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REVIEW PAPER

Hybrid Rocket Technology

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ABSTRACT

With their unique operational characteristics, hybrid rockets can potentially provide safer, lower-cost avenues for spacecraft and missiles than the current solid propellant and liquid propellant systems. Classical hybrids can be throttled for thrust tailoring, perform in-flight motor shutdown and restart. In classical hybrids, the fuel is stored in the form of a solid grain, requiring only half the feed system hardware of liquid bipropellant engines. The commonly used fuels are benign, nontoxic, and not hazardous to store and transport. Solid fuel grains are not highly susceptible to cracks, imperfections, and environmental temperature and are therefore safer to manufacture, store, transport, and use for launch. The status of development based on the experience of the last few decades indicating the maturity of the hybrid rocket technology is given in brief.

Keywords: Solid grain, oxidiser, propellant, hybrid, regression rate, specific impulse, ignition

1. INTRODUCTION

Any propulsion system that is not entirely homogeneous can be called a hybrid, but the classic hybrid rocket motor that interests the propulsion community today might best be described as a combination of a solid and a liquid system. More specifically, it is usually a motor using a solid fuel and a liquid oxidiser as shown in Fig.1. It could be the reverse, a solid oxidiser and a liquid fuel, but the availability of suitable fuels and oxidisers favours the former combination.

1.1 Advantages of Hybrid System

A hybrid system has several advantages over its solid and liquid counterparts. Notable among them is safety of handling, storage, and operation. The safety of the hybrid rockets stems from the physical separation of the liquid and solid ingredients. The chemicals used are such that even if uncontrolled amounts of the liquid oxidiser come in contact with the solid fuel, the reaction is non-explosive or nonflammable unless purposely ignited. In considering very large engines or those which must be subjected to harsh handling, one of the tremendous advantages of any hybrid solid fuel is that the grain can be cracked or broken without having any effect on its burning. It has been conclusively verified that burning does not take place within cracks or between the grain and the combustion chamber wall of a hybrid motor[1].

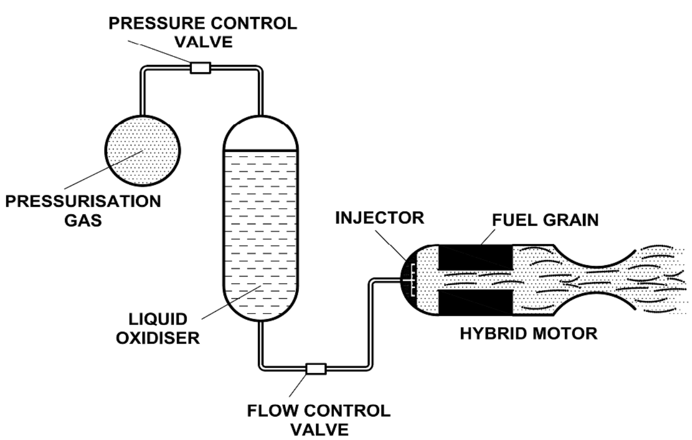

Figure 1. Schematic of hybrid rocket motor.

Another advantage of hybrid rocket over an all-solid system is the very high mechanical properties of the solid fuel grain. The binder content of a propellant grain for an all-solid system is usually kept to the lowest practical level whereas the binder level in hybrid fuels is high, leading to much better mechanical properties. Since the solid is separated from the liquid phase, one can also use highly energetic ingredients in the solid grain.

Probably the most important advantage of hybrid rocket motors over the solid rockets is their ability to change thrust over a wider range, and to shutdown and restart. The vehicle can be made safe and inert by stopping the oxidiser flow to the motor and venting the oxidiser tanks. Regenerative nozzle cooling and liquid injection thrust vector control are the other added advantages over pure solids.

In comparison with the liquid engines, hybrid rockets require only half as much feed system hardware, and therefore, can be less complex with higher reliability. The specific impulse of hybrid rockets is generally higher than solid rockets and the density-specific impulse

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is greater than liquid bi-propellant rockets. However, the former system very significantly enhances safety.

Further advantages of hybrid motors are that these minimise health hazards, environmentally benign, safe to manufacture, test, process, and operate. The hybrid fuels have a TNT equivalence of zero. Capital cost is also moderate, since there is no significant investment in special facilities or personnel safeguards.

1.2 Disadvantages

Apart from the innate reluctance of introducing a new system, certain disadvantages led to non-operationalising the hybrids in a big way. The mixture ratio tend to shift during the steady-state operation of a hybrid motor even if the oxidiser mass flow is held fixed and so is the specific impulse. Their combustion efficiencies (0.93 to 0.97) are low compared to liquids or solids. They have lower density-specific impulse and thus a larger system volume than solids and leave large slivers.

A major limitation however is the regression rate characteristics of the solid fuel in hybrid systems. Regression rates tend to be very low, an order of magnitude less than the state-of-the-art solid propellants and is dependent upon the fuel grain geometry. Another serious problem that cropped up during the development phase of hybrid rocket motors was the pressure oscillations that can appear under certain conditions. Although these are not unstable, these have reached in some cases double the motor operating pressure.

2. EARLIER DEVELOPMENTS IN HYBRID ROCKET TECHNOLOGY (1930-1970)

An interesting discussion of the history of hybrid rocket development is presented by Altman.[2] The very first reported experiment on a hybrid rocket motor in the late 1930's was conducted by Smith and Gordan. In the same period, Oberth in Germany did some work on LOX-graphite rocket[2].

The Pacific Rocket Society successfully flew a hybrid rocket with LOX and a rubber-based fuel reaching an altitude of 30,000 feet in June 1951. During the late 1940's, Moore and Berman tested a hybrid rocket motor with 90 per cent hydrogen peroxide (H_2O_2) as oxidiser and Polyethylene (PE) as fuel.[2]

In 1952, William Avery of Applied Physics Laboratory, USA introduced the idea of a reverse hybrid rocket motor using jet propellant as liquid fuel and ammonium nitrate as solid oxidiser[1]. Both Thiokol and United Technology Centre, USA further studied other versions of the reverse hybrid in the mid-1960s. This approach was eventually abandoned because of poor combustion behaviour and insignicant performance improvement compounded with the difficulties encountered in compressing the charges.

During the 1960's, ONERA in France used a hypergolic propellant combination based on red fuming nitric acid (RFNA) and an amine fuel consisting of metatoluene diamine/nylon[2]. The motor was capable of throttling over a range of 5:1 to optimise flight performance. The Volvo-Flygmotor in Sweden used a hypergolic combination of nitric acid and tagaform (polybutadiene with an aromatic amine).

The Sand Piper Programme of the United States Air Force in the mid 60's was a target drone vehicle based on a storable propellant combination composed of Mon-25 (25 per cent NO, 75 per cent N_2O_4) as an oxidiser and a polymethylmethacrylate (PMMA)-magnesium (Mg) as fuel. To meet the requirement of a heavier payload, a modified version of Sand Piper was later introduced by the US Air Force known as high altitude supersonic target (HAST).

A series of studies was sponsored by National Aeronautics and Space Administration (NASA), USA in the mid 60's on high-energy space engines[2]. One concept was based on the utilisation of the very energetic reaction between lithium and fluorine, by incorporating lithium in an hydroxyl-terminated polybutadiene (HTPB) binder and fluorine mixed with oxygen to create what is known as FLOX.

Other combinations attempted were oxidisers like chlorine/fluorine compounds such as ClF_3 and ClF_5 with high-energy fuels like hydrides of metals such as beryllium and aluminum mixed with suitable polymeric binders. NASA researchers also conceived an idea on high performance space engine based on the beryllium-oxygen-hydrogen reaction. Regression rates of metalised and non-metalised hybrid fuels were conducted by the Lockheed Propulsion Company in the early sixties based on lithium hydride-butyl rubber-fluorine-oxygen system[3,4].

3. DEVELOPMENTS IN HYBRID ROCKET TECHNOLOGY DURING 1970-1990

The work on hybrid systems continued even though there was a slight lull in interest on hybrid rockets during the 1970-1990. In India, experimental studies on hybrid systems for aniline formaldehyde-RFNA and PVC plastisol-LOX combination were conducted by Durgapal and others at Birla Institute of Technology (BIT), Ranchi, in the 1970's[5-7]. Twenty-five firings were carried out and significantly, the relation between the upper limit of oxidiser flow rate and the port area for combustion was established. The effect of aluminised PVC plastisol was also investigated at BIT, Ranchi for improving the regression rate and empirical relationship obtained between metal loading and regression rate[8]. Theoretical and experimental studies on hybrid combustion were conducted by Gany and others at the Israel Institute of Technology, Technion, during this period[9].

In the 1980's, Paul, Mukunda, and others successfully conducted experiments at the Indian Institute of Science (IISc), Bengaluru using RFNA and rubberised difurfurylidene cyclohexanone for a hypergolic fuel system[10]. This work brought out the effect of liquid-solid heterogeneous reactions in hypergolic hybrid system.

A US company Starstruck in 1984, launched out of the water a 30,000 pound thrust hybrid rocket[11]. Thikol and General Dynamics, USA in 1990, did static tests of a 25,000 pound thrust HTPB/LOX system. The interest in large-scale hybrid rockets gained renewed attention.

4. DEVELOPMENTS IN HYBRID TECHNOLOGY DURING 1990-2000

Under a Space Act Cooperative Agreement, NASA/ Marshall Space Flight Centre and industry initiated a Joint Government/Industry Research and Development Programme (JIRAD) in March 1992 for applied research in hybrid propulsion[11,12]. JIRAD addressed issues of hybrid motors such as:

- fuel regression rate characteristics,
- fuel web burn out,
- combustion efficiency,
- combustion stability,
- throttling characteristics, and
- nozzle throat material response.

HTPB and gaseous oxygen (GOX) were used as fuel and oxidiser respectively. The scaling effects for large size motors testing was established[13].

Another major effort initiated by the Defence Advanced Research Projects Agency (DARPA) of the USA was the hybrid technology option project (HyTOP) in 1994[12]. The aim of the HyTOP was to bring large-scale hybrid motors to flight status. This project envisaged building of 4 1.1MN developmental hybrid motors (H-250K).

The Hybrid Propulsion Demonstration Programme (HPDP) was established in 1995 by NASA and the US Industry Consortium as a continuation of HyTOP to provide a single directed effort to bring hybrid propulsion technology to maturity. Under HPDP, 19 static tests of 11-inch diameterand 24-inch diameter sub-scale LOX/HTPB hybrid motors were successfully completed at NASA-Marshall. These sub-scale motor firings successfully demonstrated non-pyrotechnic ignition, combustion stability and efficiency.

In a significant effort, the Environmental Aero Science (eAc) successfully demonstrated four hybrid rocket flights from NASA's Wallops Flight Facility during 1996-97[12]. This hybrid rocket named Hyperion Launch Vehicle was developed under the Sounding Rocket Programme of HPDP. The Hyperion Sounding Rocket used nitrous oxide (N_2O) and HTPB as the oxidiser and fuel, respectively, and achieved an altitude of 36.6 km. Encouraged with these successes, Environmental Aero Science, in conjunction with Cesaroni Technology, initiated a Performance Enhancement Programme on its Hyperion Sounding rocket to reach an altitude of 61 km.

Another major player involved in the HPDP programme was the American Rocket Company (AMROC). The Company made significant contributions in the development of hybrid motors for orbital and sub-orbital vehicles and other propulsive stages[12]. In 1993, it conducted four tests of its 1.1MN hybrid motor using liquid oxygen and HTPB grain. In 1995, the design and development of the first turbo pump-fed LOX/HTPB hybrid motors were taken up by the company and final static test firing conducted in 1999. AMROC was also active in developing hybrid motors that use N_2O as an oxidiser for small-scale 0.18MN thrust.

The United States Air Force Academy and the Air Force Research Laboratory (AFRL) in January 1994, successfully launched a 6.4 m long, 2670-N thrust LOX/HTPB hybrid rocket to reach 3-km altitude. In 1995, this rocket was modified to deliver 3570-N for 15s to reach 4.6 km altitude. The United States Air Force Academy also studied the auto ignition in hybrid rocket that used H_2O_2 and regenerative cooling of hybrid rocket nozzle using N_2O[12].

The Air Force Research Laboratory is working on a concept called forward injected gas generator (FIGG) hybrid, the details of which are not available in open literature. It appears that FIGG concept uses high-density storable oxidisers and gas generator solid fuels. By applying this concept, AFRL claimed to have achieved a high fuel-regression rate, very stable combustion, on-demand throttling, and the ability to extinguish during the test and restart. AFRL, along with Thiokol, and Rocketdyne are collaborating with the Technical R&D Institute of Japan to develop FIGG hybrid propulsion for tactical missiles.

Several studies have been reported about the use of dual-mode hybrid rocket operation[12]. The combination of a monopropellant in a hybrid rocket motor offers the possibility of having this mode of rocket operation. In the dual mode of operation, the liquid monopropellant and the solid grain together can act as a hybrid rocket while the liquid monopropellant alone can act as a monopropellant 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 spontaneous, and hence, the rocket is re-startable more readily and reliably. Researchers from Raefel in Israel have claimed in 1996 the realisation of a dual-mode hybrid rocket using hydrazine as the liquid fuel monopropellant.

In the late 1990's, George, Krishnan and others carried out systematic experimental investigations for regression rate enhancement for HTPB/GOX system at the Indian Institute of Technology Madras, Chennai[14]. Regression rate correlation of HTPB/GOX system with addition of ammonium perchlorate (AP) and/or *Al* was obtained from more than 40 tests conducted.

5. DEVELOPMENTS IN HYBRID TECHNOLOGY DURING 2001-10

Lockheed Martin began work under cooperative agreement with NASA to develop a low-cost hybrid-based sounding rocket system. On 18th December 2002, it launched a 60,000-lbf-thrust multi-port HTPB/*Al* sounding rocket from NASA Wallops Island Flight Facility[15]. The rocket did not reach the target apogee altitude apparently because of a partial structural failure of the multi-port fuel grain. Even so, this LOX-fed vehicle represents a significant advance in hybrid rocket technology.

One of the most significant hybrid development efforts in industry in the recent past is the development of propulsion system for SpaceShipOne, an X-prize entry built by Scaled Composites Inc[16]. On June 21, 2004 SpaceShipOne successfully lofted a spacecraft into a low-earth orbit using a nitrous oxide-fed HTPB-based hybrid rocket motor.

Work at Stanford University in collaboration with NASA, Ames, has lead to the identification of paraffin (SP1A)-based high regression rate fuels. Two 4-inch sounding rockets were successfully flown as part of the Standford/ Lockheed Martin Rocket Engineer Programme in 2004, which demonstrated the liquefying hybrid technology[17]. Different types of propellants with higher regression rates are being researched world over, and one such candidate is an ethanol with gelling agent-based propellant[18].

6. STUDIES IN HYBRID ROCKET TECHNOLOGY

6.1 Regression Rate Enhancement

McDonnel Douglas Aerospace has developed a high performing second-generation fuel, based on a combination of amine fillers that enables tailoring of the regression rate exponent. The characteristics of this fuel include higher density with higher density-specific impulse and higher regression rate. Environmental Aero Science also reported an enhanced regression rate using an azide-based polymer for the fuel grain[12].

Strand, *et al.* supported the inclusion of particulate additives like aluminum and coal in solid fuel to enhance regression rate[19]. Researchers at Pennsylvania State University conducted a series of investigations and found that the addition of ultra-fine aluminum powder having mean particle size between 0.05 μm and 0.10 μm could significantly increase both regression rate and mass burning rate compared with pure HTPB.[20] The mass burning rate increased by 70 per cent, over that of pure HTPB. Based on observations of the different fuel surfaces, the primary mechanism of regression enhancement is thought to be associated with aluminum heat release or particle micro-explosion at or near the solid fuel surface.

George, *et al.* conducted experiments on HTPB/ GOX hybrid rocket motor and brought out the effects of addition of AP or aluminum in the fuel, the variation of oxidiser-fuel ratio, and the variation of characteristic dimensions of fuel grain[14]. While the addition of AP and/or *Al*, and the reduction of grain port diameter enhances the regression rate, the effect due to latter (the physical effect) is the most significant.

One of the effective ways of increasing regression rates is the addition of solid oxidiser (AP) in the fuel in small percentages. This configuration is called mixed hybrid, and regression rate enhancement higher than 400 per cent is reported[21]. Mixed hybrid of HTPB with addition of ammonium nitrate (AN) up to 30 per cent and GOX as oxidiser shows that increasing levels of solid oxidiser decreases motor performance[22].

A high paraffin-based fuel having 3-4 times higher regression rate has been demonstrated at Stanford University[23]. Regression rate characterisation for a series of castable grains was conducted for a nitrous oxide hybrid motor[24]. Studies to improving regression rate using helical grain configurations were conducted, though substantial benefits were not seen[25].

6.2 Vortex Hybrid Motor

It is possible to enhance the regression rate of fuel by different methods of oxidiser injection. One of the methods is the vortex hybrid motor proposed by Orbital Technologies Corporation, USA[26].

The key characteristics of this engine is a unique co-axial, co-swirling, counterflowing vortex pair that has been found to induce much higher solid fuel regression rates than those of similar classical hybrid engines. To generate this flow field, oxidiser, such as GOX is injected through a swirl injector located between the aft end of the fuel grain and the inlet of the converging portion of the exit nozzle. The injector ports are aligned circumferentially tangent, or nearly so, to the fuel grain surface.

Figure 2 shows a schematic diagram of the vortex

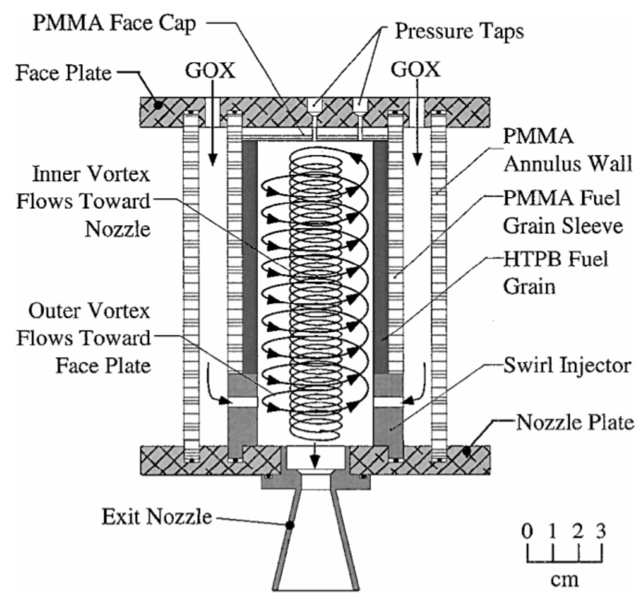

Figure 2. VH-20 engine schematic[22].

hybrid engine (VH-20). Both PMMA and HTPB fuel grains were tested in the engine. Engine throttling and restart were demonstrated as well. Average solid-fuel regression rates up to seven times faster than those in similar classical hybrids were measured in the vortex hybrid engines. Reasonably uniform regression rate profiles along the length of the grain port were obtained with proper swirl injector design. The test programme demonstrated successful throttling and restart of the vortex hybrid engine.

6.3 Liquefying hybrids

A fast burning, long chain hydrocarbon-based (non-polymeric) paraffin hybrid fuel has been developed and successfully tested by researchers at Stanford University in a lab-scale motor[27]. The results indicate regression rates 3-4 times larger than the rates of the conventional polymeric fuels. These newly identified high regression rate fuels burn in a fundamentally different way than the slow-burning, evaporative-diffusive-dominated combustion process of conventional hybrid fuels.

During combustion, a thin, hydrodynamically unstable liquid layer forms on the melting surface of the fuel. Entrainment of droplets from the liquid-gas interface substantially increases the rate of fuel mass transfer, leading to much higher surface regression rates than can be achieved with conventional polymeric fuels (hence, the term liquefying hybrids).

To further demonstrate the feasibility of this approach, a series of scale-up tests using several oxidisers, including GOX, LOX, and N_2O_2, were carried out on intermediate-scale motors. A new hybrid test facility designed to study these fuels was developed by NASA and Stanford researchers at NASA-Ames and commissioned in September 2001. More than 30 tests have been carried out using a scale-up motor of 10 inch outer diameter and of 3000-lbf thrust. These test data are in agreement with small-scale low pressure and low-mass-flux laboratory tests and confirm the high regression rate behaviour of the fuels at chamber pressures and mass fluxes representative of commercial applications.

6.4 Hydrogen Peroxide Hybrid Rocket

The monopropellant H_2O_2 has attracted the interest of propulsion community as a possible alternative to hydrazine-based propellants[28]. The major advantages of H_2O_2 are its high density, storability, non-toxic nature, high oxidiser to-fuel ratio for optimum operation, low vapour pressure, and high specific heat. Also, hybrid rockets with H_2O_2 as the oxidiser can be used in a dual-mode operation.

The researchers at Purdue University have conducted a number of experiments using concentrated H_2O_2 as oxidiser and PE as fuel and regression rate characterisations have been obtained[29]. They developed a consumable catalyst bed for the disintegration of H_2O_3 and also demonstrated the spontaneous ignition of the PE fuel.

Systematic experiments on a lab-scale hybrid rocket motor using concentrated H_2O_2 as oxidiser (>86 per cent) and HTPB as fuel, were demonstrated[30]. Hybrid motor employing H_2O_2/PE combination with improved ignition devices was demonstrated successfully at Tokai University, Japan[31].

Studies were carried out at Carlton University, Canada, for metallised and non-metallised HTPB with H_2O_2 and regression rate correlation obtained. A numerical model for predicting the regression was also developed[32].

6.5 Issues of Thrust Throttling

Hybrid motors can be throttled by regulating the flow rate of liquid oxidiser. But the trouble is that, the fuel flow rate depends on the total propellant flow rate and does not vary linearly with the change in oxidiser flow. Usually, as the thrust is decreased by reducing the oxidiser flow rate, the mixture ratio decreases making the system increasingly fuel-rich.

Experimental attempts were made to compensate for this problem by injecting the oxidiser at both the ends of the chamber; that is, the amount of oxidiser needed to maintain the proper mixture ratio, was added to the after burner region (between the fuel grain end and the nozzle). Even though this works, the penalty is through the added system complexities and weight.

Another approach was to develop a pressure-sensitive fuel, so the change in chamber pressure, which results from the change in liquid flow rate, will compensate for the difference in response of the solid fuel to throttling[1]. A method for real-time control of mixture ratio and chamber pressure in a hybrid motor using an ultrasonic pulse-echo technique was suggested by Boardman[33], *et al.* The technique allows rapid sequential measurement of fuel web thickness during motor operation at multiple combustion port axial locations, thereby enabling direct computation of instantaneous fuel regression rate, fuel flow rate, and ultimately, motor operating mixture ratio. Using such data, oxidiser flows into motor combustion ports and the aft mixing chamber of a hybrid motor can be varied to achieve operation at a constant pressure and constant mixture ratio.

The capability of a N_2O/HTPB hybrid rocket motor for thrust modulation for a specified mission is demonstrated by calculation[34]. For most of the present-day applications, the system design is optimised over the range of mixture ratios encountered with very little degradation of average specific impulse due to throttling.

6.6 Combustion Instabilities in Hybrid Rockets

Though the hybrid combustion process tends to produce somewhat rougher pressure versus time characteristics than either liquid or solid motors, unbounded growth of pressure oscillations has not been observed in many hybrid motor firings. So it is believed that a well-designed hybrid rocket would typically limit combustion roughness to approximately 2 per cent to 3 per cent of mean chamber pressure.

However, tests conducted at NASA's Marshall Space Flight Centre on 11 inch diameter hybrid motors utilising a gaseous oxygen/HTPB propellant system have produced large amplitude combustion pressure oscillations at both acoustic and non-acoustic frequencies[35]. Other experimenters have also revealed similar behaviour in smaller laboratory-scale hybrid motors using the same propellant system. Acoustic oscillations have exhibited a frequency approximating the first longitudinal acoustic mode of the combustion chamber.

Hypotheses for the cause of the oscillations have included periodic vortex shedding from fuel grain faces and en masse flaking of pyrolised combustion products from the fuel grain surface[36]. This is attributed to the mixing of un-reacted fuel and oxidiser in a periodic fashion.

The most probable cause of instabilities in sub-scale motors using gaseous oxidisers is found to be from inadequate flame holding. The sub-scale tests indicate that the motor internal configurations establishing a hot-gas re-circulation zone at the leading edge of the diffusion flame sheet produced stable combustion. Configurations lacking this flow feature exhibited spontaneous, nonlinear, large-amplitude chamber pressure oscillations at acoustic frequencies[36].

Out of the two basic types of instabilities exhibited by hybrid motors in static test environments, the oxidiser feed system-induced instability (non-acoustic) is essentially a chugging type and arises when the feed system is sufficiently soft. Stiffening the feed/injection system can eliminate this oscillation. This is accomplished by increasing the injector pressure drop and eliminating sources of compressibility in the feed system[37].

The flame-holding instabilities in hybrids are typically manifested at acoustic frequencies and appear in longitudinal modes. Flame-holding instabilities arise due to inadequate flame stabilisation in the boundary layer and are not associated with feed system flow perturbations.

Flame-holding instability can be eliminated by several means, all of which act to stabilise combustion in the boundary layer. The first method is to use a pilot flame derived from injection of a combustible fluid such as hydrogen or propane to provide sufficient oxidiser preheating in the leading-edge region of the boundary layer flame zone[33].

A second method involves changing the injector flow field to ensure that a sufficiently large hot gas re-circulation zone is present at the head-end of the fuel grain[36,38], Fig.3 (a & b). Such a zone can be created by forcing the upstream

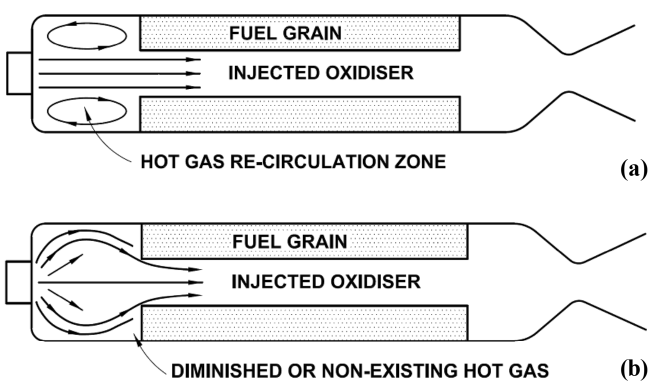

Figure 3. (a) Strong, and (b) weak re-circulation zones in axial injection[38].

flow over a rearward-facing step, at the head-end of the diffusion flame. Conical injection generally produces a much smaller and usually ineffective re-circulation zone.

The re-circulation zone acts to entrain hot gas from the core flow, which provides sufficient oxidiser pre-heating for the leading edge of the boundary layer diffusion flame to stabilise combustion.

Despite recent advances in understanding causes of and solutions for combustion instability in hybrid motors, development of a comprehensive, predictive theory of combustion stability remains one of the major challenges in hybrid rocket technology development[38].

6.7 Theoretical Modelling

Several prediction methods have been evolved for estimation of regression rates for different fuel/oxidiser combinations. A convective heat feedback modelling approach was applied and results compared well with the experimental data[39]. A space-time averaged regression rate expressions has been developed for hybrid rockets[40]. Applied mixture theory is being used for estimation of hybrid propellant characteristics such as regression rate and specific impulse[41]. An enthalpy-balance model, in which fuel-grain ablation heat is balanced by convective heat transfer from the combustion flame, compares well with the experimental data[42].

A preliminary step towards computational fluid dynamics studies were undertaken for the 24" JIRAD hybrid rocket motor to understand flow field characteristics by applying multi-phase, multi-species combustion modelling[43]. Yang[44], *et. al.* developed a model based on the fluid heat coupling method and dynamic mesh technique[44]. It is seen that serious work is not yet attempted in the application of computational fluid dynamics to hybrid rockets. Computational fluid dynamics can play a major role in resolving the hybrid flow field and scaling issues in hybrid motors which are currently not well understood[38].

7. APPLICATIONS OF HYBRID ROCKETS

The feasibility of most of the outstanding features predicted for hybrids has been demonstrated; namely high impulse performance, start-stop operation, thrust modulation, temperature and pressure insensitivity, and efficient throttling over a range of 10 to 1. Successful tests have been completed over a wide range of thrust levels from < 0.1 to > 250,000 lb and for durations from 0.1 s to 300 s. Some remaining features, such as suitability for segmenting and clustering, appear even more probable than were several years ago, but their demonstration must wait for more ambitious programmes than those now in progress.

7.1 Applications for Space Vehicles

There is a large interest in hybrids for very large boosters of space shuttle class. Also, hybrid engine providing very low thrust levels for large durations and capable of at least 20 or 30 re-starts can be employed for space vehicles, intended for manoeuvering and attitude control. Hydrogen peroxide hybrid rocket motors are ideal candidates for upper-stage missions because of their spontaneous ignition and non-toxic characteristics.

Several engines can even be clustered to operate from a single pressure-fed liquid tank. The engines can be independently modulated to operate at different thrust levels, and their directions of thrust can be modified using a liquid thrust vector control system operated off the main tank. Hybrid propulsion is particularly attractive for space missions that call for long-term coasting or storage with intermittent operation. Hybrids offer extreme resistance to space environments, along with simple on-off, very precise impulse, and modulated thrust control.

7.2 Applications in Missiles

Several rigid combustion chambers coupled to a single oxidiser tank can provide the single, continuous, fixed or programmed thrust required for large missiles. In a totally storable system, and under the usual ordnance restrictions, a design of this type can provide specific impulses of 20 s to 40 s above those of conventional solids[44].

Hybrid motors can be used exclusively or in combination with solid motors for missiles systems. One concept is to have a large post-combustor which initially has solid propellant for the boost phase of the missile and the sustainer phase to operate for long duration in hybrid mode. In case of air-to-air missile, where safety of carrier aircraft is of utmost importance, dual-thrust hybrid system is an attractive choice for enhanced range.

CONCLUSIONS

Though the research in hybrid rocket propulsion was making rapid developments in the past several years, it wasn't given serious attention by vehicle engineers, probably because of the gap thatexisted between actual versus theoretical performance. There were many problems which prevented their entry into the industry in a big way, such as low recovery of theoretical specific impulse, uneven fuel burnout along the length of combustion chamber, unpredictable decay in thrust level with time, high losses in efficiency with thrust modulation, and low regression rates. Many of these problems seemed insurmountable, but solutions at least adequate to permit practical application have been found for all of them.

With the increased emphasis on safety becoming an ever important factor, especially for manned missions, a hybrid rocket is a viable alternative. The successful use in SpaceShipOne has finally demonstrated that hybrid propulsion has come of age and will be further enhanced for use in many other systems.

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