typically a solid grain (paraffin or hydroxyl-terminated polybutadiene, or HTPB). These parts are united in the hybrid motor's fuel chamber, which also serves as the combustion chamber. This paper examines the technical developments that have occurred since 1995 in the creation of these motors. There are techniques for monitoring the combustion reaction products in the rocket plume and testing the rocket motors' thrust.

Keywords: Applications, Advantages, Hybrid rocket motors, Limitations

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INTRODUCTION

It is optimal to use rocket engines to propel spacecraft and some weapon systems because they not only carry their own oxidizer (making the propulsion independent of the surrounding atmosphere), but also offer a high energy system. A combustion chamber and a nozzle can be thought of as the two main components of every rocket engine. The combustion chamber is in charge of generating hot, highly pressurised gases. Gases are ejected from the nozzle at a high velocity (on the order of 2-3 kin/s), effectively converting thermal energy into kinetic energy. Thrust is produced by the exhaust gases' increased motion. A hybrid rocket motor is a type of rocket propulsion system that combines features of both solid and liquid rocket engines. It operates by using a solid fuel and a liquid or gaseous oxidizer, which are typically stored separately. When ignited, the oxidizer is injected into the combustion chamber, where it reacts with the solid fuel to produce thrust. The basic components of a hybrid rocket motor include the combustion chamber, fuel grain, oxidizer injection system, and nozzle. The combustion chamber houses the fuel grain and provides the space for the combustion process to occur. The fuel grain, usually a solid material such as rubber or a plastic-based compound, is designed to burn steadily and provide a controlled release of energy.

The oxidizer, which can be a liquid or gaseous substance like nitrous oxide (N_2O), is stored separately from the fuel grain. It is typically stored in a high-pressure tank and injected into the combustion chamber through a valve or injector system. The oxidizer reacts with the fuel grain, generating hot combustion gases that are expelled through a nozzle to create thrust. One significant advantage of hybrid rocket motors is their inherent safety compared to traditional solid and liquid rocket engines. Since the oxidizer and fuel are stored separately, the risk of accidental detonation or explosion is reduced. Additionally, hybrid motors can be easily throttled or shut down by controlling the flow of oxidizer, allowing for greater control over thrust. Some of the characteristics of solid- and liquid-fuel rocket motors are combined to create a hybrid rocket motor. However, the hybrid motor operates differently from solid or liquid fuel rockets. The solid fuel rocket motor really uniformly blends fuel and oxidizer into a single solid mass, which is ignited by a flame at the exposed end and burns to produce gases that propel the rocket motor. Until ignition, when they are mixed at the injector port and become combustible, the liquid fuel rocket motor keeps the fuel and oxidizer apart in separate chambers. Therefore, the combustion chamber of a solid fuel rocket is the same size as the fuel chamber.

The components are combined in a tiny combustion chamber on the liquid fuel rocket. Nevertheless, both types of rockets burn their fuel and oxidizer in a homogenous mixture in the combustion chamber. The liquid oxidizer and solid fuel are kept apart in a chamber in the hybrid rocket motor. There is a changing ratio of oxidizer to fuel inside the combustion chamber because the fuel ignites when it comes into touch with the liquid oxidizer. Therefore, the average makeup of the oxidizer/fuel mixture governs motor performance [1].

History of Hybrid Rocket Motor

The history of hybrid rockets is as old as the evolution of rocket engines in general. When liquid and solid fuel rockets were developed in the 1930s, the first rocket motors were being developed as discussed below:

Early Concepts and Experiments (mid-20th century): The idea of hybrid rocket propulsion emerged in the 1940s and 1950s. Scientists and engineers began exploring the concept of using a solid fuel grain with a liquid or gaseous oxidizer. Early experiments focused on small-scale prototypes and proof-of-concept demonstrations.

British Hybrid Experiments (1960s): In the 1960s, British aerospace engineer Stephen Jacob initiated significant research on hybrid rocket motors. His work at the Royal Aircraft Establishment (RAE) involved investigating various fuel and oxidizer combinations, including rubber-based fuels and nitrous oxide as the oxidizer.

Space Shuttle Solid Rocket Boosters (1970s): Although not true hybrids, the Space Shuttle Solid Rocket Boosters (SRBs) incorporated some hybrid-like features. The SRBs used a solid propellant, but the inclusion of a liquid oxidizer called ammonium perchlorate in the mixture allowed for controlled thrust modulation during flight.

Development of Amateur Hybrid Motors (1980s): In the 1980s, the development of hybrid rocket motors gained traction in the amateur rocketry community. Hobbyists began experimenting with various fuel formulations and oxidizer injection techniques, leading to the creation of reliable and cost-effective hybrid motors for recreational use.

NASA Hybrid Research (1990s): NASA's Hybrid Rocket Engine Development Program, initiated in the 1990s, aimed to explore the feasibility and potential advantages of hybrid propulsion for space applications. NASA conducted extensive research and development, investigating advanced fuel formulations, injectors, combustion stability, and performance optimization.

Commercial Applications (2000s): The 21st century witnessed an increasing interest in hybrid rocket motors for commercial purposes. Companies like Armadillo Aerospace and XCOR Aerospace explored hybrid propulsion systems for suborbital space tourism vehicles. These endeavours aimed to capitalize on the safety, simplicity, and reliability aspects of hybrid motors.

Recent Advances and Projects: In recent years, hybrid rocket motor technology has continued to advance. Research focuses on enhancing performance, efficiency, and reliability through innovative fuel grain designs, novel oxidizer combinations, and improved combustion processes. Additionally, hybrid motors are being considered for niche applications such as CubeSat propulsion and sounding rockets.

Overview of Hybrid Rocket Motor

A hybrid motor uses propellants that are stored in separate stages, which is different from other rocket propulsion systems. Typically, liquid oxidizer and solid fuel are employed. A reversed hybrid configuration is the opposite. The fuel, which is often a polymer, is kept in a case. Depending on the desired thrust, the form of the fuel cross section is typically either a ring or a star [2].A combustion chamber is positioned inside a fuel grain's internal port. The heat transmission through convection and radiation causes the inner fuel surface to melt and vaporise. A liquid oxidizer is pumped into the combustion chamber. Because there is only one liquid propellant used in a hybrid, the injector plate is much simpler than it is in a liquid rocket engine. The close vicinity of the fuel inner surface is where the mixture creation and combustion process occur. At Fig. 1, a hybrid motor system is displayed.

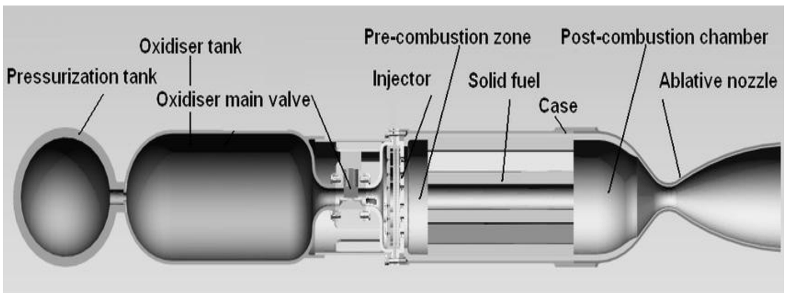

Fig. 1 Hybrid Rocket Motor Scheme

A second vessel is needed for a hybrid motor, where the afterburning process takes place. A post-combustion chamber is what it is termed. Because there isn't enough time or room in the inner port for complete combustion, this chamber is crucial. A convergent-divergent nozzle is the thruster. Systems for feeding liquid oxidizers may be pressurising or turbo pump systems. One of the three chemical rocket propelling systems that are now in use are hybrid rocket motors. The physical phase that the chemical reactants are held in the rocket motor defines this classification type. The fuel and oxidizer of a solid rocket motor (SRM1) are typically an ammonium perchlorate-based oxidizer that is carefully blended with aluminium powder in a polymeric matrix (typically HTPB2). To create the propellant grain, this combination is cast inside the combustion chamber. Fuel and oxidizer are both liquids in a liquid rocket motor (LRM3). A hybrid rocket motor is a type of propulsion system that combines features of both solid and liquid rocket engines. It operates by utilizing a solid fuel and a liquid or gaseous oxidizer, which are typically stored separately. When ignited, the oxidizer is injected into the combustion chamber, where it reacts with the solid fuel to produce thrust.
The basic components of a hybrid rocket motor include:

Combustion Chamber
This is the primary component where the combustion process takes place. It houses the fuel grain and provides the necessary environment for the controlled burning of the fuel.

Fuel Grain
The fuel grain is a solid material, often made of rubber or a plastic-based compound that serves as the propellant. It is designed to burn steadily and provide a controlled release of energy. The geometry and configuration of the fuel grain play a crucial role in determining the motor's performance.

Oxidizer Injection System
The oxidizer, which can be a liquid or gaseous substance such as nitrous oxide (N2O), is stored separately from the fuel grain. It is typically stored in a high-pressure tank and injected into the combustion chamber through a valve or injector system. The oxidizer combines with the fuel grain to initiate and sustain combustion.

Nozzle
The nozzle is responsible for directing and accelerating the hot combustion gases generated by the combustion process. It is designed to optimize the flow of exhaust gases and generate the desired thrust.

Some key benefits of hybrid rockets are as follows [3].

Safety
Due to the inert nature of the hybrid rocket fuel, handling is quite safe. The hybrid system, in contrast to an SRM, is non-explosive since it is impossible to thoroughly mix the fuel and oxidizer. As a result, a hybrid system that has been constructed can be handled, stored, and moved with fewer limitations than an SRM.

Simplicity
As the oxidizer flow in the combustion chamber determines the combustion in a hybrid system, the system can be controlled by simply adjusting the oxidizer flow rate using a valve. As a result, a hybrid system may be throttled considerably more easily than an LRE, where it is necessary to control two flow rates while maintaining a specific ratio of fuel and oxidizer. The hybrid system can also be turned off thanks to the control of the oxidizer flow, which adds to its practicality and safety.

Propellant Versatility
A wide variety of fuels are available for hybrid systems. As opposed to liquid rockets, solid additions like energetic metals can be used to boost performance. Additionally, liquid oxidizers frequently offer substantially higher specific impulse than what is seen for solid rockets. Due to the large variety of propellants available for hybrid systems, they can be utilised in almost any situation where rockets are deployed, with sounding rockets, tactical missiles, and space engines being the most common uses.

Low Cost
Because hybrid systems are more straightforward than liquid rockets and safer than solid rockets, their overall operational costs are frequently cheaper for hybrids than for liquid and solid rockets. For a variety of reasons, hybrid rockets may be less expensive than conventional propulsion systems. The hybrid rocket offers a number of benefits in terms of development, handling, and storage. The previously mentioned safety features of hybrid rocket motors reduce operational expenses. It is undoubtedly easier to manage a non-explosive system with difficult-to-assemble reactants during ground operations. Additionally, the inert nature of the fuel grain suggests that production costs are lower than those associated with solid propellant production [4,5].

Reliability

Hybrid rocket motors have a reputation for high reliability. The separation of oxidizer and fuel eliminates the possibility of chemical interactions during storage, which can degrade the propellant or cause instability. This separation also reduces the risk of combustion instability, making hybrids more reliable and predictable.

Controllable Oxidizer Mass Flow

The mass flow of the oxidizer into the combustion chamber can be managed, if required. Two important effects result from controlling the oxidizer mass flow: first, throttling can be achieved by commanding the engine's thrust on demand; second, the thrust can be stopped (the mission can be aborted), and if an appropriate ignition system is used, the motor can be repeatedly started and stopped.A liquid system can also achieve throttle ability and restart ability, but as was already said, the mechanical complexity of the control system of a liquid motor is twice that of a hybrid system. These qualities are challenging to achieve in solid rocket engines. Due to the complexity of SRM thrust termination systems, the only way to regulate the thrust is to change the combustion chamber pressure.

Temperature Stability

The fuel grain regression rate is not significantly affected by temperature. This suggests that ambient temperature has little impact on the actual combustion chamber pressure. SRM designers are concerned about the relationship between combustion chamber pressure and grain temperature since an increase in pressure could cause the MEOP to be exceeded. However, some HRM setups that are described to as self-pressurized are very sensitive to temperature changes since the oxidizer is kept in the tank as a saturated liquid, and the equilibrium pressure is affected by the temperature of storage.If required, an in-line flow control valve can be used to control this issue.

Environmental Friendliness

Hybrids have a cleaner combustion process compared to solid rocket motors, as they typically use non-toxic and non-corrosive oxidizers like nitrous oxide (N2O) and environmentally friendly fuels like hydroxyl-terminated polybutadiene (HTPB). This makes hybrids more environmentally friendly and avoids the release of harmful combustion by-products.Many of the propellant formulations that are available and contribute to HRM's versatility are "green," meaning that no environmentally harmful or poisonous materials are used in the reaction process. The most common oxidizer in SRM is ammonium perchlorate since it containsthe vapours from chloride are not particularly green. O_2/H_2 used in LRMs is the most environmentally friendly rocket propellant formulation, however it cannot be stored.Hydrazine, which may be stored and is utilised as a liquid, is dangerous when it is not degraded. In applications where hazardous reactants are currently used, hybrid rockets may be a more environmentally friendly option. We are happy to use hydrogen peroxide/hydrocarbons as a storable green propellant formulation at the University of Padova.

DISADVANTAGES OF HYBRID ROCKET MOTOR

Low regression Rate

The smaller fuel web (grain thickness) that hybrid fuels often have is due to their lower rate of regression. To achieve the requisite amounts of thrust, it may be necessary to create fuel grains having many apertures. Multiport fuel grains may be necessary to expand the grain surface area in order to meet thrust requirements, however doing so may result in a relatively low bulk density and many unburned fuel slivers. However, recent efforts have made it possible to boost regression rates, which lessen the impact of this drawback.It's also crucial to keep in mind those long-duration applications with modest thrust requirements, such target drones and hovering vehicles, can benefit from a low regression rate.

Combustion Efficiency

There is less intimate mixing of the fuel and oxidizer as a result of the diffusion fames in hybrid systems. In comparison to liquids and solids, this efficiency loss is approximately 1-2% higher for hybrids. Reactants are not intimately combined or forced together in a hybrid rocket, in contrast to solids and liquids. This does not rule out the potential of discovering some unreacted oxidizer and fuel towards the rear of the combustion chamber. The achieved characteristic velocity (c) is significantly less than the theoretical one as a result of this imperfect diffusive combustion. The combustion is finished using a variety of methods. The employment of diaphragms, mixing plates, and swirling injection are among the most noteworthy [6-8].

Volume Efficiency and Packaging Issues

Less configuration flexibility exists for hybrid rocket motors in terms of liquids and solids. In an LRM, the propellant takes up the majority of the volume. With the right tank design, this liquid can be shaped as you like to fill the desired capacity. The combustion chamber is not particularly large. The combustion chamber makes up the majority of the system in a solid rocket.

There are numerous propellant grain designs that can meet the same impulse requirements because the regression rate depends on the combustion chamber pressure. The solid rocket is a versatile arrangement when it comes to packaging, implying a wide range of geometries and aspect ratios.

Since the oxidizer in a hybrid rocket is liquid, it can be kept with packing flexibility similar to that of a liquid rocket. When the design of the combustion chamber is taken into account, packing problems appear. There aren't many various fuel grain designs that can be designed that can meet the same total impulse demand because of the link between regression rate and oxidizer mass flux [9].

Slower Transients

Due to the presence of the fuel grain, the combustion chamber of a hybrid rocket is substantially larger than the one of a liquid rocket with the same thrust. Due to fuel grain regression, the internal petrol volume also fluctuates over the course of burning. This suggests that compared to LRMs, the filling/emptying characteristic time is substantially longer. Transients during throttling and ignition are slower. Hybrids can't be used in some applications that call for a precise, quick, and repeatable motor response due to their slow transient nature [10].

APPLICATIONS OF HYBRID ROCKET MOTORS

Spacecraft Propulsion

Hybrid rocket motors have been used in spacecraft propulsion systems. They have been considered for applications such as attitude control, orbit insertion, and orbital adjustments. Their controllability and throttle ability make them suitable for precise manoeuvres required in space missions.

Suborbital Research Flights

Hybrid rockets have been utilized in suborbital research flights, where they provide propulsion for scientific experiments, technology demonstrations, and atmospheric research. Their safety, reliability, and cost-effectiveness make them attractive for these applications.

Education and Amateur Rocketry

Hybrid rocket motors have gained popularity in educational institutions and amateur rocketry communities. They offer a safer alternative to solid rocket motors, allowing students and enthusiasts to gain hands-on experience with rocket propulsion systems.

High-Altitude Research

Hybrid rockets have been used in high-altitude research missions, such as weather monitoring, atmospheric studies, and stratospheric balloon launches. The controllability and reliability of hybrid motors make them suitable for collecting scientific data in challenging environments.

Small Satellite Launchers

Hybrid rocket motors have been proposed as propulsion systems for small satellite launchers. Their simplicity, reliability, and cost-effectiveness make them attractive for launching small payloads into orbit.

Emergency Launch Abort Systems

Hybrid rockets have been considered for emergency launch abort systems in crewed space missions. Their safety and controllability provide an added layer of protection for astronauts during critical launch and ascent phases.

Upper Stage Propulsion

Hybrid rocket motors have been studied as potential propulsion systems for upper stages of launch vehicles. Their throttle ability and specific impulse make them suitable for precise orbital manoeuvres and payload deployment.

Space Tourism

Hybrid rocket motors have been used in the development of suborbital space tourism vehicles. Their safety, reliability, and controllability are crucial factors for providing a comfortable and secure experience for space tourists.

CONCLUSION

In conclusion, hybrid rocket motors offer several advantages that make them attractive for a range of applications. The inherent safety, controllability, and reliability of hybrid motors set them apart from other propulsion systems. Their ability to be easily shut down, separate storage of oxidizer and fuel, and reduced risk of combustion instability make them inherently safer than solid rocket motors. Hybrid rocket motors have shown promise in a range of applications including spacecraft propulsion, suborbital research flights, education, high-altitude research, small satellite launchers, emergency launch abort systems, and space tourism. Continued research and development in this field will likely lead to further advancements and expand the utilization of hybrid rocket motors in the future.

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