Acta Astronautica 145 (2018) 1–10

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

On use of hybrid rocket propulsion for suborbital vehicles

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ARTICLE INFO

Keywords:
Rocket
Sounding rocket
Hybrid rocket motor
Rocket propulsion
Optimisation
Suborbital flight

ABSTRACT

While the majority of operating suborbital rockets use solid rocket propulsion, recent advancements in the field of hybrid rocket motors lead to renewed interest in their use in sounding rockets. This paper presents results of optimisation of sounding rockets using hybrid propulsion. An overview of vehicles under development during the last decade, as well as heritage systems is provided. Different propellant combinations are discussed and their performance assessment is given. While Liquid Oxygen, Nitrous Oxide and Nitric Acid have been widely tested with various solid fuels in flight, Hydrogen Peroxide remains an oxidiser with very limited sounding rocket applications. The benefits of hybrid propulsion for sounding rockets are given. In case of hybrid rocket motors the thrust curve can be optimised for each flight, using a flow regulator, depending on the payload and mission. Results of studies concerning the optimal burn duration and nozzle selection are given. Specific considerations are provided for the Polish ILR-33 “Amber” sounding rocket. Low regression rates, which up to date were viewed as a drawback of hybrid propulsion may be used to the benefit of maximising rocket performance if small solid rocket boosters are used during the initial flight period. While increased interest in hybrid propulsion is present, no up-to-date reference concerning use of hybrid rocket propulsion for sounding rockets is available. The ultimate goal of the paper is to provide insight into the sensitivity of different design parameters on performance of hybrid sounding rockets and delve into the potential and challenges of using hybrid rocket technology for expendable suborbital applications.

1. Introduction

Observed renewed interest in space transportation includes increased activity in suborbital spaceflight. While several companies work on reusable space vehicles, the market remains dominated by sounding rockets. Long duration storability, lack of extensive on-ground facilities and late experiment installation access, even an hour before launch [1], are significant qualities. Relative system simplicity enabled the development of hundreds of sounding rockets around the world [2]. Apart from being scientifically valuable tools, sounding rockets serve as technology demonstration platforms. In many cases they enable the development of key launch vehicle technologies. While the vast majority of sounding rockets uses solid rocket propulsion [3,4], a number of new development programmes consider use of hybrid propulsion for suborbital missions. Several vehicles yet to come to the market are intended for manned flight and will require additional safety measures. Hybrid propulsion, being simpler than bipropellant systems, ensures increased safety due to the separation of fuel and oxidiser and use of typically non-explosive compounds, unlike in solid propulsion. With only slightly elongated pre-launch operations [5] it has high theoretical performance [6,7]. Potential performance led to interest in using hybrid propulsion in small satellites. Early trade-offs and tests were conducted at university of Surrey [8,9]. This included work on alternative fuel grain geometries [10], enabling the possibility of utilising hybrid propulsion systems with compact envelopes within spacecraft. More recent studies also consider use of hybrid rocket motors for larger spacecraft platforms [11]. However up to now, literature provides no information on any hybrid rocket motor tested in-orbit. Despite considering hybrids for orbit-keeping, orbital transfers, satellite deorbit and even lunar and mars landers, more attention is presently given to their use in suborbital rockets and small launch vehicles. However, the difficult history of hybrid rocket technology, with several big programs having significant technological complications, led to its very limited use in operational products. The following paragraph presents key heritage development activities with focus on in-flight use of hybrid rocket propulsion.

Initial use of hybrid propulsion in rockets dates back to 1933 when the Soviet GIRD-9, using liquid oxygen (LOX) and gelled kerosene, was successfully launched. Early work with hybrid propulsion took place also in Germany (with LOX ad N_2O as oxidizers) and in the United States (using GOX, LOX) [12]. Initial tests included a wide range of fuels. In

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https://doi.org/10.1016/j.actaastro.2018.01.027
Received 16 September 2017; Received in revised form 29 November 2017; Accepted 12 January 2018

Abbreviations

DLR	Deutsches Zentrum für Luft-und Raumfahrt (English: German Aerospace Center)
FLOX	Liquid Fluorine and Liquid Oxygen
GOX	Gaseous Oxygen
HTP	High Test Peroxide
HTPB	Hydroxyl-Terminated Polybutadiene
LOX	Liquid Oxygen
O/F	Oxidiser-to-Fuel
ONERA	Office National d'Etudes et de Recherches Aérospatiales (English: French National Aerospace Research Center)
PBAN	Polybutadiene Acrylonitrile
PE	Polyethylene
SRM	Solid Rocket Motor

1950 at General Electric occurred the first wider investigation of Hydrogen Peroxide as the main oxidiser [12]. The nominal fuel was Polyethylene (PE). Since then various American entities worked on hybrid propulsion with key development taking place at United Technologies Corporation (UTC), Lockheed Propulsion Company, Stanford Research Institute, Starstruck Company, American Rocket Company (AMROC), Environmental Aeroscience Corporation, Thiokol, Pratt & Whitney, Rocketdyne, Allied Signal, Scaled Composited, Space Dev, Sierra Nevada Corporation and NASA [7,12]. Development activities ranged from laboratory research to large propulsion systems with thrust exceeding 1 MN. Several programs ended with in-flight use of hybrid motors - both for sounding rockets and drone propulsion (Sandpiper, HAST, Firebolt of UTC). Key achievements include demonstrating a specific impulse of 380 s by the Lockheed Chemical Systems Division using Li/LiH/PBAN fuel with FLOX [13], what is an unofficial record for hybrid propulsion. Key in-flight test attempts include unsuccessful launches of the LOX/polybutadiene-propelled Dolphin rocket and the AMROC SET-1 [14]. Some missions were successful, as the Hyperion (N_2O, HTPB) sounding rocket demonstrator's flight to over 36 km [15] and HYSR (LOX/HTPB+Aluminium) demonstrator's flight up to 42 km [14]. A major breakthrough was the Space Ship One vehicle (N_2O/HTPB), which enabled obtaining the X-Prize [16]. Follow-up work concerns the Space Ship Two with a N_2O/Polyamide hybrid motor [17]. Currently significant research takes place at Stanford University [18] and University of Purdue [19] with increased interest in the field due to the emergence of new commercial players. Apart from advancements in the United States, Germany and Soviet Union notable historical research was carried out in India [7,12] and successful flights of small sounding rockets took place in Europe. This includes Swedish vehicles from the HR Program [20] and the SR-1 sounding rocket developed during 1962–1971 [21]. Propellants based on Nitric Acid/Polibutadiene +aromatic amine were used [22]. The LEX vehicle from ONERA also used a hypergolic propellant combination (nitric acid or RFNA and an amine fuel consisting of metatoluene diamine/nylon). The single-stage LEX sounding rocket was one of the most efficient small suborbital vehicles - with a launch mass of merely 80 kg it enabled reaching an altitude of 100 km [23]. Its motor was throttleable over a 5:1 range to optimize flight performance. Eight flights, all successful, were completed during 1964–1967 [22]. More recent in flight tests of hybrid rocket vehicles in Europe include hobbyist activities of Copenhagen Suborbitals [24] and members of Romanian ARCA [25]. Recently French [26], German [5,27] and Dutch [28] student programmes enabled conducting launches of small experimental hybrid rockets. The most eminent student rockets launched during recent years include Stratos II (N_2O/sorbitol+paraffin+aluminium) from Delft Aerospace Rocket Engineering (DARE) from Delft University of Technology [28] and HEROS 3 (N_2O/paraffin) from University of Stuttgart, supported by DLR [29]. Nowadays hybrid rocket motor development takes place in a few dozen countries worldwide with several new sounding rockets using hybrid rocket propulsion to be introduced in the following years.

2. Modern hybrid sounding rocket technology demonstrators

Table 1 provides key data of example technology demonstrators form the last decade. Rockets with apogees in the range reachable by high-altitude balloons are not considered, due to their limited commercial potential. As can be seen, theoretical altitudes of 100–150 km are typical for technology demonstration and possible use for microgravity experimentation and atmospheric research. The Polish ILR-33 “Amber” and Norwegian Nucleus utilise HTP as oxidiser, what is a novelty for in-flight hybrid testing. The hybrid motor of ILR-33 “Amber” uses hydrogen peroxide obtained in HTP class at a concentration of 98%, using in-house technology [30], while Nucleus utilises 87.5% HTP grade. ILR-33 “Amber was successfully test-flown in October 2017, becoming the first rocket in the world to demonstrate in-flight use of 98% hydrogen peroxide. The altitude was however limited to 15 km due to test range requirements. The latter rockets use nitrous oxide. Little information about the Peregine project was published since 2014, until recent news confirmed that the project is being continued [31]. The Atea 1 design of Rocket Lab was launched once, in 2009. Very limited information on its performance is available, however the company announced the mission a major success.

3. Selection of hybrid rocket propellants for sounding rocket application

While historical propellant applications have been listed in paragraph 1, it can be seen in Table 1 that modern small sounding rockets do not use LOX as oxidiser. The lack of ground facilities enabling LOX handling at most suborbital launch sites makes in impractical for small applications. Nitrous oxide is the most popular choice in many projects due to its

Table 1
Data of modern small rocket demonstrators using hybrid rocket propulsion.

Rocket	ILR-33 “Amber” [32,33]	Nucleus [34,35]	Atea 1 [36]	Peregine [37,38]
Maximum diameter [mm]	230	356	150	406
Length [m]	5.00	9.00	6.00	9.75
Launch mass [kg]	<200	820	60	850
Hybrid propellant type	98% HTP/PE	87.5% HTP /HTPB+C	N_2O /polymer-based	N_2O/paraffin
Fuel grain geometry	multi-port	multi-port	unknown	single-port
Propellant mass fraction [ ]	not released	0.58	0.75	0.52
Motor burn duration [s]	40.0	25.0	14.5	18.0
Rocket staging	hybrid main stage with SRM boosters	hybrid single-stage rocket	hybrid booster stage with dart	hybrid single-stage rocket
Maximum apogee [10^3 m]	100	120	150	100
Status	test-flown	development	test-flown	development