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Advanced Low-Cost Hypersonic Flight Test Platforms

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Abstract

Hybrid rockets are a specific type of propulsion system characterized by the use of a liquid oxidizer and a solid fuel. This peculiarity provides very specific features respect to the other chemical propulsion systems. Compared to solid rockets, hybrids are throttleable and restartable, they are environmentally friendly and much safer to manufacture, store, manage and operate with a dramatic impact on costs. Respect to liquid propulsion systems, hybrids are much simpler since the combustion chamber is not regeneratively cooled and they need less than half of the liquid feed system. Thanks to these peculiarities hybrid rocket propulsion systems are perfectly suited to be installed and operated on low costs, partially reusable test platforms for hypersonic in-flight test. These affordable flight test platforms can be used to provide otherwise not or only partially available real test data on components or subsystems in the hypersonic regime, as, for example, thermal and mechanical loads, advanced materials behavior, aerodynamics, air-breathing propulsion. University of Padua and T4i started doing research in this field since 2006, acquiring a unique in the world expertise in the frame of paraffin-based hybrid rockets together with a wide expertise on nitrous oxide and hydrogen peroxide as oxidizers. Different type of motors up to 25 kN of thrust have been designed, developed and tested. Starting in 2019 a sounding rocket has been developed as a low-cost test platform for flight demonstration of new technologies, including propulsion. The presentation provides an overview of the work performed up to now and describes the new interesting opportunities made possible by advanced hybrid rocket systems applied to hypersonic flight test platforms.

Keywords: *Hypersonic, Hybrid, Throttling, Flight, Testing*

1. Introduction

1.1. Hypersonic applications

The hypersonic field has recently gained a lot of attention, both for military and civil applications. The military has seen the rise of hypersonic weapons, with strong developments pursued by Russia, China, India and the US. In the civil market, two fields are related with the hypersonic world. One is the transportation market, where very high-speed planes (cruising or suborbital) are conceived and studied in several research projects (e.g. ATLLAS, LAPCAT, STRATOFLY, FAST20XX [1-5]). However, hypersonic transportation seems still a long time to come. The other more actual application is related with the reentry from suborbital or orbital spaceflight, which is gaining a lot of momentum thanks to the recent trend toward reusability.

1.2. Hypersonic research

Hypersonic is a general term to indicate very high speeds, considered in general above Mach 5. There is not a strict barrier, as the characteristics of the hypersonic regime can appear at different speeds

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and different intensities depending on several geometric and boundary conditions [6]. The features of the hypersonic regime are very high temperatures, real gas effects, chemical reactions, high shock intensity, large entropy variations, low Mach angles, high heat transfer, shock-boundary layer interactions. These aspects are very complex by themselves and furthermore they are coupled together. This makes the hypersonic regime very challenging and very difficult to model analytically and numerically. Testing at those extreme conditions is also hard to replicate entirely on ground with wind tunnels and other facilities. In order to validate all numerical and experimental data generated on ground, it is therefore necessary to perform real flight testing at hypersonic speeds. Thanks to the current renewed interest in the hypersonic regime (after the first main phase post WW2), several platforms are under developments to give the opportunity for flight testing. One example is the X-60A [7], developed by Generation Orbit. It is an air launched liquid rocket around 1400 kg of mass, 1.7 m wide, 8 m long, able to accelerate over Mach 5. The company Stratolaunch is developing the Talon-A [8]. It is a fully reusable, autonomous, liquid rocket-powered Mach 6-class hypersonic vehicle with a length of 8.5 m, a wingspan of 3.4 m and a launch weight of approximately 2700 Kg. The Talon-A will conduct over 1-minute of hypersonic flight testing, and glide back for an autonomous, horizontal landing on a conventional runway. The Talon-A is air launched with Stratolaunch giant carrier.

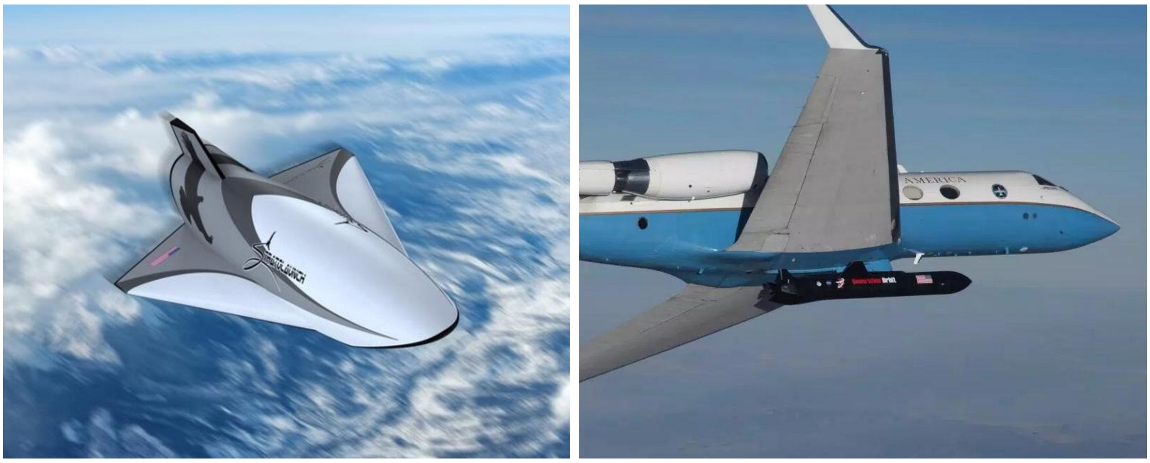

Fig 1. Talon-A (left) and X-60A (right)

Hypersonic experiments are also performed with ground launched sounding rockets (e.g. SHEFEX [9] or HEXAFLY [10]). Unfortunately, again due to the extreme conditions encountered, which provides significant challenges, hypersonic flight testing is still rare and expensive. The current trend seems directed toward an increase of the corresponding activities without, however, a complete disruption. In this paper is thus underlined the importance of achieving almost routinely hypersonic flight testing at low cost, filling the gap between numerical activities, various types of ground testing and expensive large scale flight testing. A possible simple proposal is presented in the following chapter.

2. Small hypersonic test platform

2.1. Key features

Analyzing the required characteristics for a flexible low-cost hypersonic platform, the following list of must have has been defined:

- Small size;
- Air launched;
- Simple airframe design;
- Low-cost green storable throttleable rocket propulsion.

The small size is necessary to reduce recurring and non-recurring costs. However, at the same time the small size makes more difficult to achieve and sustain hypersonic speeds, so a trade-off is necessary. Air launch guarantees several fundamental benefits. First of all, the carrier aircraft is a reusable system with a limited hourly cost. A key factor is that the carrier is used frequently and/or together with other purposes (like a military fighter for an Air Force), otherwise costs can become prohibitive. For this type of missions, air launch provides an initial altitude and speed, which translate in huge mass saving for the platform, going hand to hand with the previous characteristic. In fact, without air launch is not possible to have meaningful performance with a small size. Air launch can be subsonic or supersonic. Subsonic air launch is much simpler and still provides the majority of benefits, so it is generally the preferred option. However, supersonic launch could be selected when maximum performance is sought, particularly if the platform/carrier combination has been already qualified for this condition (as in the case of the platform presented in the next section). Air launch provides also important flexibility advantages. Safety range limitations are dramatically reduced as the carrier can take-off from a normal airfield, flight regularly in the air traffic and move to another place where the test can occur. The test can be performed in the stratosphere above the clouds, relaxing dramatically the ground launch constraints due to weather conditions. With air launch, the flight path of the test bed can be selected also more conveniently for the specific testing purposes. For ground launch the rocket has to accelerate in the lower, denser part of the atmosphere against gravity and drag while shifting from an almost vertical attitude to a horizontal one. The simple airframe design bullet refers to the fact that, in order to decrease costs and improve operational responsiveness, flexibility and ease of use, it is important to avoid complex design/manufacturing solutions and exotic materials. One big issue with hypersonic flight test platforms is that, because the system should reach hypersonic speeds, you need somehow to face hypersonic related challenges. This can create a sort of death spiral that can be frequently seen in hypersonic test bed development: in order to design a hypersonic vehicle, you need to test hypersonic technology, in order to test hypersonic technology, you need a hypersonic vehicle. To avoid this negative outcome, it is important to simplify and decouple the problems. One important aspect is to limit the time spent at hypersonic speed, which in turn allows to choose ablative thermal protections and rocket propulsion. Ablative thermal protections are a cheap and lightweight (for short times) way to guarantee a thermal barrier to the rocket structures. Rocket propulsion has a high thrust to weight ratio (for short times, otherwise the propellant mass becomes too high), it is independent on the external conditions (Mach, temperature, pressure etc.) except for a little effect on thrust by the ambient backpressure and can reach theoretically any speed or altitude. The development of an ablative protected, rocket powered platform is definitely the simplest way to go for a hypersonic test bed. Finally, regarding propulsion, the rocket should have the aforementioned characteristics: low cost, green, storable and throttleable. Low cost is very important as the cost of the propulsion system is often a major part of total costs. A low-cost propulsion system should limit the number of parts and exotic materials, have a simple architecture, using commercial of the shelves technologies and manufacturing processes. Green propellants are also necessary for low costs, as their low toxicity and reduced safety hazards compared with traditional ones guarantee easier storage and handling procedures, allowing faster and simpler operations. Storability of the propellant is important for two reasons: first of all, it simplifies the propulsion system and reduce costs, eliminating the needs for cryogenic compatibility. Moreover, storability improves operational flexibility, as there is no time limit after the propellant is filled on the system, allowing for better abort options, rescheduling of activities, carrier transfer, propellant storage on ground. Throttling and thrust termination capabilities are paramount for hypersonic testing as they allow to reach and keep the exact required conditions for each specific test, giving the possibilities to select different flight profiles, even on demand. Only liquid and hybrid rockets can fully exploit this possibility, while solid rockets performance is dependent on the propellant grain formulation/shape, which cannot be easily modified from launch to launch, and it is also sensitive to the initial temperature, without the possibility to actively adjust the thrust profile in flight.

2.2. AQM-37

There is an interesting historical example of a small supersonic/hypersonic vehicle developed long time ago and still used today, the AQM-37 Jayhawk target drone [11-14]. It is an air-launched supersonic target drone manufactured by Beechcraft (now Raytheon) capable of simulating air-to-air, air-to-surface threats or inbound ICBM warhead packages for fleet shoot-down exercises. More than 5000 AQM-37 targets of all variants have been delivered since the early 1960s. The AQM-37C/D is still in limited production for the U.S. Navy. The AQM-37 uses a liquid rocket engine built by Rocketdyne (LR64-NA-4). The liquid rocket engine has a maximum thrust of 3.8 kN, it is pressure-fed with nitrogen and uses corrosive, dense, storable, highly toxic hypergolic propellants (IRFNA-MAF4), which spontaneously ignite when mixed together. This simplifies ignition and combustion but tends to make them troublesome to deal with, particularly in civil applications and nowadays, as safety and pollution are more stringently considered. Total propellant mass is 128 kg. The liquid rocket has two separated chambers, aligned one above the other. The bigger upper chamber is necessary for the higher thrust (boost) during the acceleration phase while the smaller lower chamber propels the system during the cruising phase (sustain). To avoid handling of the propellants, the liquid engine is pre-packaged, like a typical military missile. The nitrogen pressurization is filled at 228 bars prior to operations and remains effective for 72 hours, after which the system starts to depressurize. The AQM-37 is relatively small in size, with a length of 4.27 m, a diameter of 0.33 m, a wingspan of 1 m and a weight around 280 kg. It has a delta wing and front movable canards, the latter controlling the attitude together with the wing ailerons. The AQM-37 has been carried and launched by fighters like the F4, the A6, the A4 and more recently the F16. A Trapeze Ejection System pushes the target forward and down. Launches can be made from Mach 0.6 at 1000 ft. (300 m) to Mach 1.8 at 55000 ft (17 km). The AQM-37 is able to reach Mach 3 at 80000 ft (24 km) or Mach 4 at 100000 ft (30 km) in horizontal flight. In ballistic flight, apogees of 100 km can be reached with terminal speeds around Mach 5 on reentry. The AQM-37C Flight Test Reliability is 95% based on over 1000 flights and counting. The drone is not recoverable, and also includes a destruct package, which is automatically activated by any major system malfunction. The AQM-37 could fly a preprogrammed course and/or respond to guidance commands from the ground.

Fig 2. AQM-37 Jayhawk target drone

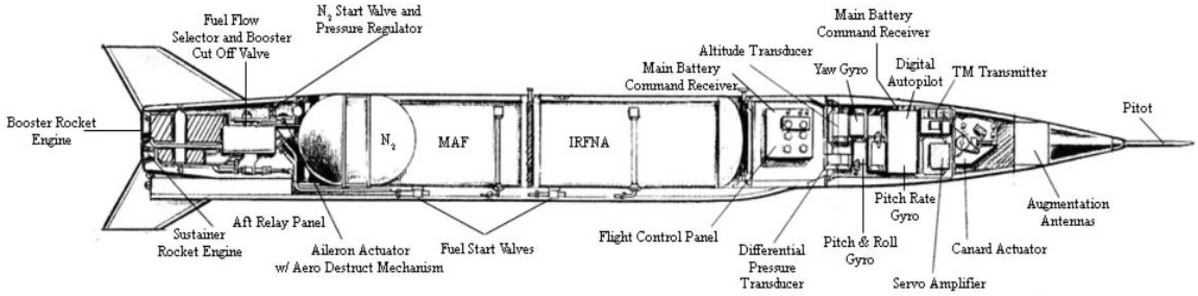

Fig 3. AQM-37 detailed cut away view

Fig 4. Rocketdyne (LR64-NA-4) liquid rocket engine

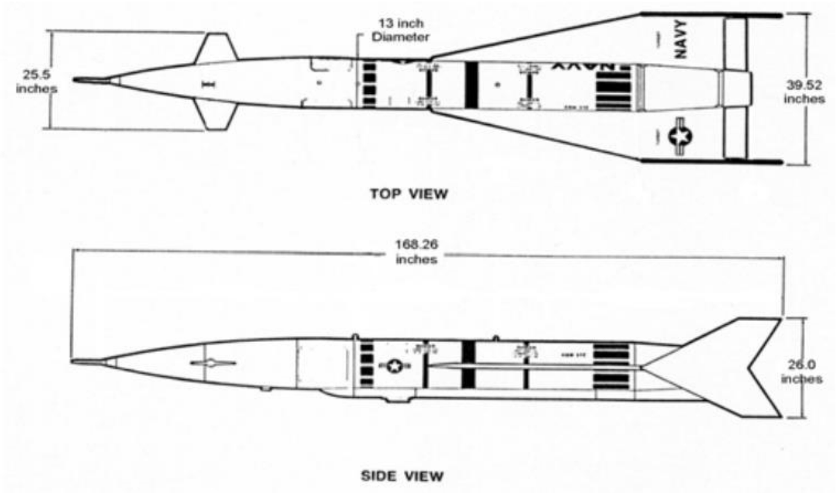

Fig 5. AQM-37 shape and dimensions

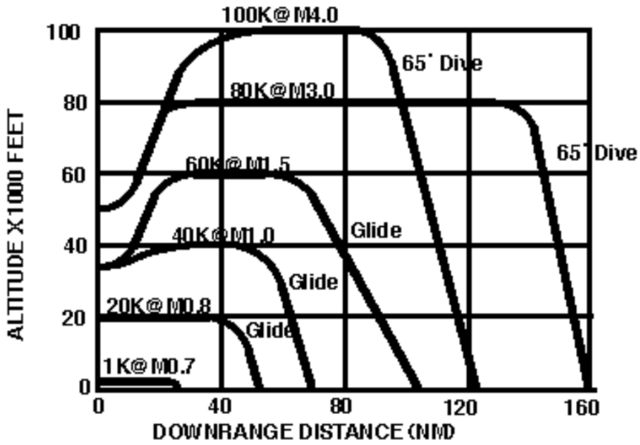

Fig 6. AQM-37 typical flight profiles

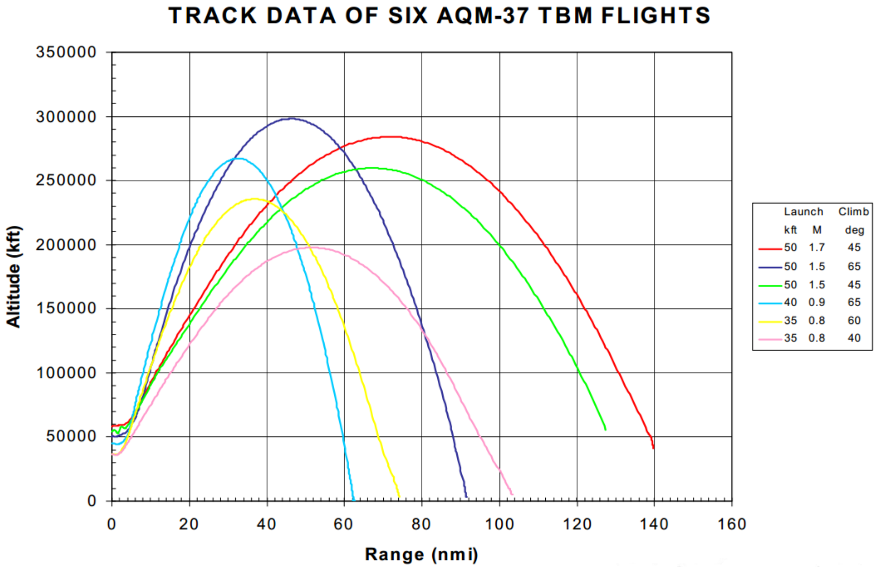

Fig 7. AQM-37 ballistic flight profiles

Performance of the AQM-37 is highly supersonic, at the boundary of hypersonic flight. The original AQM-37 is able to perform lateral maneuvers for course correction as well as dives and pull-ups to simulate missile threats, so it is designed to be well robust. It is possible to expect that a new scaled design, with a larger size and employing modern up-to-date technologies could be able to perform well in the low-end of the hypersonic regime.

2.3. AQM-81

In the late 1960s the Air Force investigated an alternate propulsion scheme for the AQM-37 under project "Sandpiper" [11, 15-17]. The program involved fitting a few AQM-37As with hybrid engines that used a solid fuel with a storable liquid oxidizer. The idea was to replace the original two-chambers liquid engine with a throttleable single chamber hybrid unit. United Technology Center and Beech Aircraft began work on the Sandpiper, using a storable propellant combination composed of mixed oxides of nitrogen (MON-25) as an oxidizer (25% NO, 75% N2O4) and a metallized polymethylmethacrylate (PMM)/Mg fuel. The first of six flights occurred in January 1968, 18 months after start of the program. Throttleability over a range of 8:1 was required after launch at about 40000 ft (12 km) to attain speeds up to Mach 4 at an altitude of 100000 ft (30 km). The flight duration was in excess of 300 s. The layout of this motor is shown in Fig. 8. The tests were judged promising, and so the Air Force went on to establish a "High Altitude Supersonic Target (HAST)" program in the 1970s. To allow a larger payload, in contrast to the Sandpiper, the thrust chamber diameter was increased from 10 to 13 inches. Meanwhile the propellant changed to IRFNA/PB/PMM (PB/plexiglass). Instead of N2, the oxidizer was pressurized by a ram air turbine with an inlet below the center fuselage (Fig. 9), which also provided electrical power. The thrust range on command was controlled by a throttle valve providing a 10:1 range. The grain configuration was also changed from a single cylindrical port to a cruciform using four liquid injectors. Unlike the Sandpiper, which was expendable, the HAST was recoverable by use of an onboard drogue chute trough soft landing or retrieval in midair by helicopter. This work later became the AQM-81 Firebolt target missile system, under development by Teledyne Ryan Aircraft. The AQM-81 was larger than is predecessor, with a length of 5.2 m and a mass of 560 kg. The propulsion configuration and performance were the same as for HAST. The engine, built by the Chemical Systems Division (CSD) of United Technology, was throttleable between 0.53 kN and 5.3 kN. After air launch at about Mach 1.5 from an F-4 aircraft, the hybrid rocket could propel the XAQM-81A to speeds greater than Mach 4 at altitudes of 30 km. In this program, 48 thrust chamber assemblies were delivered. The flight test program was successfully completed in the 1984. These drones were the only hybrid flight programs built to military specifications. However, the AQM-81A never went into serial production.

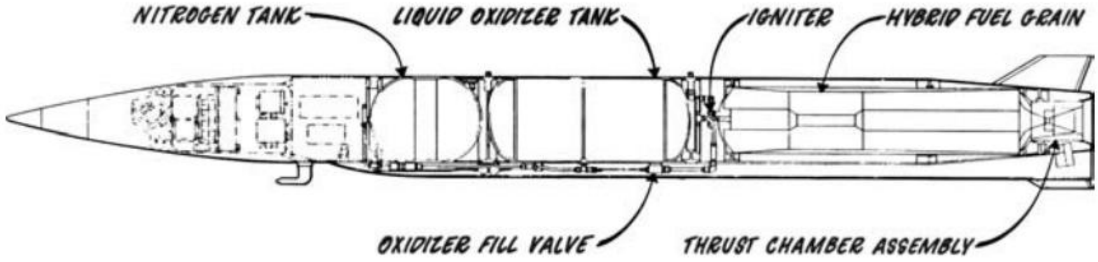

Fig 8. Sandpiper hybrid rocket target vehicle

Fig 9. AQM-81A hybrid target drone

2.4. New proposal

Based on the key features identified, it is possible to claim that a new enlarged design inspired by the AQM-37/AQM-81 systems could be a perfect platform for moderate hypersonic testing. A larger size together with the use of more modern lighter materials like carbon composite could help improving the performance up to the required hypersonic level. The platform fulfills the first three requisites: being relatively small, air-launched and having a simple (and proven) airframe design. Adaptation to higher speeds should make use of relatively inexpensive ablative materials. Regarding the propulsion system, the original engine can be replaced with a modern design, advanced and competitive green hybrid rocket. Hybrid rockets are much simpler than their liquid counterpart, are safe to store and operate, and provide low manufacturing and operational costs. Propellant combination should be Hydrogen Peroxide with a plastic fuel. Hydrogen peroxide is storable, green, can be concentrated in situ and filled only prior to the mission, contrary to the old toxic hypergolic stuff. Hydrogen peroxide can be decomposed through a catalyst bed, simplifying ignition and allowing for multiple start-stop capability. Moreover, the liquid mass flow can be easily controlled and the decomposition/gasification of the oxidizer prior to injection guarantees high efficiency and stability on a wide range of throttle levels. Therefore, this kind of propulsion system is the perfect candidate to fulfill or the corresponding requisites: low-cost, green, storable, throttleable. This kind of propulsion system has been developed, among others, by the group at university of Padova (UNIPD) and its spin off Technology for propulsion and innovation (T4i). Thanks to its low cost and off the shelves manufacturing technologies, the platform can be designed to be expandable (like the AQM-37) and serially produced. Alternatively, the platform can be designed with limited modifications to be recoverable with a parachute (as the AQM-81) and reusable after partial refurbishment, mainly regarding the external thermal protections and the ablative combustion chamber.

3. Hybrid propulsion at UNIPD/T4i

3.1. Initial phase

The chemical propulsion group at University of Padua was established around 2006. Since the beginning, the activity has been completely focused on green propellants, both for economical and logistical limitations and because of the recent increased interest in the propulsion community to replace conventional toxic propellants. The Padua propulsion group started developing hybrid rockets based on nitrous oxide as oxidizer. Almost immediately the main focus on the fuel side shifted to paraffin wax thanks to its high regression rate which allow for a single port design. In a timeframe of only 3 years the group developed from scratch and tested dozens of times a 25 kN peak thrust N2O-paraffin booster for RATO (Rocket Assisted Take Off) applications [18-19]. A version with a battleship combustion chamber flew in 2009 while a lightweight full composite version flew in 2010. After that experience the research continued at lab-scale with GOX and N2O as oxidizers and several plastics like paraffin and HDPE as fuels [20-22]. In 2014, the spin-off Technology for Propulsion and Innovation (T4i) was established with the aim of increasing the Technology Readiness Level of the university research, developing real products and bringing them to the market.

Fig 10. N2O-paraffin hybrid RATO booster: rendering (left), flight (right)

3.2. Hydrogen peroxide

After the initial experiences the group decided to start researching on concentrated hydrogen peroxide. The choice was motivated by several reasons:

- The only commercial green liquid oxidizers are LOX, N2O and H2O2;
- LOX is cryogenic and suited only for a small niche of applications (mainly launchers);
- H2O2 is very versatile because it can be decomposed relatively easily in liquid phase and can be used in restartable and throttleable liquid monopropellants, bipropellants, hybrids and gas generators;
- A trade-off between H2O2 and N2O showed the first to be generally higher performing in demanding applications while the second is better in simpler applications (in self-press mode).

The main issue regarding H2O2 is its availability. N2O and LOX are available in pure form while H2O2 is available in aqueous solutions. Commercial solutions of H2O2 are largely available and cheap but their concentration can reach only 70%, a value too low for high performance. Few companies provide higher grades (like Evonik Propulse) but the procurement is more difficult and expensive than the commercial grades. In order to simplify the procurement of the hydrogen peroxide the group decided to use the commercial grade provided by Solvay (60% concentration) and concentrate it above 90%. For that purpose, a distillation unit has been developed in partnership with WEPA Technologies (Peter Weuta). The unit is completely autonomous with integrated safety controls and remotely controlled and is able to concentrate continuously around 1 kg per hour of hydrogen peroxide above 90%, 24 hours a day, 7 days a week, with 3% waste concentration. The possibility to produce the concentrated hydrogen peroxide in situ simplifies significantly the transportation issues and keeps costs down. Moreover, it is possible to have direct control on the concentration level (in order to increase performance or lowering the freezing point). Starting in 2014, the group has performed hundreds of monopropellant, bipropellant and hybrid rocket tests at lab-scale (100-1000 N) with hydrogen peroxide. More than 50 scale up tests of hybrid rockets with thrust above 5 kN (sea level) have been also performed. Hybrid firing times up to 80 s have been achieved [23]. Thanks to catalyst decomposition of the hydrogen peroxide, the hybrid motors have the capability to cold start, to run stable and efficiently, to stop and restart multiple times and to be throttled.

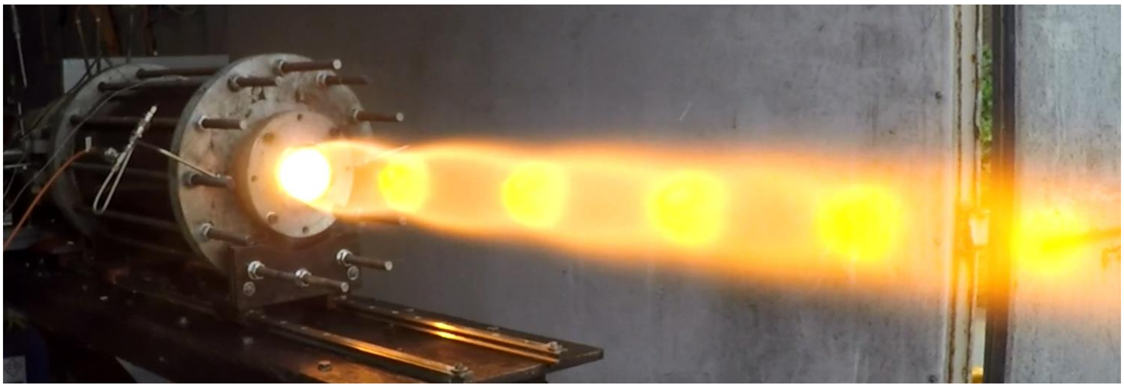

Fig 11. H2O2 hybrid rocket firing (5 kN at sea level)

A cavitating venturi variable pintle flow control valve has been developed in house [24]. The valve is able to choke the oxidizer mass flow and decouple the feed system from the combustion chamber dynamic. Afterwards a stepper electric motor has been connected to the movable flow control valve [25]. With this set-up an outstanding real time throttling ratio of 12.6:1 has been achieved showing the possibility to perform different thrust profiles on demand [26]. A remotely controlled human manual throttling test has been also performed.

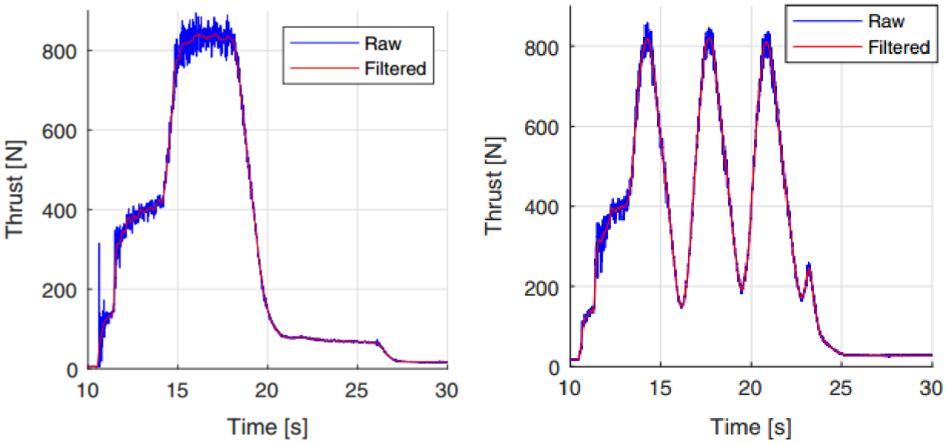

Fig 12. Throttling of a H2O2 hybrid rocket: step command (left), sinusoidal command (right)

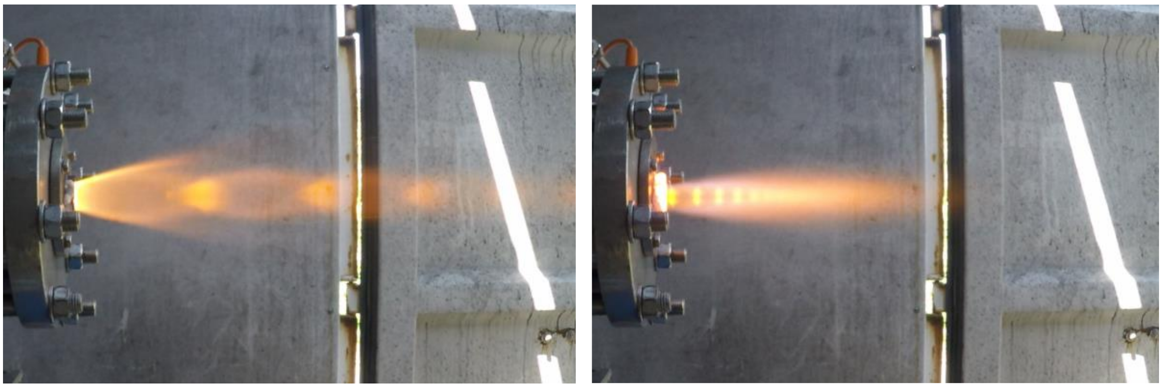

Fig 13. Throttling of a H2O2 hybrid rocket: max thrust (left), min thrust (right)

Afterwards, the team started to develop a 200 mm diameter, 6 m long sounding rocket propelled by a 5 kN thrust hydrogen peroxide-paraffin hybrid rocket. The aim of the passive, aerodynamically stabilized, sounding rocket was to serve as a flight test bed for new technologies in the structures and propulsion system. The sounding rocket was finally launched succesfully on February 24, 2022, from the Poligono Interforze of Salto di Quirra (PISQ) in Sardinia, within the project Aviolancio (air-launch), coordinated by the Italian Research Center (Consiglio Nazionale delle Ricerche, CNR) and the Italian Air Force (Aeronautica Militare Italiana, AMI).

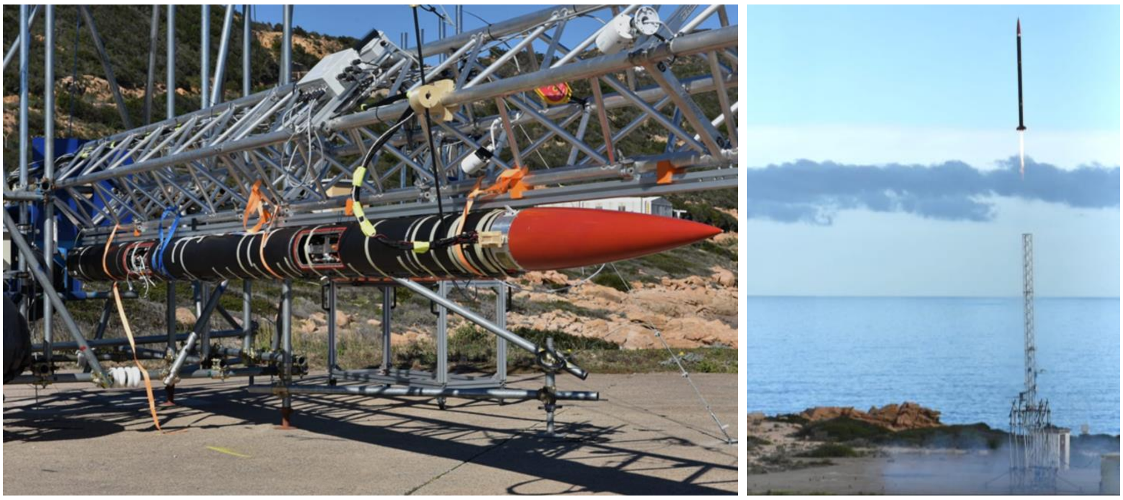

Fig 14. H2O2 sounding rocket: on the ramp (left), at launch (right)

It is possible to think that this technology could represent the starting point for the effective low-cost and flexible air-launched guided hypersonic test-bed proposed in the previous chapter. The aircraft platform could be a fighter operated by an Air Force or a private entity [27].

4. Conclusions

In recent years, the interest toward hypersonic research has grown significantly. However, the hypersonic regime is extremely complex and very difficult to model. Moreover, ground testing cannot provide easily all the required information. Consequently, there is a strong need for flight testing opportunities. Unfortunately, there is a tremendous lack of platforms that can guarantee frequent and inexpensive flight at hypersonic speeds. In this paper, a possible realistic solution to this issue is presented. A hypersonic flight test platform inspired to the AQM-37 and AQM-81 target drones has been proposed. Four key characteristics have been defined to achieve the targeted levels of flexibility and costs: small size, air launch, simple airframe design and low-cost green storable throttleable rocket propulsion. Finally, Hydrogen Peroxide based hybrid propulsion has been shown to perfectly fit those requirements.

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