Hybrid Rocket Technology: An Overview

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[Presented as a plenary paper at the 6th Asia pacific International Symposium on Combustion and Energy Utilization, Kualalumpur, Malaysia, May 20-22, 2002]

A brief introduction to hybrid rockets is given. The hybrid-rocket-technology development in the last ten years is surveyed. On the point of view of specific impulse, hybrid rockets are equivalent to bi-propellant liquid rockets, including cryogenics. And, they are simpler and therefore have potential to become more reliable than bi-propellant liquid rockets. They can be restarted and throttled and therefore can perform better than solid propellant rockets. To fully realize these advantages, there are challenges to be met, such as enhancing regression rate of solid fuels, or improving the combustion efficiency. Covered globally are the results in the last ten years of the various developmental programmes, conducted to meet the challenges in the application of hybrid rocket technology. Importance of enhancing the regression rate of conventional hybrid rocket fuel is brought out. The various chemical and physical routes being investigated to enhance the regression rate are explained and discussed.

Introduction

In hybrid rocket motors, one of the two propellants (oxidizer or fuel) is in liquid phase and the other is in solid phase. The combination of a solid fuel and a liquid oxidizer is the most common one, Fig. 1. [1]

Even though the idea of hybrid rocket motor was conceived as early as 1937, it was only after 1960s they were built successfully with good combustion efficiency. A discussion of the history of hybrid rocket development is presented by Altman.[2] After a lull of about two decades in hybrid rocket research, quite a few research and developmental activities have been reported in recent years.[3, 4] The motivation for this has been the growing interest towards 1) lower developmental and operational costs without much loss in specific impulse and density specific impulse, 2) safer operational characteristics, and 3) better environmental friendly exhaust.

Hybrid rocket motors offer the following advantages over their solid and liquid counterparts:

1) solid fuels are safer than solid propellants on the points of view of manufacture, transportation, and storage;
2) compared to solid rockets, the performance of hybrid rockets is much less sensitive to cracks and debonds in fuel grains;
3) unlike solid rockets, hybrid rockets have the ability to change thrust over a wider range, and to shutdown and restart;
4) relative to liquid engines, hybrid rockets require only half as much feed system hardware and therefore display higher reliability;
5) hybrid rockets generally have the values of specific impulse higher than solid rockets and of density specific impulse greater than liquid bi-propellant rockets, Fig. 2.[1]

On the other hand, the disadvantages of hybrid rockets are:[1]

1) the variation of mixture ratio and hence that of specific impulse during steady state operation and throttling;
2) the lower combustion efficiencies (0.93 to 0.97) compared to liquids or solids;
3) the lower density specific impulse and thus a larger system volume than solids;
4) the higher sliver fraction; and
5) low regression rate of solid fuel resulting in rather awkward envelope of propulsion system that degrades the application of hybrid motors.

The survey of the literature in the recent ten years on the research and development of hybrid rockets indicates the clear maturity of the hybrid rocket technology. The hybrid rocket propulsion system has been endorsed for flight in many of the space- and defence-applications. Many sounding rockets, powered by hybrid rockets, have been flown. The ground firings of large hybrid booster-motors (1.8-m diameter) of launch-vehicle class have been successfully conducted. The application of hybrid rocket motors as propulsion modules for micro-satellites is seriously being investigated.

In support of the above observation, the present paper surveys globally the various developments in hybrid rocket technology in the last decade. Also, the paper discusses the methods being investigated for enhancing the regression-rate of hybrid-rocket fuels.

The disadvantage of low regression rate of solid fuel has attracted the attention of many researchers and means to enhance the regression rate are being tried through various routes. The disadvantageous effect due to low fuel-regression rate can be understood by considering the thrust equation and its variations, Eqs. (1) - (3).

$$F = \dot{m} I_{sp} = (\dot{m}_{ox} + \dot{m}_f) I_{sp} = \dot{m}_f \left[(\Phi + 1) I_{sp} \right] \quad (1)$$

$$F = \dot{r} A_f \left[\rho_f (\Phi + 1) I_{sp} \right] = \dot{r} D_p L \left[\pi \rho_f I_{sp} (\Phi + 1) \right] \quad (2)$$

$$F \propto \dot{r} D_p L \quad (3)$$

where,

F	=	thrust
$\dot{m}$	=	mass flow rate of propellant
I_{sp}	=	specific impulse
$\dot{m}_{ox}$	=	mass flow rate of oxidizer
$\dot{m}_f$	=	mass flow rate of fuel

Φ	=	oxidizer: fuel mixture ratio by mass
A_f	=	regressing area of fuel grain
ρ_f	=	fuel density
$\dot{r}$	=	regression rate of fuel
D_p	=	internal port-diameter of fuel grain
L	=	length of fuel grain

For the chosen fuel and oxidizer, the value of the quantity within the brackets of Eq. (1) is essentially constant. Taking the simple case of cylindrical port for the fuel grain, the thrust depends on the fuel regression rate, $\dot{r}$ the port diameter, D_p, and the grain length, L, Eq. (3). The regression rate of conventional hybrid-fuel being around 1.5 mm/s, the resulting fuel grain dimensions and hence the motor dimensions are rather awkward for the desired thrust — either too large a diameter or too long a length.

Developments in Hybrid Rocket Technology

As to be expected, majority of the developmental efforts on the application of hybrid rocket propulsion are reported form the United States of America (US). These and other technology developmental efforts may be grouped under applications of 1) sounding rockets, 2) satellite launch vehicles, 3) micro-satellites, and 4) defence applications.

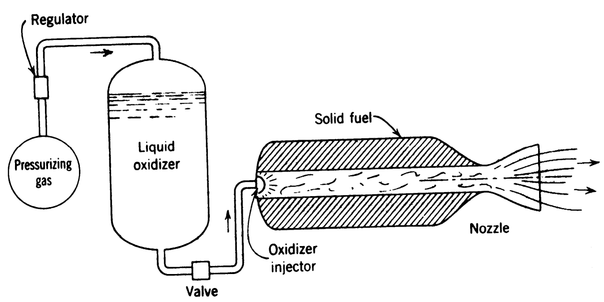

Fig. 1 Simplified schematic diagram of typical hybrid rocket engine (adopted from Ref. 1)

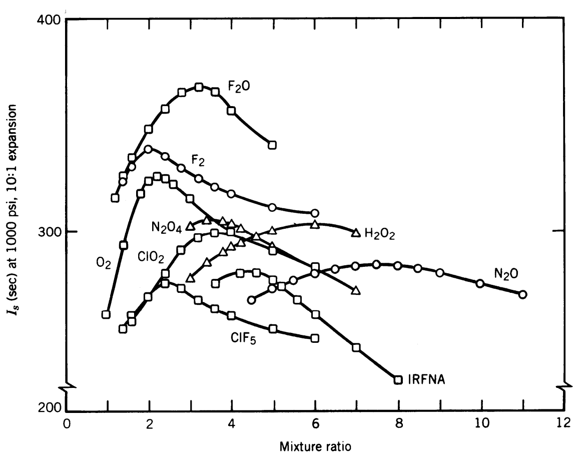

Fig. 2 Theoretical vacuum specific impulse of selected liquid oxidizers and hydroxyl-terminated-polybutadiene solid fuel (adopted from Ref. 1)

NASA

Program JIRAD

In order to develop hybrid rocket technology a programme known as Joint Government/Industry Independent Research and Development Program (JIRAD) was established in the early 1990s in the US.[5, 6] The programme ended in 1994. Thiokol led the programme; Rocketdyne provided the injectors; United Technologies Chemical Systems Division (CSD) provided the motor design and fuel grains; NASA-Marshall provided test facilities and operations support. Martin Marietta and American Rocket Company (AMROC) also played substantive roles.

JIRAD addressed issues of hybrid motors such as 1) fuel regression characteristics, 2) fuel web burnout, 3) combustion efficiency, 4) combustion stability, 5) throttling characteristics, and 6) nozzle throat material response. Under JIRAD, the large number of test firings of 280- and 610-mm (11- and 24-inch)-diameter hybrid motors were the centrepiece of this effort. Twenty firings of 280-mm motors and fifteen of 610-mm ones were conducted. The thrust levels ranged form 4500- to 13400-N (1000- to 3000-lbf). Hydoxyl-terminated-polybutadiene (HTPB) and gaseous oxygen (GOX) were used as fuel and oxidizer respectively. Tests encompassed 1) chamber pressures up to 6.9 MPa (1000 psi), 2) ratios of mass flow rates of oxidizer and fuel (Φ) between 1.1 and 3.3 (stoichiometric ratio ~ 3), and 3) maximum-average total-mass-flux level of 560 kg/m^2-s (0.8 lbm/in^2-s). Demonstrated performance parameters are 1) combustion efficiencies of at least 95%, 2) stable and unstable combustion regimes, and 3) smooth and stable transients through throttling.

HyTOP & HPDP

With an objective to bring large-scale hybrid motors to flight status, the hybrid technology option project (HyTOP) was initiated in 1994 with funding from Defense Advanced Research Projects Agency (DARPA) of the US.[6] The project members were Martin Marietta, CSD, and AMROC. The project envisaged building on AMROC's development four 1.1 MN (250000-lbf) hybrid motors (H-250K). Of these, two qualification motor firings, and one flight of H-250K motors were planned. For the flight version of H-250K, Air Force Phillips Laboratory was to help the HyTOP team with H-250K motor testing. Martin Marietta was to develop a lightweight aluminium-lithium tank, composite structures, and a novel pressurization system. CSD was to develop the nozzle and the liquid injection thrust vector control system.

The hybrid propulsion demonstration program (HPDP) was established in 1995.[7] This is a continuation of the original HyTOP. HPDP, conducted by NASA and the US industry consortium, sought to provide a single directed effort to bring hybrid propulsion technology to maturity to enable full-scale engineering development of hybrid boosters for space launch applications. The program included three major tasks: 1) demonstration flights of a sounding rocket in the late 1966 from Wallops Island, 2) static firings of sub-scale liquid oxygen (LOX)/HTPB hybrid motors of 280 mm (11 inch) and 610 mm (24 inch), and 3) three static firings of a full scale hybrid motor of 1.1MN (250,000 lbf) thrust by early 1999. HPDP consortium included NASA-Marshall, Lockheed Martin, Thiokol, Pratt & Whitney's Chemical Systems Division, Boeing Rocketdyne, AlliedSignal, and Environmental Aeroscience Corporation (EAC). DARPA, NASA-Wallops, and the Air Force Research Laboratory contributed to the HPDP's technical demonstrations.

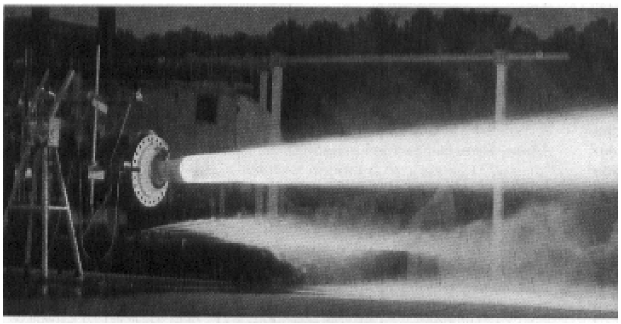

Fig. 3 The submerged flex-bearing thrust vector control (± 4°) on a 610-mm (24") diameter, 53.5 kN (12000 lbf), 20 s, LOX/HTPB/Escorez hybrid motor at NASA-Marshall (Adopted from Ref. 7).

Under HPDP, during 1995-'97 several — appear to be nineteen — static tests of 280- and 610-mm (11- and 24-inch)-diameter sub-scale LOX/HTPB hybrid motors were successfully completed at NASA-Marshall, Fig. 3.

These sub-scale motor firings successfully demonstrated non-pyrotechnic ignition — possibly electric operated torch igniter — as well as combustion stability and efficiency. These firings also validated nozzle design and refurbishment techniques and evaluated candidate nozzle and insulation materials and scale-up effects.

Under the sounding rocket programme of HPDP, the EAC successfully demonstrated[8, 9] hybrid rocket flights from NASA's Wallops Flight Facility using its Hyperion launch vehicle of 5.7 m long and 152 mm diameter during 1996-'97, Fig. 4 — the high L/D ratio of the vehicle possibly resulted from the low regression rate of fuel. The hybrid rocket uses nitrous oxide (N_2O) and HTPB as the oxidizer and fuel respectively, and delivers an average thrust of 6240 N for 15 s. In 1996, two check-out flights at low-altitudes (~7.6 km) verified oxidizer loading, launch and abort procedures, and transonic stability. Both rockets were flown off the same pad within 90 minutes, demonstrating simple and safe launch pad operations of hybrid launch vehicles.

In January 1997, a third hybrid-rocket flight achieved an altitude of 36.6 km. In April 1997, a fourth and final flight integrated a parachute recovery system and achieved an altitude 33.5-km. The recovered rocket hardware demonstrated 99% fuel utilization.

EAC, in conjunction with Cesaroni Technology, has initiated a performance enhancement program on its 152-mm diameter N_2O/HTPB hybrid Hyperion sounding rocket to reach an altitude of 61-km (200,000 feet).

The design and fabrication of turbopump-fed LOX/HTPB 1.1 MN (250000 lbf) thrust hybrid motors were completed during 1997-'98. After cold-flow injector-tests at NASA-Marshall, the firing of 1.1 MN thrust hybrid motor was done at NASA-Stennis. The HPDP culminated by the third test firing of 1.1 MN (250,000 lbf) thrust motor on September 9, 1999 at NASA Stennis, Fig. 5.[10, 11] The hybrid motor was of 1.78 m (70 inch) diameter and 13.7 m (45 feet) length. The test duration was for 35 s. From the photographs in Fig. 5, it can be construed that the motor had submerged flex-bearing thrust vector control.

American Rocket Company (AMROC)

The contributions of AMROC in the development of hybrid rocket technology in the 1980-90s were significant. The company was active in developing hybrid rocket motors for commercial use for orbital and sub-orbital vehicles and other propulsive stages. But, it failed to find commercial support and went defunct by mid 1990s.

In 1993, the company conducted four tests of its 1.1 MN (250,000-lbf) hybrid motor. The motor used liquid oxygen and an HTPB grain in its 1.83-m (72-inch) diameter and 9.75-m (32-feet) long filament wound case — the motor of HPDP is of 1.78-m diameter and 13.7 m length. Thrust vector control was demonstrated by the injection of liquid oxygen in the nozzle. Using the restartable characteristics of hybrid rockets, the single grain was tested in four separate 10-15-s duration firings. Combustion instability was experienced in the first test. The cause for this was found to be due the grain casting method and the method was successfully corrected for the subsequent motors.

AMROC was also active in developing hybrid motors that use nitrous oxide (N_2O) as an oxidizer for small-scale 0.18 MN (40,000-lbf) thrust.

In 1995 AMROC conducted the first firing of a pump-fed hybrid motor at NASA-Stennis. In all the eight tests, the motors were reported to have performed comparably to a pressure-fed motor.

USAF

The United States Air Force (USAF) developed different hybrid rocket propulsion systems for sounding rockets and tactical missiles.

In January 1994, the United States Air Force Academy successfully launched a 6.4-m (21 feet) long, 2670-N (600-lbf) thrust LOX/HTPB hybrid rocket to reach 3-km (10000 feet) altitude. In the next year, this rocket was developed to deliver 3570-N (800-lbf) for 15 s to reach 4.6 km (15000-feet) altitude. In 1997 the Academy developed an 890-N (200-lbf)-thrust hybrid-rocket propulsion-system that used N_2O and polyethylene. The Academy studied the autoignition in hybrid rocket that used H_2O_2 and the regenerative cooling of hybrid rocket nozzle using N_2O.

The Air Force Research Laboratory (AFRL) is engaged in the development of hybrid rocket propulsion for tactical missiles. The Laboratory is studying a novel concept known as forward injected gas generator (FIGG) hybrids. By applying this concept, AFRL achieved a high fuel-regression rate, very stable combustion, on-demand throttling, and the ability to extinguish during burning and restart. AFRL, Thiokol, Rocketdyne are collaborating with the Technical R&D Institute of Japan to develop FIGG hybrids propulsion for tactical missiles. FIGG concept uses high-density storable oxidizers and gas generator solid fuels.

Fig. 4 Successful hybrid rocket flight using Hyperion launch vehicle. A flight in April 1997 reached an altitude of 34 km. The hybrid rocket used nitrous oxide and HTPB as propellants (adopted from Ref. 9).

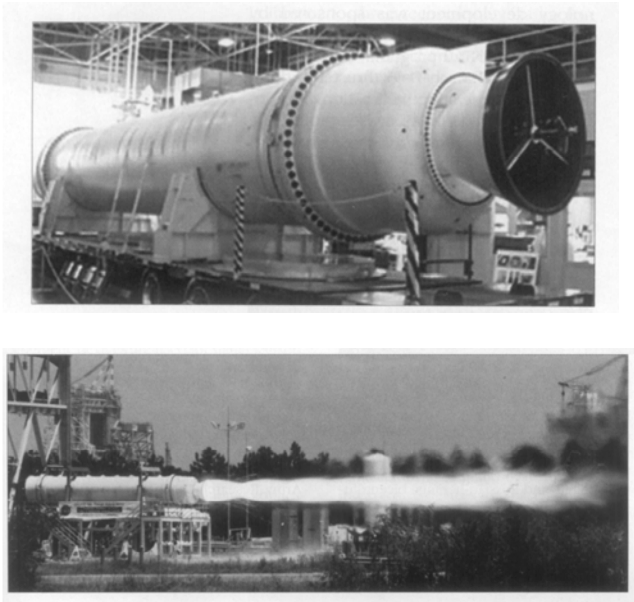

Fig. 5 The 1.1 MN thrust turbo-pump fed LOX/HTPB hybrid motor (the third in the series) is being tested at NASA-Stennis on September 9, 1999. The motor is 13.7-m long, 1.78-m diameter, and weighs about 56800 kg. The test duration was 38 s (adopted from Refs. 10 and 11).

Dual Mode Hybrid Rocket Program in Israel

In hybrid rocket motors, one of the two propellants (oxidizer or fuel) is in liquid phase and the other is in solid phase. The combination can be a solid fuel and a liquid oxidizer (the most common one) or *vice versa.* In either of this combination, if the liquid propellant is a monopropellant then the combination offers a possibility of having two different modes of rocket operations: 1) the liquid monopropellant and the solid grain acting as a hybrid rocket and 2) the liquid monopropellant acting as a monopropellant rocket. This arrangement of having two different modes of operations in a hybrid rocket is known as dual mode hybrid rocket. For the dual mode hybrid rocket, in addition to the increased flexibility in the operational modes, by the exothermic decomposition of the liquid monopropellant, the ignition of the solid grain is automatic and hence the rocket is restartable more readily and reliably.

Interestingly, as an extension to this dual mode concept, the liquid monopropellant with a second liquid propellant onboard can act as a bi-propellant liquid rocket resulting in "triple mode hybrid rocket". However, the study of such a propulsion system having three modes of rocket operations has not been reported in the literature.

In the dual mode hybrid rocket, the liquid monopropellant can be basically an oxidizer or a fuel. For example, the monopropellant hydrogen peroxide (H_2O_2) is primarily an oxidizer. On the other hand, the monopropellant hydrazine (N_2H_4) is fundamentally a fuel. If the monopropellant is an oxidizer, say H_2O_2, finding a suitable solid fuel for the hybrid rocket operation is not difficult. But if the monopropellant is a fuel, on the point of view of energetics, finding a suitable solid oxidizer for the hybrid rocket operation is simple, but not so on the standpoint of structural- and process-requirements. However, the researchers from Raefel in Israel have claimed in 1996 the realization of a dual mode hybrid rocket using hydrazine as the liquid fuel monopropellant.[8] In this, the hydrazine monopropellant rocket mode serves for the maneuvers of smaller velocity increment, while the hybrid rocket mode (they call this as "inverse hybrid") attends to the ones of larger velocity increments.

Upper Stage and Satellite Propulsion Systems

In 1999, NASA has awarded a contract to Lockheed Martin Astronautics, along with subcontractors Boeing Rocketdyne and Thiokol, to begin development of a peroxide-oxidized hybrid motor for upper stage application in reusable launch vehicles.[11]

Propulsion System for Microsatellites (Secondary Payloads)

For decades, launch vehicles have accommodated small "piggyback" spacecraft — secondary payloads — but most of these secondary payloads do not have any means of changing orbits once deployed from their host launch vehicle. Therefore there is a widespread need for small and inexpensive propulsion and guidance modules that can boost small secondary payloads from their drop-off orbits to more desirable orbits." SpaceDev, a company in the US, has been awarded in August 1999 a contract of about 700,000$ to develop the propulsion and guidance modules using the hybrid rocket concept. The micro-kick hybrid motor under this concept is storable, restartable, throttleable, modular and scalable. It is about 130-mm (5") diameter and 305mm (12") length with a total thrusting time of about 45 s.

ONERA in France is working on the development of H_2O_2/ polyethylene hybrid propulsion system for a 100-kg micro-satellite.[12]

Sub-Orbital Flight Vehicle

In 1999**,** Lockheed Martin began work under cooperative agreement with NASA to develop a low-cost hybrid-based sounding rocket system.[11] The vehicle is being designed to produce thrust in excess of 223 kN (50000lbf) and to lift a 545 kg (1200-lb) payload to an altitude of 282 km (175 miles). Flight tests are scheduled to begin in 2000 from NASA's Wallops Flight Facility.

Hybrid Rocket Studies in Universities

Research activities in various universities indicate the interests of the related countries in hybrid rocket development. Table 1 has been prepared from the information found in Refs. 5-11.

Regression Rate Enhancement Studies

Combustion Processes

The complete modelling of hybrid motor combustion is quite complicated due to various physical and chemical processes. The model has to consider in a fuel grain passage a reacting flow created by the two distinctly different fluids: one, the mostly-vaporized-oxidizer entering the fore end of the fuel grain passage and the other, the fuel vapor blowing from the passage-wall, Fig. 6.[13] The boundary layer growing from the fore end of the passage contains the diffusion flame front within. Fuel is vaporized as a result of the heat transferred from the flame front to the fuel surface. The fuel vapor convects towards the flame front while the oxidizer from the free stream diffuses into the boundary layer also towards the flame front from the opposite direction. Furthermore, at motor operating conditions characterized by high Reynolds number a finite flux of unreacted oxidizer to the fuel wall could exist through the mechanism of bulk turbulent eddy transport across the flame front. The flame front is established at a location within the boundary layer determined by the stoichiometric conditions under which combustion can occur.

Table 1 Hybrid rocket research activities at various universities[a]

Year	University	Activities
1993 - '98	University of Alabama in Huntsville	Performed a detailed design study of a pump-fed hybrid sounding rocket. Conducted experiments in combustion stability on a lab-scale motor by analyzing vortex shedding on a rearward facing step. Design and fabrication of a new low-cost cryogenic injector for hybrids (supported by Thiokol, and Rocketdyne). A conceptual design of a hybrid motor for an upper stage (supported by NASA-Marshall and Boeing). Tested fuels containing small amounts of ammonium perchlorate to produce a two- to five-fold increase in regression rates. Evaluated seven different LOX injector configurations in an 11" diameter hybrid motor (supported by NASA-Marshall, Thiokol, and Rocketdyne). Development of ultrasonics for regression rate measurement.
1993 - '98	Indian Institute of Technology Madras, India	Studies on regression rate enhancement through additives and geometric variation of grain for GOX/ HTPB systems (supported by Indian Space Research Organization).
1993 - '95.	A consortium of Utah universities (Unity4)	Developed a hybrid sounding rocket and conducted five static tests of GOX/HTPB motor design that will lead to testing with liquid oxygen in 1994. Conducting a program to fly a scientific payload on a hybrid rocket that uses GOX/HTPB propellant. Five motor tests were performed in the development process. Development of a hybrid powered vehicle capable of launching small scientific payloads to 39.6 km (130000 feet).
1993 - '95.	University of Arizona	Conducted experiments investigating the boundary layer structure of hybrid combustion using GOX/HTPB. Tested hybrids using HAN as oxidizer.
1993	University of Maryland	Developed designs for a hybrid rocket orbital maneuvering system for its Ranger teleoperated robot spacecraft. Designing a 100-kg to-orbit hybrid launch vehicle and a hybrid powered on-orbit maneuvering system for a telerobotic flight experiment.
1994 - '97	United States Airforce Academy	Successfully launched a 6.4 m (21-feet) long, 2670 N (600-lbf)-thrust LOX/HTPB hybrid to 3050 m (10000 feet). Developed a hybrid rocket motor that delivered 3570 N (800 lbf) of thrust for 15 s and powered a sounding rocket to approximately 4570-m (15000 feet). Development of small sounding rocket system using nitrous oxide (N_2O) and polyethylene. Thrust = 890 N (200 lbf). Studied the hybrid/H_2O_2 autoignition problem through 20 static firings. Studied regenerative nozzle cooling using N_2O.
1994 - '98	University of Arkansas - Hybrid Rocket Facility	Conducted experiments in rocket plume spectroscopy with a hybrid fuel grain doped with metallic salts. Regression rate studies. Effects of energetic fuel additives.
1994 - '98.	Purdue University	Design optimization studies for Titan strap-on boosters use LOX- and H_2O_2-fed hybrids. Tested hybrids using H_2O_2as an oxidizer and polyethylene as a fuel. Experimental efforts with highly stabilized 85% H_2O_2/polyethylene fuel. Stable ignition and combustion obtained at total mass flux levels of 560 kg/m^2-s. Experimental efforts with highly stabilized 85% H_2O_2/polymethylacrylate fuel. Development of consumable igniter systems. Application of genetic algorithms to determine the optimum propulsion system design.
1995	Instituto Nacional de Tecnica Aerospacial (Spain) & TNO Prins Maurits Laboratory (the Netherlands)	System study toward the potential of hybrid propulsion for a small-class launcher. Experimental work conducted to investigate the performance of conventional and energetic fuels with oxygen (supported by the European Space Research and Technology Centre).

Table 1 Hybrid rocket research activities at various universities (contd.)[a]

Year	University	Activities
1995 - '99	The Pennsylvania State University	Developing non-intrusive techniques for GOX and LOX/HTPB regression rate studies. Combustion behavior of GOX/HTPB combination to enhance regression rates. Development of data on the thermophysics of solid-fuel decomposition and CO_2 laser-augmented ignition and combustion. Development of gas generator fuel formulations. Combustion studies on the effects of oxidizer concentration, temperature, and pressure.
1996 - 2000	Technion - Israel Institute of Technology	Studies on scaling effects.
1997	Stanford University	Research into transient combustion behavior in hybrid rockets.
1998	University of New Orleans	Numerical studies of the transient combustion behavior.
1998	University of Pune, India	Hybrid grain ballistics of GOX/HTPB hybrid motors.

[a]Information compiled essentially from Refs. 5-11.

The thickness of the flame is determined by the reaction rate at which the oxidation can occur. This rate is mainly dependent on pressure and typically follows an Arrhenius relationship. However, this is unimportant for the location of the flame front, as diffusion rate is lower than reaction rate. The primary mechanism of heat transfer to the fuel surface is by convection and radiation. There is a strong coupling between the convective heat transfer and the rate of fuel vaporization ("blowing" rate) since the blowing decreases the convective heat transfer to the fuel surface. There is also an indirect coupling between the convective and radiative heat transfers because the latter tends to increase the blowing rate, which in turn tends to decrease the convective heat transfer.

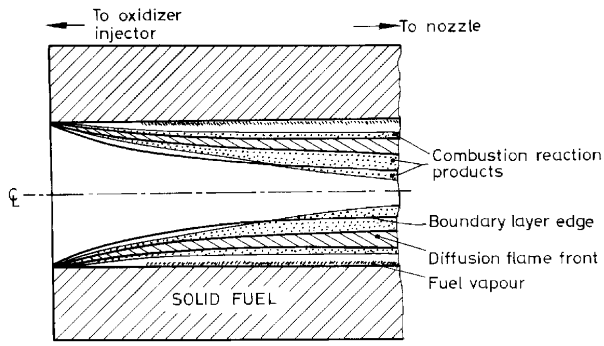

Fig. 6 Combustion processes in hybrid rocket motor.[13]

At the fore end of the grain the free stream consists of pure oxidizer at a low temperature. Along the fuel grain passage the oxidizer concentration decreases and the temperature increases, Fig. 6. With the two zones on either side of the flame front**,** vitiated by the combustion products, the combustion, though stoichiometric, is occurring drawing the increasingly "diluted" oxidizer and fuel-vapor along the grain. Since the oxidizer concentration reduces along the passage, the diffusion flame within the boundary layer moves away from the fuel surface. In the limit, if all the available oxidizer is consumed at a location along the grain passage, theoretically no flame can exist downstream of this location. However, the heat transfer to the fuel surface will continue from the hot combustion products causing the continuance of fuel vaporization. In the absence of any combustion downstream of the location, the blowing fuel vapor will only cool the passage flow.

For hybrid motors, most of the presently projected fuel and oxidizer combinations in their basic form have fuel regression rate around 1.5 mm/s or less under motor operating conditions. As discussed previously, this low regression rate of solid fuel is the basic problem, which degrades the application of hybrid motors. Addressing this issue many studies have been conducted in recent years. These studies can be grouped into 1) chemical and 2) physical.

Chemical Routes to Enhance Fuel Regression-Rate

Cryogenic Hybrid Rocket

Under chemical route, for achieving enhanced regression rates one may identify either an altogether new set of hybrid propellants or some additives to the conventional hybrid propellants. Coming under the first category, the cryogenic hybrid rocket is an interesting proposition. Freezing the propellants provides a beneficial gain in propellant density of approximately 30%.

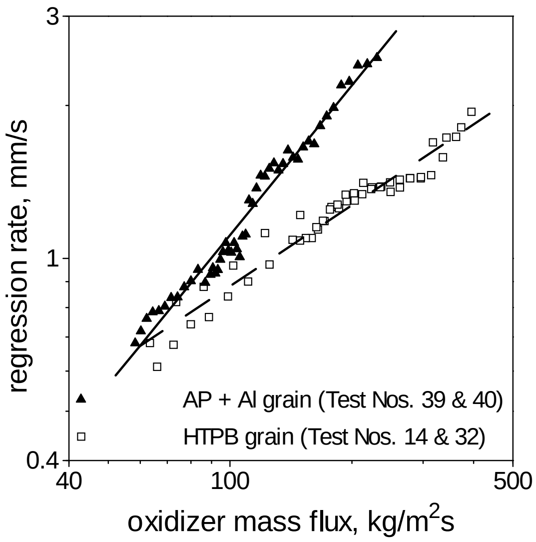

Fig. 7 Regression rates of HTPB grains with initial port diameter = 20 mm and AP + Al grains with initial port diameter = 12 mm.[18]

In 1996 Philips Laboratory has reported to have investigated several cryogenic hydrocarbons. Gaseous and liquid hydrocarbons have been solidified at the cryogenic temperature and investigated for their suitability as hybrid fuel. Compared to conventional hybrid fuels one order of magnitude enhancement in regression rate without premature melting or sloughing of cryogenic solid fuel has been reported.[8]

In 1998, Orbital Technologies in the US (ORBITEC) reported to be studying the cryogenic hybrid rockets by using frozen gas/liquid, such as hydrogen peroxide, oxygen, carbon monoxide, acetylene, methane, or hydrogen as solid grain. After the exploratory phase, ORBITEC seems to have chosen a solid oxygen and liquid hydrogen system for further investigation. The Air Force Rocket Propulsion Directorate has been conducting similar experiments and also funding the studies of ORBITEC.[10,11]

Additives

In order to enhance the regression rate of solid fuel, under the other chemical route, *viz.*, identifying some additives to the conventional hybrid propellants, Strand et al.[14] supported the inclusion of particulate additives (aluminum and/or coal) in solid fuel as an approach to enhance fuel regression rate. In addition to enhancing the regression rate, the inclusion of aluminium particles increases the specific- as well as density-specific-impulse. However, the hybrid rocket with aluminized fuel is less environmental friendly because its exhaust contains the oxides of aluminium. Ramaholli et al.[15] claimed a 30% increase in regression rate of HTPB fuels with the use of a "chemical bond-breaking catalyst". In 1996, McDonnell Douglas Aerospace completed a fuel development programme. The higher performance second generation fuel is based on a combination of amine fillers that enables tailoring of the regression rate exponent. The fuel's characteristics include higher density with higher density-specific impulse and higher regression rate. EAC in 1997 reported an enhanced regression rate by using an azide-based polymer for the fuel grain.

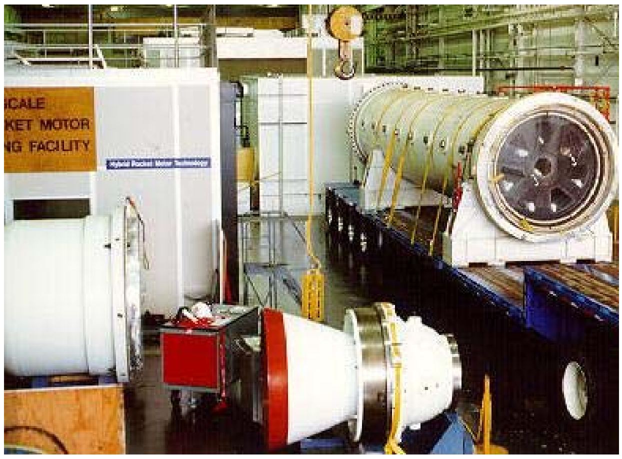

Fig. 8 Hybrid motor assembly at NASA- Marshall — note the wagon wheel grain configuration for the fuel grain (adopted from www.nasa.gov).

Physical Routes to Enhance Fuel Regression-Rate

Under the physical routes to enhance the regression rate of solid fuel there can be two methods: 1) by changing the characteristic dimension(s) of the port and 2) by changing the injection pattern of the liquid propellant.

Characteristic Dimension of Fuel Grain-Port

The studies to enhance the regression rate by changing the characteristic dimensions are as follows. Korting et al.[16] conducted experimental study with PMMA and polyethylene as fuels, and oxygen and oxygen-nitrogen mixtures as oxidizers. One of their important observations was that a rearward facing step could have a noticeable effect on combustion behavior — increasing the regression rate by changing the profile of the burned fuel grain. Lewin et al.[17] by their experimental study in a GOX /HTPB hybrid motor showed that the fuel grains of shorter length (89 mm) had a higher regression rate than that of longer length (203 mm). George et al.[18] conducted a systematic experimental investigation on the methods of enhancing the regression rate in GOX/HTPB hybrid rocket motor. The effects of the addition of ammonium perchlorate (AP) or aluminum in the fuel, the variation of oxidizer-fuel ratio, and the variation of characteristic dimensions of fuel grain are presented. While the addition of AP and/or Al, and the reduction of grain port diameter enhance the regression rate, the effect due to the latter (the physical effect) is the most significant one, Fig. 7.[18]

By considering Eq. (2), it is clear that the regressing area of the fuel grain, A_f, determines the motor configuration. For the possible *base-regression rate* of fuel, by choosing a grain configuration that gives a large burning perimeter, the length of the grain can be brought down to give an acceptable L/D ratio —a non-awkward motor envelope. This is usually achieved by choosing a wagon wheel grain for the hybrid rocket (see Fig. 8) that gives large burning perimeter. Furthermore, the wagon wheel grain with its multiple ports has a smaller characteristic dimension compared to a single cylindrical port, and this enhances the regression rate above the *base* value. This choice of wagon wheel grain, however, sacrifices the structural- and process-superiority that is possible with a simple cylindrical port.

Vortex Hybrid Rocket Motor

The studies to enhance the regression rate by changing the injection pattern of the liquid propellant are as follows. There are two methods reported in the literature. The two methods seem to be fundamentally same on the point of view of the fluid dynamics of oxidizer injection and port flow.

The first method is that of FIGG, proposed by the Propulsion Directorate of the US Air Force for its development of hybrid propulsion for tactical missiles. And, this has been previously dealt under section USAF. The clarity of information on the method is lacking.

The second method is known as vortex hybrid method, reported by Orbital Technologies.[10, 11] In this, rather than using a wagon-wheel design having a large number of ports for combustion, the concept uses a co-rotating, counter-flowing combusting vortex in a cylindrical, single central port of the fuel grain. The nozzle-end injected oxidizer spirals up along the wall towards the head-end, causing very accelerated regression, and then migrates to the port centre, where it spirals down towards the nozzle end and exits. For this enhanced regression rate, one has to meet with enhanced stagnation-pressure loss in the combustion chamber. Also, the exiting nozzle flow may have some vorticity that may give a wanted/unwanted spin to the rocket. The vortex hybrid concept is said to increase the fuel regression rate by up to a factor of 10.

The vortex-hybrid concept was demonstrated at thrust levels up to 1330 N (300 lbf). The idea is being developed by the Orbital Technologies under NASA peroxide hybrid programme.

Conclusions

Hybrid technology is maturing and has been endorsed for flight. Sounding rockets using hybrid rocket concept have been flight proven. Hybrid rocket motor products could include: small and large boosters for use in sounding rocket applications, tactical missiles, university class satellite launches and low Earth-orbit launches; strap-ons for expendable and reusable launch vehicles; smaller specialized motors for use in upper stages; and for complete launch systems. The technology of propulsion by hybrid rockets has moved from the level of ground testing to that of flight-testing. The next few years should define the technology's place in the launch- and missile-industry.

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