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Hybrid Rocket Motors Propellants: A Historical Approach

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Abstract. *This paper brings a historical perspective about the development of hybrid propellants rocket motors. The concept for hybrid propellants has been known for more than 50 years. Initially it was used in small rockets built to military specifications during 1960s to 1980s. Despite the advantages of hybrid propellants against solid and liquid rocket motors, and the experience acquired during two decades, a hybrid rocket motor has never been developed for launcher vehicle or space vehicle until this century. This occurs because the classical hybrid propellants used polymeric fuels, which have a low burning rate, leading to a complex geometry fuel grain. Numerous tests with different configurations of grain geometry, injector geometry and position, types of injection and metal addition were carried out to increase the regression rate, leading to a rocket motor with a complex injector system that forces a rate five times greater rate. In the early 1990s, several US research groups began to investigate cryogenic fuels. During the tests with solid hydrocarbons, regression rates ten times higher than those of classical polymeric fuels were found. Combining those hydrocarbons fuels with some of the injection and metal doping techniques, rates twenty times greater than the classical were achieved. After many series of tests and experimental analyses, a mathematical theory that describes this type of fuel were developed and extended to cryogenic and non-cryogenic fuels, the Liquefying Hybrid Propellants.*

Keywords: *Hybrid Propellants, Hybrid Rocket, Historical Review*

1. INTRODUCTION

According to Humble *et al.* (1995) there are five rocket motor types able to generate enough thrust to lift a rocket, its fuel and payload, namely the cold gas motor, the solid, liquid, hybrid and nuclear propellant. Sutton and Biblarz (2010) also consider the electric motors, as the plasma, ionic and laser propulsion system. The cold gas has the advantage of simplicity, but lacks on performance, being used as positioning control systems on sattelites. Nuclear propellant rocket motors uses the energy of a fission reactor to heat a gas that will be accelerated at the nozzle. Notwithstanding the high specific impulse(I_{SP}) and thrust level, the ambiental and politics opposing factors and the system's complexity have been prohibitive in its operation. The eletric motors have the advantage of huge I_{SP}, two to six times greater than a liquid propellant rocket motor (LPRM), but they either don't generate enough thrust for rocket takeoff (ionic motor), (Choueiri (2004)), or, in the case of a laser motor, need complicated adaptative lens system to focus the laser at the rocket, (Resendes *et al.* (2007)).

The solid, liquid and hybrid propellant rockets are the most commom types used by mankind since 2000 B.C., with the discovery of the black powder. The solid propellant rocket motor (SPRM) has a high density since both oxidant and fuel are mixed before flight, is simply to operate, and is smaller than other rockets, but are hard to be manufactured, to be controlled and may explode easily. It has a low I_{SP} and the exaustion gases are commonly toxic, but it can easilly use metallic additives in the propellant grain, that may be even more toxic. The LPRM has a higher I_{SP} than SPRM, has lower toxicity and are safer, because the fuel and the oxidant aren't mixed untill they reach the combustion chamber, but has a lower density, a more complex system with injectors and pressurized tanks, and can't easilly use metallic additives. The greatest advantage of LPRM compared to SPRM are the interruption/throttling/restart capability, that increases its safety and allows the control of thrust generated by the rocket motor, (Humble *et al.* (1995)).

Hybrid propellant rocket motors (HPRM) combine the advantages and disadvantages of SPRM and LPRM. Since the standard type has a solid fuel with the injection of a liquid oxidant, it has a higher fuel density than LPRM and can use metallic additives, but has a lower I_{SP}, characteristic of a SPRM, and it also has the thrust termination and throttling/restart capability, like a LPRM. Being made of a solid component as the propellant, it requires a simpler, and lighter, system compared to LPRM, keeping its safety, allowing a easier manufacture and operation system, without the SPRM explosion hazard, (Bertoldi (2007)).

These characteristics made HPRM an attractive alternative to SPRM and LPRM, but some disadvantages limited its use to research and amateur groups. The low regression rate means that medium size rocket motor need multiple ports to provide enough burn surface area, what implies a low bulk density and large ammounts of residual fuel. These factors guided the research in the combustion mechanisms of a HPRM during the past eighty years.

There are several ways to divide the timeline of hybrid rockets history. Altman (1991) divides it as Early History, from 1933 to 1960, the Fundamental Studies Era, form 1960 to mid of the 1960s, the Large Size Rockets Project, from mid of the 1960s to mid of the 1990s, and the High Regression Rates, from mid of the 1990s to today. The same division is used by Altman, Chiaverini and Kuo (2007). Karabeyoglu proposes a division in three propositions, Early Hystory, Era of Enlightenment, from 1960 to 1980, and Recent History, from 1981 to present. Both propositions are correct, but the first better represents the changes in the Hybrid Rockets History, and will be used by the authors. However, the naming for the particular period of science development is most adequate in Karabeyoglu's proposition, and will be adopted for this work.

2. Early History

The development of Hybrid Propellants Rocket Motors starts in the 1930s, when solid and liquid rockets were at its initial development. The solid rockets were used first because the gunpowder history, and were used by renowed researchers as Robert Goddard, despite of warnings from Hermann Oberth, one of the pioneers in rocketry. The incidents involving explosions of gunpowder led to the use of liquid rockets. In the mean time, the first recorded work with hybrid rocket were made by Sergei Korolev and Mikhail Tikhonravov, in 1933, at the Russian program GIRD, which first flight reached 1.5 km using a 500 N motor that burned for 15 s a mixture of gasoline and collophonium(gelled gasoline) and LOX, (Chiaverini and Kuo (2007)).

In 1937, tests conducted at I. G. Farben with a 10 kN motor using coal and gaseous N_2O achieved the same unsuccessful results of Oberth's test with LOX and graphite, caused by the carbon's high heat of sublimation, leading to a almost null regression rate. In mid-1940s the Pacific Rocket Society did the first significant effort with a hybrid rocket. It used LOX with several solid fuels, as Douglas fir wood, wax with carbon black and rubber, Herrick and Burgess (1959) *apud* Chiaverini and Kuo (2007). The Society tested several designs until the XDF-23, a LOX oxidizer and rubber based fuel with a aluminum alloy nozzle successfully flew in 1951, reaching an altitude of around 10km. The Society didn't reported any ballistic test, but its knowledge is proven by the statement: "The chamber pressure of a solid-liquid rocket engine is proportional to oxidizer flow and not to the internal surface area exposed to the flame. Thus, there is no danger of explosions due to cracks and fissures in the charge as with solid propellant rockets commonly used for boosters", (Ewing (1947) *apud* Chiaverini and Kuo (2007)).

In the late 1940s untill 1956 George Moore and Kurt Berman made an analytical and experimental investigation at General Eletrics Company, using polyethilene as fuel and hydrogen peroxide as oxidizer, (Moore and Berman (1956) *apud* Altman (1991)). The objective of the analysis were to augment the performance of the H_2O_2 as a monopropellant, but they noticed that adding a small amount of that fuel(15%) resulted in an increase of I_{SP} of 70%. As a result, the authors concluded that longitudinal uniformity was remarkable, grain cracks didn't affect the combustion, hard starts were never observed, combustion was stable because the fuel surface acted as its own flameholder, throttling was easily accomplished with a single valve, and a high liquid-to-solid ratio was desirable to simplify uniform burning in the combustion chamber, and noted that the thermal instability of H_2O_2 was a problem, (Chiaverini and Kuo (2007)).

3. Era of Enlightenment

In the 1960s there was a great increase of interest in hybrid propulsion in the US Military Forces, such as U.S. Army, Navy and Air Force and ARPA(currently called DARPA), sponsoring around 40 research projects. The U.S. companies also started to research with its own funds, being the most known of them the Rocketdyne, Thiokol and, the most important of them, UTC.

The UTC group was the responsible for developing the solid rocket booster for Titan vehicle, but in 1959 David Altman started to assemble a group to investigate the fundamentals of hybrid combustion, which made several experiments during the 1960s. The development of the hybrid demonstrator in 1960 enabled provided a safe and inexpensive laboratory tool for investigating the combustion machanisms of hybrid propellants. During 10 years of use, more than a thousand tests were made, with dozens of fuels and oxidizers. In 1961, Marxman and Gilbert developed the first hybrid regression rate equations, published by Marxman and Gilbert (1962), Chiaverini and Kuo (2007).

One of the greatest accomplishments of that period was the development of regression rate models, by Marxman *et al.* (1963), that were based on schlieren photographs taken by Muzzy, and which could show both momentum and combustion layers, the impact of blowing on reducing the heat flux, the use of a total effective heat of vaporization to account for various thermal reactions at the surface and the contribution of radiation when coupled with convection. According to Chiaverini and Kuo (2007), this model is so complete that still being used.

The following years weren't remarkable by its scientific development, because the focus was at the development of the motors, studying refinements for the regression rate models, throttling transients and hypergolic fuels.

4. Large Size Rockets Projects

In the mid-1960s the small size hybrid rocket motors started to be scaled to large size rocket motors, with special attention to the HTM series of UTC and U.S. Air Force, that tested a 0.95 m diameter motor with N_2O_4 as oxidizer and Aluminized PB as fuel in a 12 port wagon-wheel grain that generated 20 kN of thrust, to the United Tech CSD, that achieved a measured I_{SP} of 400 s using polybutadiene and ammonium nitrate with lithium as fuel and F_2/O_2 as oxidizer, and to the LEX-02 that allegedly flew with polyamide and metatoluene as fuel and nitric acid and N_2O_4 as oxidizer achieving a thrust of 10 kN.

From mid-1960s to early-1980s there is a great lack of information. In this period there was an intense study in design of sounding vehicles with hybrid rocket motors and flight systems, but little information could be found.

In 1981 the STARSTRUCK Company was created to develop a 17 m long sounding rocket weighting 8.2 ton: the Dolphin. The propellants were LOX and PB fuel, achieving a thrust of 155.7 kN in a 1 m diameter motor. After 6 full-scale static tests it was launched form the coast of an island of Pacific Ocean, but due to a frozen thrust vector valve it worked for just 3 s, when it started to diverge in pitch and was self-destructed. At the time, the Dolphin was the biggest hybrid rocket motor ever flown, despite its short duration.

In 1985 the company was renamed to AMROC, and, with private funding, it started to design motors from 22.2 kN to 1.1 MN, based on LOX and HTPB. In the seven years that followed its restart, 124 static tests were made, more than a dozen with a 333.6 kN motor, the largest hybrid rocket motor ever tested until that time. Scaling the motor wasn't a problem since the UTC HTM-38 defined the pattern for the ports on the solid grain. In 1989 a rocket with a motor of 330 kN of thrust, named SET-1, was tested in the Pacific coast, but the freezing of an oxidizer valve during the launch made it tumble and it just burned the propellant. Despite this new failure, the company continued with the idea of launching a 1.1 MN rocket motor, as the first or second stage of the AQUILA vehicle. The motor was tested four times in 1993. To prove its worthiness, the project HyFlyer Sounding Rocket was created, but since the AMROC didn't have enough funds to develop a rocket capable to flight carrying a 644 kg payload to an altitude of 545 km for a 10 minutes gravity-free trajectory, the project were renamed Hybrid Technology Option Project(HyTOP), and a group of companies were called, under the command of AMROC, Martin Marietta and CSD, with the support of NASA. During 1993 and 1994, tests with the motor were carried out, but after a small time of burning, it suffered a low frequency instability. Work in the solution was too expensive, and in 1995 AMROC lost its sponsor and quit the project.

The program was again renamed, this time to Hybrid Propulsion Demonstration Program(HPDP), with Thiokol Company taking the place left by AMROC. The focus of the new project wasn't develop a flight vehicle, but the motor itself. The grain ports pattern was changed to one with fewer ports and one active central port, but a incomplete vaporization of the LOX in the entrance of the ports caused a low-frequency instability and high-amplitude pressure oscillations appeared on the oxidizer flow. The experience with all those tests, during ten years, showed the necessity to provide head end heating to vaporize the LOX before the entrance to the ports, Chiaverini and Kuo (2007).

5. High Regression Rate

The necessity to design a large size rocket booster was increased since 1986, due to the Challenger disaster, when NASA started to sponsor the replacement of solid rocket booster by hybrid boosters. In late-1990s, the major problem of large scale hybrid rockets was the low regression rate due to the diffusive nature of the combustion process, (Karabeyoglu *et al.* (2003)). The regression rate is the radial burn velocity of the solid fuel grain, causing a low thrust level.

Early efforts to augment the regression rates started in 1960s, using energetic fuel additives, such as ammonium perchlorate(AP NH_4ClO4) and ammonium nitrate(AN NH_4NO3). These systems were known as liquid augmented solid propellants, but there is a critical concentration of each combination above for which the fuel acts like a low grade propellant, becoming explosive. Other types of additives were tested, but in most cases, although effective, the method adds costs due to increased risk compared with a conventional hybrid engine, (Chiaverini and Kuo (2007)).

Another approach was to use designs that generate a high turbulence condition at the fuel burning surface, increasing the heat transfer coefficient. There are several ways to achieve it, adding a easily vaporized component that creates vacuoles to roughen the surface during its vaporization. This can be enhanced by the use of cristalline additives, as did Boardman *et al.* (1997), with swirling injectors or injection at the aft end of the chamber, as did by Knuth *et al.* (1998); Yuasa *et al.* (2001); Knuth *et al.* (2002); Lee *et al.* (2005). Caravella *et al.* (1998) tested an end-burning hybrid motor that used radial flow injectors to burn PE fuel with decomposed H_2O_2. The addition of metal particles in the solid fuel was also tested. Risha *et al.* (2002) conducted a series of experiments with HTPB based fuels and nanoparticles of aluminum, achieving higher values of regression rate than the pure HTPB.

5.1 Liquefiyng Hybrid Propellants

In the early 1990s, several research groups started investigating the regression rate and the combustion of hybrid motors using cryogenic fuels as solid ethylene and solid methane. The objective was to stabilize and combust high-energy density matter(HEDM), such as solid hydrogen 4 K with 8% of atomic hydrogen. Carrick and Larson (1995) developed a demonstration burner for testing solid pentane and solid ethylene, and showed that at the same conditions the fuel achived rates 3 to 10 times faster than PMMA. DeRose *et al.* (1997) tested eight different types of cryogenic solid hydrocarbons, and measured rates 2 to 10 times higher than HTPB. Motivated by the results found, Gramer *et al.* (1998); Clair *et al.* (1998); Rice *et al.* (2000) made similar tests at ORBITEC, but using a larger motor with differente fuels, and found that solid fuels have higher density than its liquid counterpart, that lower initial grain temperature caused reduction of regression rates, as did high percentages of aluminum in the fuel grain, but measured rates 10 to 20 times faster than HTPB. Despite the advantages, the complexity of storage and the unknown process to scale the motors are factor to be balanced.

The investigations on cryogenic solid fuels didn't explain why the regression rate was higher than classical fuel. There wasn't a theory or a model to explain its physics. Gramer *et al.* (1998) used frozen paraffin during the study of metallized cryogenic hybrid fuels, and noted that they also have a higher regression rate. Karabeyoglu *et al.* (2002a) stated that the fast regression rates couldn't be explained just by the low heat of vaporization, because in Marxman and Gilbert (1962) classical regression rate equation it appears only at the blowing factor, raised to a power 0.32, what would lead to an increase of no more than 50%, in comparsion to the 400% measured, Chiaverini and Kuo (2007).

Karabeyoglu proposed an alternative mechanism of mass transfer involving the entrainment of liquid droplets from the melting surface layer. As demosntrated in Karabeyoglu *et al.* (2002a,b) a liquid layer was formed in the burning surface of the solid grain, and the liquid droplets as the result of instabilities in this layer, caused by the high velocity gas flow in the port. The model was developed in three stages due to its complexity. The first stage was to investigate the formation of the melting layer, followed by the linear stability of the thin liquid layer under high shear stress, and finally the instability was linked to the entrainment of the droplets using experimental results and semi-empirical relations developed in nuclear engineering and film-cooling literature. As a last stage, the classical theory for the regression rate was extended to the liquid droplet entrainmentand, for that, three major changes were needed. The first was the effective heat of gaseification, which is reduced because the evaporation energy, used to transfer fuel mass from the surface, is partially avoided by the entrainment mechanism, and the enthalpy is reduced because a fraction of the fuel is now in the liquid state. The first mechanism is more significant than the second. Another change was necessary in the blowing factor, due to the presence of a two phase flow. At last, the ripples formed at the surface of the grains increase its roughness and the heat transfer from the flame front to the surface.

Using this theory, Karabeyoglu *et al.* (2004) formulated several non-cryogenic paraffin based fuels that were tested with various oxidizers, achieving 26.7 kN of thrust, and a regression rate 2.5 to 3.5 faster, as predicted. The model was refined in Karabeyoglu *et al.* (2005) to include the case of supercritical conditions, under which most of paraffin-based fuel system operates. The results of the research with the liquid layer theory showed that paraffin waxes have the best properties as hybrid rocket fuels among the *n*-alkanes due to their high regression rates at high melting temperatures.

6. Space Tourism

In 1996, a group of space enthusiasts, led by Peter Diamandis, proposed the challenge of a commercially sponsored flight to transport three people safely to an altitude of 100km, and repeat it in no more than two weeks. The proposal attracted several organizations, and in 2004, because of a multi-million dollar donation of Ansari brothers, the Ansari X Prize was created, with funds of US$10 million. The winner was Burt Rutan, owner of Scaled Composites, who was sponsored by Paul Allen, with the Space Ship One.

The SpaceShipOne(SS1) is a suborbital air-launched spaceplane that uses HTPB solid fuel with N_2O as oxidizer, and were released at 14 km of altitude by the jet-powered carrier White Knight. The ship did a total of 16 flights, three of them reached 100km, on July 21, September 29 and on October 04, 2004 when reached 112km in the second flight in the same week, winning the Ansari X Prize.

On September 27, 2004 Richard Branson founded Virgin Galactic Company, with one objective: to go to space. The company would develop a spaceplane that could fly paying passengers to visit the space, and to accomplish it a contract with the Scaled Composites was made. The carrier ship, a newer model of White Knight called White Knight Two, with the first model called Virgin MotherShip (VMS) Eve, were launched on July 28, 2008, and began the flight test program on December 12, 2008. On October 2009 the SpaceShipTwo(SS2), the first model called Virgin SpaceShip(VSS) Enterprise, were launched, with a flight test program that began in March, 2010, and hasn't yet finished and count around of 50 flights of VMS Eve and 25 flights of SS2, and 50 more are expected. The SS2 motor, called RocketMotorTwo(RR2), uses a formulation similar to that of SS1 propellant, also with HTPB and N_2O. The performance data isn't avaible.

A total of 370 customers have already bought a ticket to flight on SS2, which costs around US$200,000, and are expecting the end of the test program and the first flight, scheduled for 2013.

7. Conclusion

The hybrid propellant rocket motors have been studied for eighty years, with the development of combustion theories, different solid fuels and oxidizers, manufacturing techniques and test facilities, that allowed the common use in undergraduate propulsion classes to the development of a ship that can carry 6 passengers to the space. Projects as HyFlyer and HyTOP shows the need of developing safe rocket boosters with high I_{SP} and high thrust level, to achieve the requirements of space flight on Low Earth Orbit and higher, in space ships as large as Titan V, Ariane V or Soyuz, or bigger. On a smaller scale it has already been proved that this can be done, as did the SpaceShipOne and SpaceShipTwo.

The future developments of this technology is uncertain. The SpaceShipTwo may be used to carry small satellites on NASA suborbital Reusable Launch Vehicle(sRLV) program, for microgravity studies. Private companies, as Space Propulsion Group, already have paraffin based hybrid motors with 133 kN of thrust and 349 s of I_{SP}, and the number is growing.

All this data allow us to a sure and a new question, instead of an answer: the hybrid rocket motors have enough qualities and properties to be used in space propulsion in same level of solid and liquid rocket motors, but when the hybrid motor will surpass the solid ones and what will be done if they match the liquid rocket motors in an overall analysis?

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