Experimental and Theoretical Research Review of Hybrid Rocket Motor Techniques and Applications

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Abstract

A hybrid rocket motor combines components from both solid fuel and liquid fuel rocket motors. The fuel itself is a solid grain, (often paraffin or hydroxyl-terminated polybutadiene, known as HTPB) while the oxidizing agent is liquid (often hydrogen peroxide or liquid oxygen). These components are combined in the fuel chamber which doubles as the combustion chamber for the hybrid motor. This review looks at the advances in techniques that have taken place in the development of these motors since 1995. Methods of testing the thrust from rocket motors and of measuring the rocket plume spectroscopically for combustion reaction products have been developed. These assessments allow researchers to more completely understand the effects of additives and physical changes in design, in terms of regression rates and thrust developed. Hybrid rocket motors have been used or tested in many areas of rocketry, including tactical rockets and large launch vehicles. Several additives have shown significant improvements in regression rates and thrust, including Guanidinium azotetrazolate (GAT), and various Aluminum alloys. The most recent discoveries have come from research into nano-particle additives. The nano-particles have been shown to provide enhancements to many parameters of hybrid rocket function, and research into specific areas continues in the sub-field of nano-additives for fuel grains.

Keywords

Hybrid Rocket Motor, Sounding Rockets, Tactical Rockets, Space Engines, Thrust Augmentation, Large Launch Boosters, Fuel Additives, Regression Rate

1. Introduction

Rocket motors create propulsive force through ejection of burning gases, propelling the rocket forward, as shown in the basic schematic diagram in Figure 1. The stored propellant (fuel) is expelled at a high velocity, creating thrust. The equation for thrust contains a term for momentum, and a term for pressure, basic physical concepts. The momentum of an object is related to its mass and velocity, as shown below [1]:

$$F = M_G V_E + \left(P_E - P_A \right) A_E \tag{1}$$

The variables of Equation (1) and **Figure 1** are P_I which is chamber pressure; P_E is exhaust pressure; A_I is chamber cross-sectional area; A_E nozzle cross-sectional area. F is the thrust force. M_G is mass flow rate, and V_E is the velocity of the exhaust gases relative to the rocket; P_A is surrounding fluid pressure [1].

A hybrid rocket motor is made with some of the features of solid and liquid fuel rocket motors. The operation of the hybrid motor is distinct from either solid or liquid fuel rockets, though. In fact, the solid fuel rocket motor homogeneously mixes fuel and oxidizer in a single solid mass which is caused to burn at the exposed end by a flame, generating gases that lead to propulsion of the rocket motor. The liquid fuel rocket motor holds the fuel and oxidizer apart in separate chambers until the moment of ignition, when they are mixed at the injector port, becoming combustible. The solid fuel rocket, therefore, has a combustion chamber that is equal in size to the fuel chamber. The liquid fuel rocket has a smaller combustion chamber where the components are mixed. Nonetheless, in the combustion chamber of either type of rocket the fuel and oxidizer are mixed uniformly when they burn. The hybrid rocket motor holds the solid fuel in a chamber separate from the liquid oxidizer. The fuel ignites when it comes into contact with the liquid oxidizer, which means that within the combustion chamber there is a variable ratio of oxidizer to fuel. Motor performance, then, is determined by the average composition of the oxidizer/fuel mixture [2].

Hybrid rocket history dates back as far as the development of rocket motors in general. Incipient development of rocket motors occurred in the 1930s, when liquid and solid fuel rockets were devised. In that same period Sergei P. Korolev and Mikhail K. Tikhonravo developed early prototypes of hybrid rockets under the auspices of the GIRD program in Russia. The GIRD-09 flew on 17 August 1933 [2].
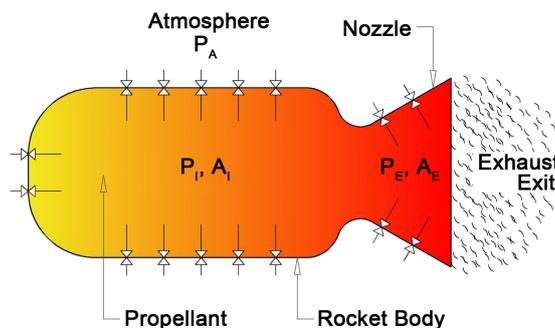

Figure 1. Schematic diagram of a basic rocket motor.

Regression rate is one way to measure hybrid rocket performance. Regression is based on the amount of solid fuel that is burned per unit time (usually expressed as inches/second). Faster burning of fuel (increased regression) should result in greater thrust, and better performance [3]. In a hybrid rocket motor the regression is calculated based on the burn from the solid propellant grain. The formula used for regression rate is [3]:

$$r = \frac{\left[\left(\sqrt{\dfrac{m_1 - m_2}{\rho \pi l_o} + r_1^{\,2}} \right) - r_1 \right]}{t} \qquad (2)$$

In this formula r represents the regression rate (inches/second); m_1 and m_2 are the initial and final fuel masses (grams); r_1 and r_2 are the initial and final port radius in inches; the fuel mass density is ρ (grams per inches³); the fuel grain length is represented by l_o (inches); and the time for fuel burn is t (seconds). This formula is used to calculate average regression rates, but it depicts the motor quite well when burn times are short [3].

HTPB (hydroxyl-terminated polybutadiene) is the most frequently used fuel for hybrid rockets. HTPB has a low regression rate. Certain additives may raise the rate of regression; a number of additives have been suggested and analyzed to learn which, if any, can increase the performance of HTPB [3].

This paper seeks to review the developments in hybrid rocket design, and improvements in function from the late 1990s until present. Several applications for hybrid rockets are represented by papers examining application of hybrid rocket motor technology to sounding rockets, tactical rockets, space engines, large launch boosters, and thrust augmentation research. The papers cover the period from 1995 to 2005.In the literature review, a number of improvements in hybrid rocket technology are represented by additional papers, which are reviewed in chronological order. These papers cover the developments of model hybrid rocket engines for testing concepts, through the discovery that Guanidinium azo-tetrazolate and Aluminum additives could have significant effects on regression rates, and then the advancement of using nano-sized particles of materials to mediate the functions of hybrid rocket motors. The papers reviewed also discuss new methods of measuring results during testing of prototypes.

2. Applications

In this section we review five applications for hybrid rocket motors: sounding rockets, tactical rockets, space engines, thrust augmentation, and large launch boosters.

2.1. Sounding Rockets

The Stanford University Sounding Rocket Program was designed to develop liquefying hybrid fuel, a novel technology. Karabeyoglu *et al.* describe three rockets at different stages of progress. A paraffin-derived fuel was found in experimental tests at different scales to have a regression rate 3 to 5 times greater than standard hybrid fuel. As a re-

sult of the studies, compact hybrid rockets can be designed that are comparable in performance to liquid and solid fuel rocket motors [4].

The study was carried out in three phases, the first of which is pertinent to this review. In this phase the researchers developed a hybrid sounding rocket to test the design of a paraffin-based propellant to replace a commercially available cellulose propellant supplied by Aerotech. The propulsion system was the stock motor from an Aerotech RMS/Hybrid 54 model kit. But the model was modified as shown in **Figure 2**. This Karabeyoglu *et al.* design was the first hybrid rocket launch to use paraffin-based propellant [4].

2.2. Tactical Rockets

This study discusses use of hybrid rocket motors when dealing with the problem of high off-boresight launch conditions. Vergez is primarily concerned with the ability of the hybrid rocket to be throttle-able in use and the advantages that it offers for guidance control in air-to-air engagements. His results demonstrate an improvement over proportional navigation laws and solid rocket motors when the throttle-able hybrid rockets are used along with linear optimal laws [5].

The equations below are offered as the guidance law for provision of hybrid rocket motor thrust control [5]:

The original paper offered these explanations of the variables:

$$A_{M_X} = G_{C_X} \left[\left(\frac{S_{R_X}}{t_{go}^2} \right) + \left(\frac{V_{R_X}}{t_{go}} \right) + K_T A_{T_X} \right] \tag{3}$$

$$A_{M_Y} = G_{C_Y} \left[\left(\frac{S_{R_Y}}{t_{go}^2} \right) + \left(\frac{V_{R_Y}}{t_{go}} \right) + K_T A_{T_Y} \right] \tag{4}$$

$$A_{M_Z} = G_{C_Z} \left[\left(\frac{S_{R_Z}}{t_{go}^2} \right) + \left(\frac{V_{R_Z}}{t_{go}} \right) + K_T A_{T_Z} \right] \tag{5}$$
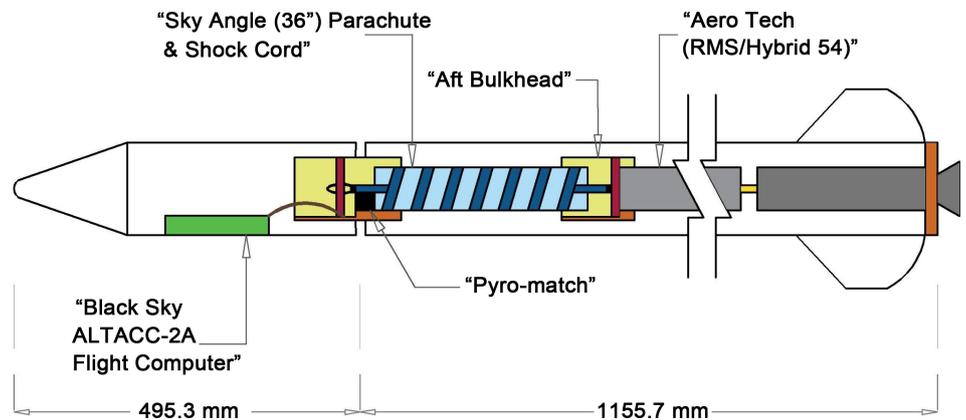

Figure 2. Structural design of the modified commercially available sounding rocket for development of paraffin-based propellant, as launched October 1999 [4].

"S_{R_X}; S_{R_Y}; S_{R_Z} = three components of relative position vector S_R referenced to the missile body" [5], Paul L. Vergez.

"V_{R_X}; V_{R_Y}; V_{R_Z} = three components of relative velocity vector V_R referenced to the missile body" [5], Paul L. Vergez.

"A_{M_X}; A_{M_Y}; A_{M_Z} = three components of missile acceleration command vector A_M referenced to the missile body" [5], Paul L. Vergez.

"G_{C_X}; G_{C_Y}; G_{C_Z} = navigational gain (usually set to 3)" [5], Paul L. Vergez.

"K_T = target acceleration gain, where" [5], Paul L. Vergez.

$$K_T = \frac{e^{-\lambda_T t_{go}} - \lambda_T t_{go} + I}{\lambda_T^2 t_{go}^2} \tag{6}$$

"where λ_T is the target acceleration response time coefficient." [5], Paul L. Vergez.

"And t_{go} is the time-to-go," [5]. The equation below is expressed from [5] [6].

$$t_{go} = \frac{2S_{R_X}}{-V_{R_X} + \sqrt{V_{R_X}^2 + \dfrac{4S_{R_X} A_{XX}}{3}}} \tag{7}$$

$$A_{XX} = A_{M_X} - K_T' A_{T_X} \tag{8}$$

Paul Vergez explains the terms quite well, as below:

"where A_{XX} is the difference between the missile acceleration command and K_T times the target acceleration in the axial direction, *i.e.*, where K_T' is K_T evaluated at the previous time interval." [5], Paul L. Vergez.

Note: the variable A_{M_X} is not used for a solid fuel rocket motor.

2.3. Space Engines

Karabeyoglu provided more information about the work at Stanford on paraffin-based fuel grains. The sizes of the fuel grains produced with this fuel were as large as 8.4 inches diameter and were as long as 45 inches. He reported that NASA Ames Research Center had done larger-scale tests using gaseous oxygen at their hybrid combustion test laboratory. The NASA tests confirmed the regression rates seen at laboratory scale at Stanford, suggesting that the fuel would be applicable for commercial uses [7]. See the Figure 3.

This study compares two fuels: a paraffin-based propellant (SP-1a) which is a fast-burning formulation, and a typical standard polymeric propellant based on HTPB. The question is which of them produces the best regression rate [7].

The regression rates for each type of propellant are shown in the equations below [7]:

Paraffin-based rocket motor:

$$r_{\text{Paraffin-based}} = 0.488 G_{OX}^{0.62} \tag{9}$$

HTPB-based rocket motor:

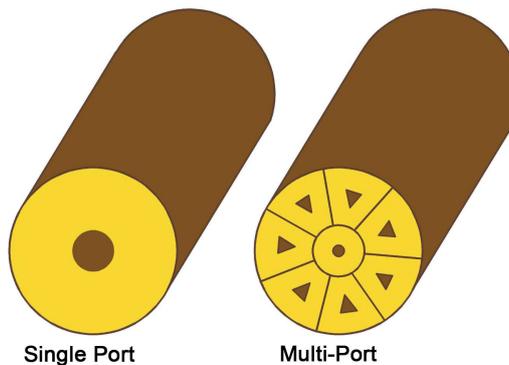$$r_{\text{HTPB-based}} = 0.146 G_{OX}^{0.681} \tag{10}$$

Figure 3. Single port (Paraffin-basedrocket motor) vs multi-port (HTPB-basedrocket motor) wagon wheel "fuel grain design" [7], ArifKarabeyoglu *et al.*

where regression rate is measured in mm/sec; mass flux (G_{OX}) is measured in g/cm^2-sec. Both equations reproduced from [7] [8].

2.4. Thrust Augmentation

This study examines the effect of the design of the fuel grain on performance characteristics of hybrid rockets. Taking into account pressure loss due to stagnation, the model includes a throttle component. The design is evaluated with hydroxyl-terminated polybutadiene (HTPB) fuel using both hydrogen peroxide at 90% and liquid oxygen as oxidizers. The aim is to develop a hybrid booster capable of the Titan 34D lift operations. Liquid oxygen is shown to be a more effective oxidizing agent in the system than hydrogen peroxide [9].

The design for the fuel grain is called "a multiport wagon-wheel fuel-section" [9] Vonderwell *et al.* It features eight spokes which produce eight pie-shaped fuel ports, and a central port is also present. This design is selected for more efficient burning of the fuel grain. The design cross-section is shown in **Figure 4** [9].

For fuel regression rate several assumptions were described: flow within the ports was assumed to be "one-dimensional", having negligible viscosity, and subject to compression. Mixing between fuel and oxidizing agent was assumed to be 100%, and universal. Also a constant regression rate from end to end for each port was assumed. **Figure 5** shows the "control volume at an arbitrary location x along the port" [9] Vonder well *et al.*

Here are the pertinent formulas from the Vonderwell research, concerning fuel regression rates (r_d) [9]:

$$r_d = 0.19 G_t^{0.8} L_f^{-0.2} \tag{11}$$

Note: L_f is the fuel grain length, and G_t is the total mass flux.

The researchers report this formula for calculation of fuel flow rate (assuming a regression rate that is constant throughout the port) [9]:

$$\dot{m}_f = r_d \rho_f Per\, x \tag{12}$$

where $\dot{m}_f$ is fuel mass flow rate; ρ_f is fuel density; *Per* is the perimeter of the fuel port; x is radial distance from entrance to the fuel port.
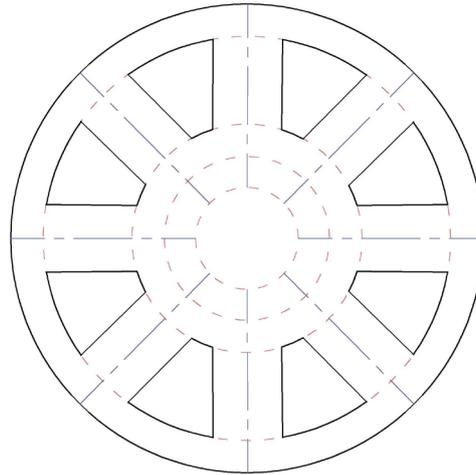
Figure 4. Cross section of 8-spoke "wagon-wheel fuel grain" [9] design as used by Vonderwell, *et al.* Note 8 peripheral ports, and one central port.
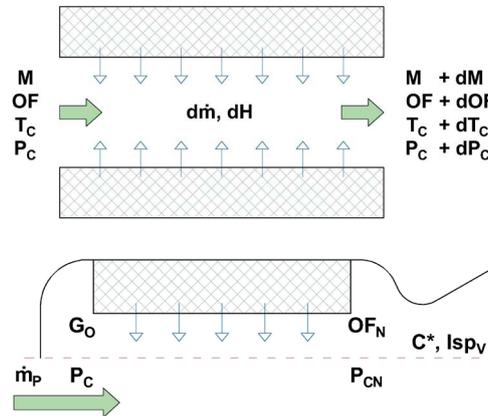

Figure 5. Schematic of control volume used to calculate the solution for a "one-dimensional flow" in a representative fuel port as used by Vonderwell, *et al.* M is Mach number; OF is oxidizer/fuel ratio; T_C is chamber temperature; P_C is chamber pressure; $\dot{m}_P$ is mass flow rate for oxidizer; H is stagnation enthalpy; G_O is initial oxidizer mass flux for port; C^* is characteristic velocity [9].

The oxidizer fuel ratio (OF) is calculated this way [9]:

$$OF = \frac{\dot{m}_p}{\dot{m}_f} \tag{13}$$

2.5. Large Launch Boosters

The report details a two-stage low-earth orbit (LEO) rocket vehicle launched in conjunction with the Canberra air platform. The design incorporates paraffin-fueled hybrid rocket motors for first and second stages. The system is shown to handle a 31 kg payload, lifting it into a 500 km orbit. The paraffin-fueled hybrids offer safety and reduced costs; the air platform and hybrid rocket system are held to be "an affordable and responsive launch system solution" [10] Karabeyoglu *et al.*, for the modern launch market.

Both stages are designed to use the rapid-burning fuel SP-1a/LOX for a hybrid motor. The design uses this "regression rate law" [10] [11]:

$$r_n = 0.117 G_d^{0.62} \tag{14}$$

Note: the regression rate (r_n) is expressed in mm/s; mass flux G_d expressed in kg/m^2.s.

3. Review of Literature

In this section we review research into several fuel additives that have shown significant progress in regression rates and thrust, including Guanidinium Azo-Tetrazolate (GAT), and several Aluminum alloys. We also review recent findings that have come from research into nano-particle additives. The nano-particles have been shown to offer improvements in various parameters of hybrid rocket function. And finally we look at some continuing research into specific areas in the sub-field of nano-additives for fuel grains.

3.1. In 1998 M. Keith Hudson *et al.*

This study used a 2-inch by 10-inch laboratory scale hybrid rocket motor in order to establish techniques for spectroscopic measurement of the chemistry of rocket plumes. Three ranges of spectral emissions were chosen for study. Baseline spectra were recorded, then the fuel was treated with various metal compounds in order provide known spectral lines, and manganese to research the effects of concentration. The small rocket was found to be a steady testbed for research into hybrid rocket motors as well as in studying simulated plumes for other types of rocket [12].

3.2. In 2000 A. M. Wright *et al.*

Guanidinium Azo-Tetrazolate (GAT) was added to hydroxyl-terminated polybutadiene (HTPB) in two concentrations by mass: 15% and 25%. Although the thrust achieved was increased with the addition of GAT, and both concentrations created roughly equal increases in thrust, the specific impulse was lowered somewhat with the additive present [13].

3.3. In 2000 Robert Shanks and M. Keith Hudson

This research was aimed at developing rocket technology that could be used to study rocket motor plumes for spectroscopy data collection. The study comprised all phases from design through construction of the laboratory hybrid rocket, the development of supporting services, the data collecting instruments, the rocket computer controls, and establishing the characteristics of the thruster that was ultimately produced [14].

3.4. 2001 Mary F. Desrochers *et al.*

The report defines a strain gauge based system for measuring thrust, devised for ground testing of rockets. Following a discussion of the theory and uses of strain gauges, complete circuitry and structural details are provided for those interested in building such a system. The described system was set up for a 50 lb degree of thrust, and in-

stalled at the University of Arkansas at Little Rock (UALR) Hybrid Rocket Facility. The system worked well for continuously recording thrust data during ground testing. The paper reports the data acquired by the system during such a test [1].

3.5. In 2004 M. Keith Hudson *et al.*

Hudson et al studied Guanidinium azo-tetrazolate (GAT) as a fuel additive to create a high regression mixture with hydroxyl-terminated polybutadiene (HTPB). Due to the presence of positively and negatively charged chemical components, the GAT salt produced measurably faster regression when added to the HTPB [3].

3.6. In 2004 Grant A. Risha *et al.*

This study measured average surface area as related to particle diameter, amount of combustible material, and depth of the oxide layer, as well as other measurements related to combustion, in fifteen types of nano-sized particles. All the measurement techniques used were standard. The study suggests additional parameters that should be studied in the future in order to understand the specific properties of nano-sized particles, in relation to propulsion characteristics of solid fuels [15].

3.7. In 2011 Daniel B. Larson *et al.*

Larson's group studied the combustion characteristics of paraffin-based solid fuel grains with aluminum compounds as additives. Lithium aluminum hydride, triethylaluminum, and diisobutylaluminum hydride were added to the formulations of paraffin fuel grains tested in cartridge loaded hybrid rockets. The study found that the lithium aluminum hydride yielded an increase in chamber pressure. One important result of the research was an understanding that qualitative evaluations of the fuel types are possible, and the formulations can be changed to be more effective in future tests [16].

3.8. In 2013 A. Sossi *et al.*

Nanoaluminum (nAl) particles were characterized for their effect on the regression rates of the solid fuel component of hybrid rockets. Particle sizes were 50 nm and 100 nm, coated with a number of different shielding organic reagents, then added to "hydroxyl-terminated polybutadiene (HTPB)-based solid fuels" [17] (A. Sossi *et al.*). The resulting combustion data were analyzed to generate a "continuous time-resolved regression rate" [17] (A. Sossi *et al.*). The coated nAl particles were found to increase the performance of nAl-enhanced HTPB preparations when compared to unalloyed HTPB when burned in the presence of gaseous oxygen (Gox). All the tested formulations enhanced regression rate. Coating agents having fluorine as a component were found to yield advantages under the test conditions of the study [17].

4. Summary

A research review of several fuel additives and five applications done by the hybrid rocket motors specialists are showed in Table 1 which summarizes the publica-

Table 1. Chosen prior research into several fuel additives and five applications for hybrid rocket motors.

No.	Year	Author Name	Problems
1	1995	D. J. Vonderwell *et al.*	Optimization of Hybrid-Rocket-Booster Fuel-Grain Design
2	1998	P. L. Vergez	Tactical Missile Guidance with Passive Seekers Under High Off-Boresight Launch Conditions
3	1998	M. K. Hudson *et al.*	UV, visible, and infrared spectral emissions in hybrid rocket plumes
4	2000	A. M. Wright *et al.*	The effect of high concentration guanidinium azo-tetrazolate on thrust and specific impulse of a hybrid rocket
5	2000	R. Shanks *et al.*	A Labscale Hybrid Rocket Motor for Instrumentation Studies
6	2001	M. F. Desrochers *et al.*	A ground test rocket thrust measurement system
7	2003	M. A. Karabeyoglu *et al.*	Development of High-Burning-Rate Hybrid-Rocket-Fuel Flight Demonstrators
8	2003	A. Karabeyoglu *et al.*	Scale-up tests of high regression rate liquefying hybrid rocket fuels
9	2004	M. K. Hudson *et al.*	Guanidinium Azo-Tetrazolate (GAT) as a High Performance Hybrid Rocket Fuel Additive
10	2004	G. A. Risha *et al.*	Characterization of nano-sized particles for propulsion applications
11	2005	A. Karabeyoglu *et al.*	Design of an Orbital Hybrid Rocket Vehicle Launched from Canberra Air Platform
12	2011	D. B. Larson *et al.*	Characterization of the Performance of Paraffin/LiAlH4 Solid Fuels in a Hybrid Rocket System
13	2013	A. Sossi *et al.*	Combustion of HTPB-Based Solid Fuels Loaded with Coated Nanoaluminum

tion year, author name and the title of the research problem.

5. Conclusion

During the past two decades, improvements in hybrid rocket technology have been steady. Methods of collecting more complete empirical knowledge of the results of the burning of solid fuel grains by the addition of liquid oxidizing agents have allowed researchers to tailor their investigations toward specific hybrid rocket motor parameters. The motor plumes can now be investigated with spectroscopic analysis, and actual motor thrust can be measured with strain gauges. This has allowed investigators to learn specific effects of varying concentrations of additives, including nanoparticles of various sizes.

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