Update on green chemical propulsion activities and achievements by the University of Padua and its spin-off T4I

F. Barato[1]*, A. Ruffin[2], M. Santi[2], M. Fagherazzi[2], N. Bellomo[2] and D. Pavarin[1,2]

[1]Department of Industrial Engineering, University of Padua, Via Venezia 1, 35131, Padua, Italy

[2]Technology for Propulsion and Innovation S.p.a, Via Emilia 15, 35043, Monselice, Italy

* francesco.barato@unipd.it

Keywords: Hydrogen Peroxide, Green Chemical Propulsion, Hybrid Rockets, Liquid Thrusters, Sounding Rocket, Throttling, Regenerative Cooling, Additive Manufacturing

Abstract. In recent years, there has been a great research interest on green propulsion, both for environmental, cost and ease-of-use considerations, further accelerated by the needs of the NewSpace Economy. Hydrogen peroxide is a green and versatile propellant that is suitable for a lot of different uses in space applications. Following a previous AIDAA publication of 2019, this paper updates the research performed on hydrogen peroxide-based propulsion by the University of Padua and its spin-off T4i with the latest achievements. Starting from the simplest propulsion systems, several monopropellant thrusters have been successfully designed and tested, ranging from a propulsion module of 1 N, to a 10 N and 200 N flight-weight items. The thrusters can operate in blowdown or pressure-regulated mode, and they have been tested for hundreds of seconds of continuous operation and for thousands of pulses. A 450 N liquid bipropellant motor that burns the monopropellant exhausts with diesel fuel has also been developed and tested. The motor uses an unconventional internal vortex flow field to achieve stability, efficiency, and self-cooling of the chamber. The nozzle throat region temperature is kept under control by regenerative cooling channels fed by the peroxide. All thrusters make extensive use of additive manufacturing. The hydrogen peroxide technology has also been applied on hybrid propulsion, which was the initial main expertise of the Padua University propulsion group. Hundreds of tests have been performed at lab-scale, mainly with paraffin wax and polyethylene as fuels, with burning time up to 80 seconds. The motors are able to start, stop and restart multiple times. A cavitating pintle valve has been developed in house in order to control the oxidizer mass flow. With this valve, the hybrid motors are able to throttle the thrust in a range of 1:12.6. A similar valve has been also employed in the integrated monopropellant propulsion system of a lunar drone, composed by a 400 N throttleable engine together with 4 small 14 N on-off attitude control thrusters. Moreover, several dozens of hybrid tests have been performed at 5-10 kN scale up to 50 seconds. Finally, a composite sounding rocket powered by a pressure-regulated 5 kN hybrid rocket has been fully designed and successfully flight tested.

Introduction

The chemical propulsion group at University of Padua was established around 2006, working on hybrid propulsion with green oxidizer (N_2O, GOX) and plastic fuels, mainly HDPE and paraffin wax. For the story before the shift to hydrogen peroxide, the reader is referred to a previous AIDAA paper [1]. Since 2014, the propulsion team and its spin-off Technology for Propulsion and Innovation (T4i) have been focused their effort on the development of hydrogen peroxide-based propulsion systems.

The choice of hydrogen peroxide is due to the fact that is a very versatile green propellant 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. Moreover, it can be stored at room temperatures at any pressure and can feed the engines with very repeatable performance.

The primary feature of this research effort is the use of stabilized hydrogen peroxide concentrated in-situ from commercial feedstock. A distillation plant capable of concentrating 1 kg/hour of hydrogen peroxide from 60% to 92% has been operated for years with little maintenance. The plant runs autonomously 24/7 and has concentrated several tons of propellant up to now. In little less than a decade the group has performed nearly a thousand monopropellant, bipropellant and hybrid rocket tests with hydrogen peroxide. In the following paragraphs the different types of motors will be described.

Monopropellant propulsion

Several monopropellant systems, ranging from 1N to 200 N, have been developed in order to operate as main engines and/or attitude control thrusters for space vehicles [2-3].

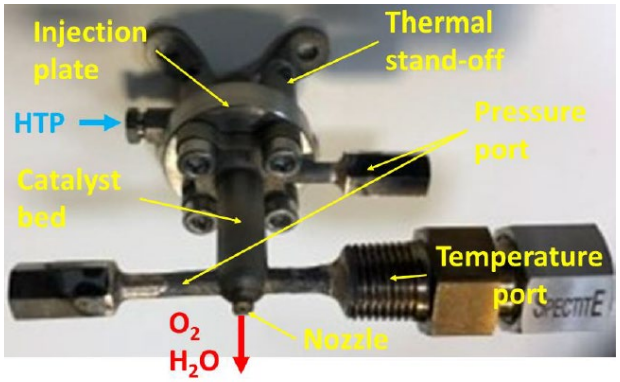

Fig 1. 1 N monopropellant thruster engineering model

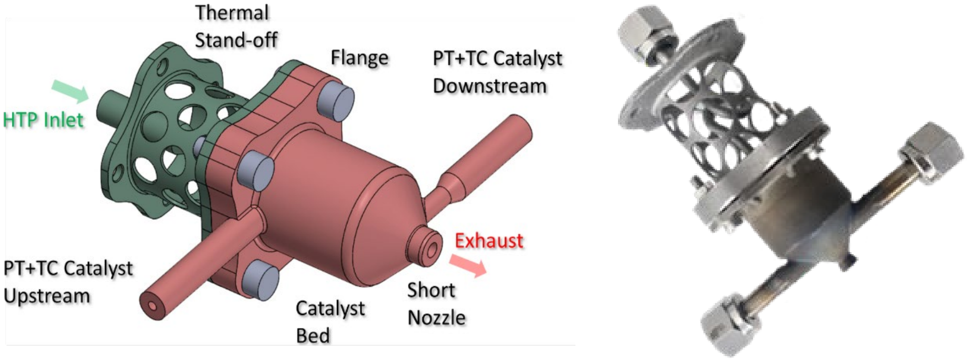

Fig 2. 10 N monopropellant thruster engineering model

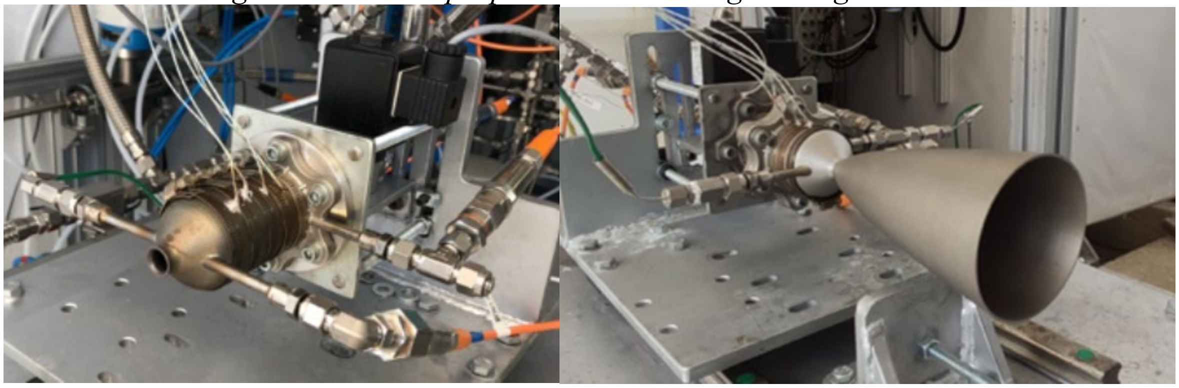

Fig 3. 200 N monopropellant thruster engineering models

The thrusters can be used both in blowdown and pressure-regulated mode from 5 bar to more than 40 bar. The thrusters are actuated with on-off solenoid valve and operated in continuous and bang-bang mode. Efficiencies above 95% have been achieved with continuous firing times up to above 1000 s. More than 4000 pulses have also been demonstrated. Depending on thruster size, valve timing can go from 30 to 100 ms. The catalyst is able of cold starting without pre-heating. The thrusters are manufactured with 3D printing Selective Laser Melting (SLM) technology. The engineering models have flanges to disassemble the thrusters and pressure/temperature sensor ports while the flight weight units have a minimum number of interfaces/components.

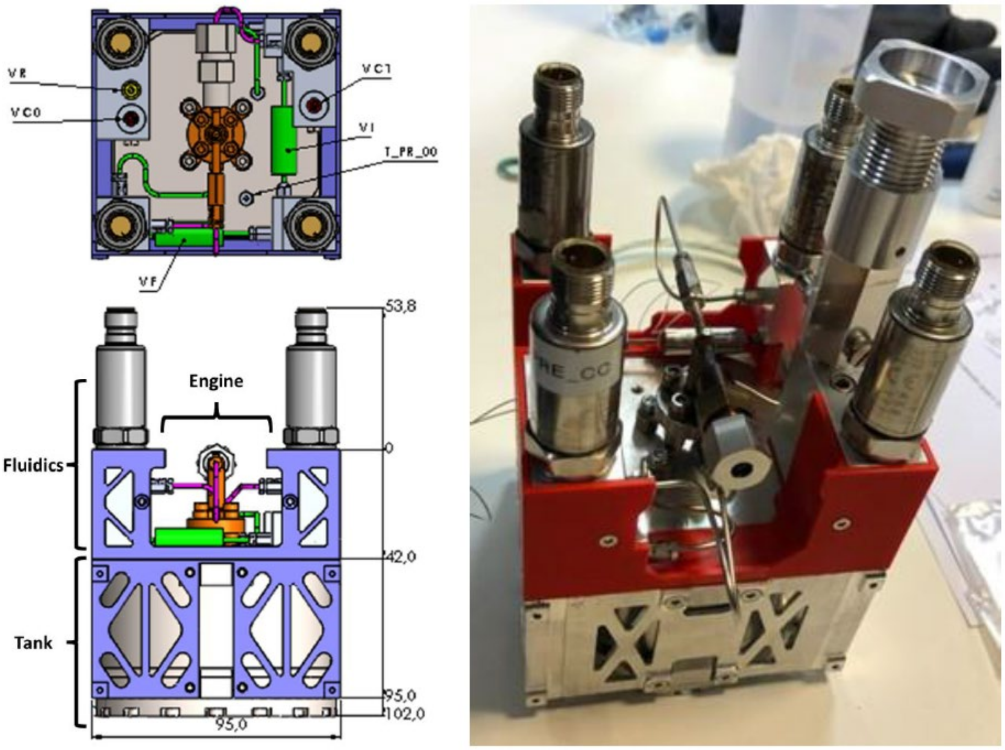

Fig 4. 1U monopropellant propulsion module engineering model

An entire monopropellant propulsion module has been developed in the frame of the PM^3 project, a modular multi-mission platform founded by the Italian Ministry of Education, Universities and Research [4]. The fundamental objective of the project was the study of a 50 kg class satellite platform characterized by the ability to accommodate multiple interoperable payloads. The propulsion system architecture is based on a simple unregulated blowdown discharge starting from a MEOP of 50 bars. The engine initial thrust in vacuum is 1N and then slowly decreases to 0.5 N at EOL as the tank pressure decreases. The fluidic line is composed by a custom piston-separated tank and few COTS components: an isolation valve, the fill and drain valves, and the firing valve. The tank is designed to be easily extended to increase propellant volume and meet the additional total impulse that may be required for other missions. Despite the tested system being an engineering model, the overall design has been flight-oriented, including the required amount of propellant in the 1U envelope. Only pressure sensors used only for test monitoring have been accommodated outside this envelope.

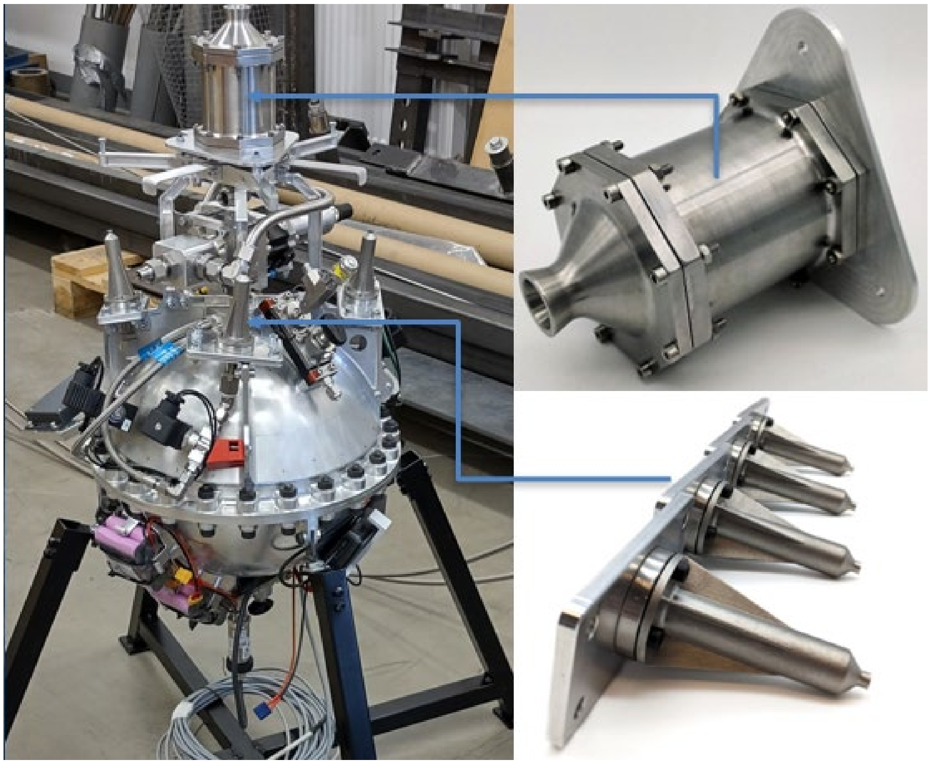

Fig 5. Moon Drone propulsion system (laid upside down): 400 N throttleable main engine (top) and four bang-bang 14 N attitude thrusters (bottom)

Fig 6. Moon Drone 400 N Main Engine Flow Control Valve

Another program involving monopropellant hydrogen peroxide is Moon drone, a small platform scouting the surrounding environment that has been proposed in support of a rover mission on the Moon [5]. The design of the Moon Drone has been performed through an ESA TRP study lead by Thales Alenia Space with partners GMV, Brno University of Technology and T4i. An Earth-related flight prototype will be tested within the program and T4i is in charge of all the thrusters' development with the support of the University of Padova. After a trade-off between several possibilities performed by TAS with T4i/UNIPD support, the propulsion design proceeded with a configuration composed by a single throttleable main engine used for the main displacements aided by 4 small thrusters operated in bang-bang for attitude control. All the thrusters were fed by the same tank, which is pressurized by nitrogen. The main engine has 400 N maximum thrust; it has a continuous regulating cavitating pintle flow control valve driven by a stepper motor in feedback, a development from a previous one already developed in-house for a hybrid rocket. The rearranged flow control valve differs from the older version for the valve body that has been optimized and reduced consistently in weight. The attitude control thrusters have a maximum thrust of 14 N, they are operated with a commercial on-off solenoid valve controlled at 10 Hz. Both types of thrusters have been designed, manufactured and thoroughly tested, demonstrating the proper fulfillment of the defined specifications and they are ready for the flight campaign of the Moon Drone prototype.

Bipropellant propulsion

A 450 N hydrogen peroxide-based bipropellant liquid engine has been designed and tested. The motor is a staged combustion engine that features a vortex-cooled combustion chamber based on a swirled oxidizer injection and uses standard automotive diesel as fuel, which is injected on the catalytic decomposed peroxide stream [6]. The cooling solution for the thrust chamber is characterized by a double co-spinning counter-flowing vortex flow. It is well known that a swirled flow improves mixing and residence time thus enhancing the combustion efficiency. Moreover, this particular flowfield allows the flame to be trapped in the inner vortex while the outer one composed only by the oxidizer act as a shield that extracts heat from the chamber walls. The motor has been successfully tested, achieving smooth ignition and shut down, stable steady combustion and efficiencies above 96%.

Afterwards a regenerative cooling for the nozzle throat region with H_2O_2 has been designed through a numerical steady 1-D code [7-8]. The nozzle with its internal channels has been produced by additive manufacturing in Inconel® 718. The cooling has been tested successfully, demonstrating the capability to keep the metal parts at reasonable temperatures in steady state and showing only moderate heating of the liquid H_2O_2.

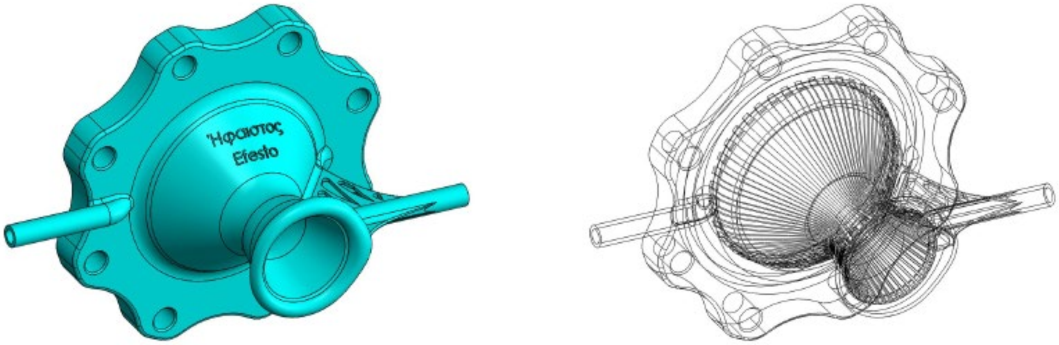

Fig 7. 450 N liquid thruster regenerative nozzle: external view (left), lattice view (right)

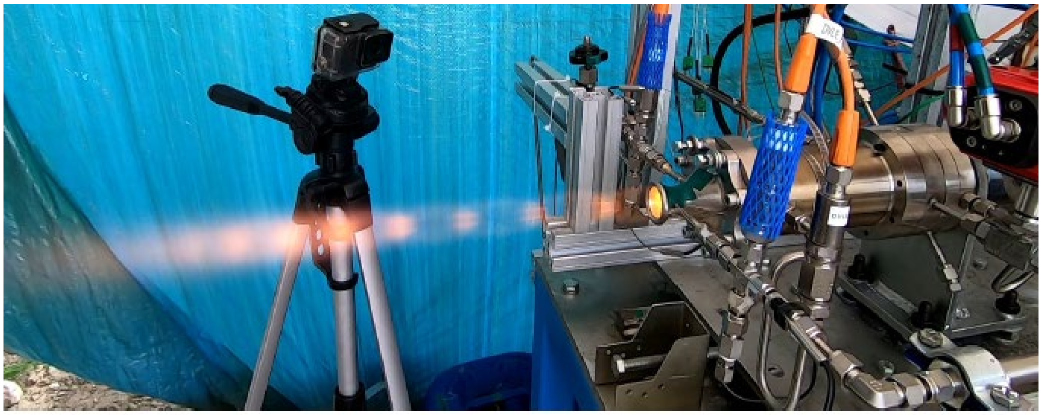

Fig 8. 450 N liquid bipropellant fire test with regenerative cooling

Hybrid propulsion

Starting in 2014, hundreds of hybrid rocket tests with hydrogen peroxide have been performed at lab-scale (100-1000 N). Hybrid firing times up to 80 s have been achieved [9]. More than 50 scale up tests with thrust above 5 kN (sea level) have also been performed up to date.

Thanks to the 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. The motors can be adapted to different missions in terms of thrust and burning times, tailoring the regression rate level of the fuel by varying the intensity of the swirled injection [10].

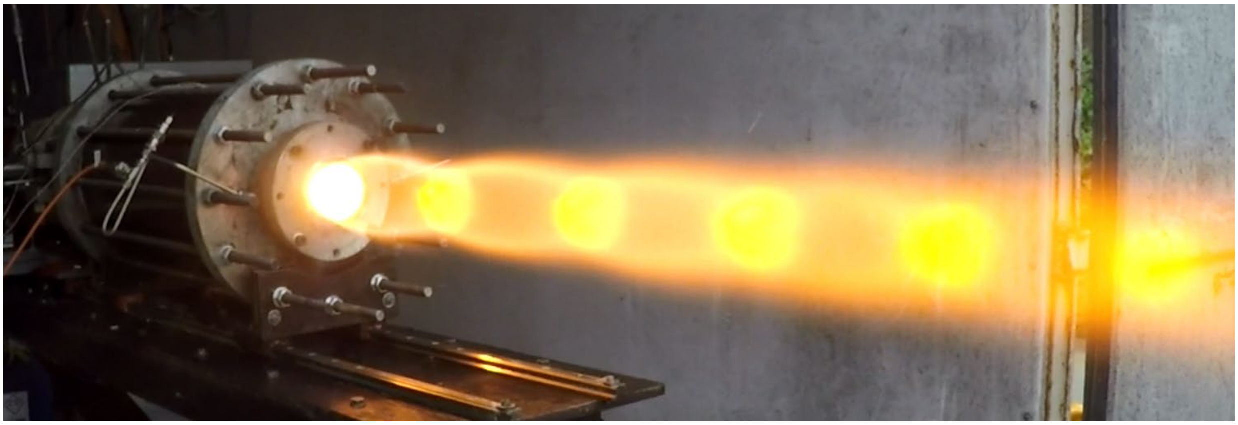

Fig 9. H_2O_2 hybrid rocket firing (5 kN at sea level)

A cavitating venturi variable pintle flow control valve has been developed in house [11]. 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 [12]. 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 [13]. A remotely controlled human manual throttling test has been also performed.

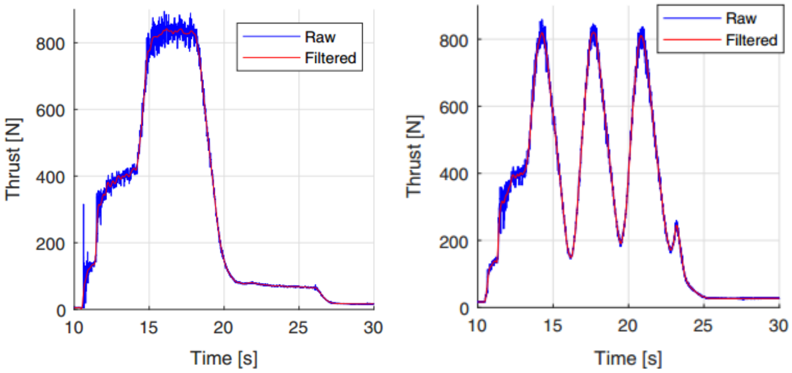

Fig 10. Throttling of a H_2O_2 hybrid rocket: step command (left), sinusoidal command (right)

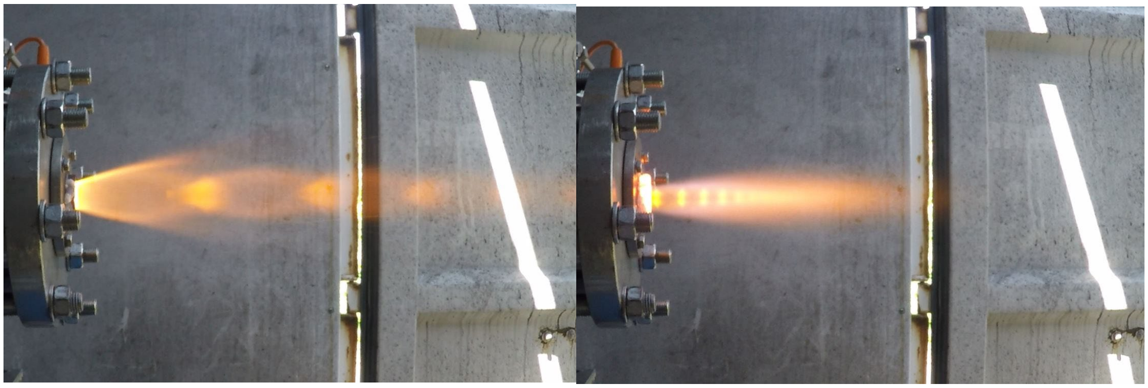

Fig 11. Throttling of a H_2O_2 hybrid rocket: max thrust (left), min thrust (right)

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 [14]. 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).

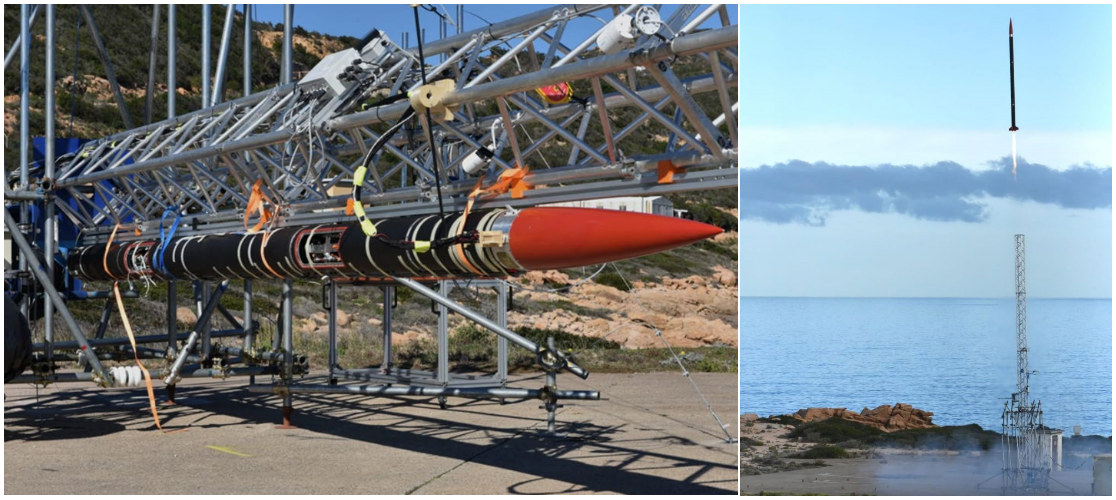

Fig 12. 5 kN H_2O_2 sounding rocket: on the ramp (left), at launch (right)

Conclusions

The University of Padua and its spin-off company T4i have been conducting research on green propulsion using hydrogen peroxide as a propellant since 2014. Hydrogen peroxide is a very versatile chemical that can be used in multiple propulsive applications.

The team has successfully designed and tested various monopropellant thrusters, ranging from 1 N to 200 N. These thrusters can operate in blowdown or pressure-regulated mode and have been tested for continuous and pulsed operations. Efficiencies above 95% have been achieved with continuous firing times up to above 1000 s. More than 4000 pulses have also been demonstrated. Depending on thruster size, valve timing can go from 30 to 100 ms. An entire 1U-1N unregulated blowdown pressure-fed propulsion unit has also been developed and tested.

The integrated propulsion system for a lunar drone, which includes a 400 N throttleable monoprop main engine and four 14 N bang-bang attitude control thrusters have been also developed and successfully tested. The main engine is actuated by a cavitating venturi pintle flow control valve developed in-house.

The team has also developed and tested a 450 N liquid bipropellant motor that burns the monopropellant exhausts with diesel fuel. This motor utilizes an unconventional internal vortex flow field for stability, efficiency, and self-cooling of the combustion chamber. The nozzle throat region is regeneratively cooled with the H_2O_2. The motor has been successfully tested, achieving smooth ignition and shut down, efficiencies above 96%, stable steady combustion and proper thermomechanical behavior.

Both the monopropellant thrusters and the liquid motor extensively employ additive manufacturing techniques to reduce the number of parts and allow complex design features.

Finally, the hydrogen peroxide technology has also been applied to hybrid propulsion, initially the main expertise of the Padua University propulsion group. Numerous lab-scale tests have been carried out, mainly with paraffin wax and polyethylene as fuels, achieving burning times of up to 80 seconds. The hybrid motors can start, stop, and restart multiple times, again utilizing a cavitating pintle valve to control oxidizer mass flow and enable deep thrust throttling. Additionally, several dozen hybrid tests have been performed at 5-10 kN scale for up to 50 seconds. Lastly, a composite sounding rocket powered by a pressure-regulated 5 kN hybrid rocket has been designed and successfully flight tested.

References

[1] F. Barato, N. Bellomo, A. Ruffin, E. Paccagnella, M. Santi, M. Franco and D. Pavarin, Status and Achievements of the Hydrogen Peroxide Chemical Propulsion Research at Padua University, Italian Association of Aeronautics and Astronautics (AIDAA) XXV International Congress, 9-12 September 2019, Rome, Italy.

[2] M. Santi, I. Dorgnach, F. Barato, D. Pavarin. Design and Testing of a 3D Printed 10 N Hydrogen Peroxide Monopropellant Thruster, AIAA Propulsion and Energy Forum, Indianapolis, IN, USA (2019). https://doi.org/10.2514/6.2019-4277

[3] D. Nissan, M. Santi, F. Barato, D. Pavarin, Testing of a Small HTP Monopropellant Thruster for Space Applications, International Astronautical Congress, Paris, France, 18-22 September 2022.

[4] M. Santi, L. Gerolin, D. Antelo, B. Montanari, M. Fagherazzi, F. Barato, D. Pavarin, Development and testing of an engineering model of a hydrogen peroxide based 1N propulsion unit, International Astronautical Congress, Paris, France, 18-22 September 2022.

[5] A. Ruffin, M. Fagherazzi, N. Bellomo, F. Barato, D. Pavarin, M. Pessana, Development of the Propulsion System for a Moon Drone Vehicle Demonstrator, AIAA 2021-3564, AIAA Propulsion and Energy 2021 Forum, 9-11 August, Virtual Event. https://arc.aiaa.org/doi/abs/10.2514/6.2021-3564

[6] M. Santi, M. Fagherazzi, F. Barato, D. Pavarin, Design and Testing of a Hydrogen Peroxide Bipropellant Thruster, AIAA 2020-3827, AIAA Propulsion and Energy 2020 Forum, 24-28 August, Virtual Event. https://doi.org/10.2514/6.2020-3827.

[7] M. Fagherazzi, M. Santi, F. Barato, D. Pavarin, Design and Testing of a 3D Printed Regenerative Cooled Nozzle for a Hydrogen Peroxide based Bi-Propellant Thruster, AIAA 2021-3235, AIAA Propulsion and Energy 2021 Forum, 9-11 August, Virtual Event. https://arc.aiaa.org/doi/10.2514/6.2021-3235.c1

[8] M. Fagherazzi, M. Santi, F. Barato, M. Pizzarelli, Simplified Thermal Analysis Model for Regeneratively Cooled Rocket Engine Thrust Chambers and Its Calibration with Experimental Data, Aerospace 2023, 10(5), 403; https://doi.org/10.3390/aerospace10050403

[9] E. Paccagnella, M. Santi, A. Ruffin, F. Barato, D. Pavarin, G. Misté, G. Venturelli, N. Bellomo. Testing of a Long-Burning-Time Paraffin-based Hybrid Rocket Motor. Journal of Propulsion and Power, Vol. 35, No. 2, pp. 432-442 (2019). https://doi.org/10.2514/1.B37144

[10] M. Franco, F. Barato, E. Paccagnella, M.Santi, A. Battiston, A. Comazzetto and D. Pavarin, Regression Rate Design Tailoring Through Vortex Injection in Hybrid Rocket Motors, Journal of Spacecraft and Rockets, 7 November 2019. https://doi.org/10.2514/1.A34539

[11] A. Ruffin, F. Barato, M. Santi, E. Paccagnella, N. Bellomo, G. Misté, G. Venturelli, D. Pavarin. Development of a Cavitating Pintle for a Throttleable Hybrid Rocket Motor, 7th European Conference for Aeronautics and Space Sciences (EUCASS), Milan, Italy (2017).

[12] A. Ruffin, M. Santi, E. Paccagnella, F. Barato, N. Bellomo G. Miste, G. Venturelli, D. Pavarin. Development of a Flow Control Valve for a Throttleable Hybrid Rocket Motor and Throttling Fire Tests, 54th AIAA/SAE/ASEE Joint Propulsion Conference, Cincinnati, OH, USA (2018). https://doi.org/10.2514/6.2018-4664

[13] A. Ruffin, E. Paccagnella, M. Santi, F. Barato, D. Pavarin. Real Time Deep Throttling Tests of a Hydrogen Peroxide Hybrid Rocket Motor, Journal of Propulsion and Power, Published Online: 4 April 2022. https://doi.org/10.2514/1.B38504

[14] F. Barato, D. Pavarin, Advanced Low-Cost Hypersonic Flight Test Platforms*,* HiSST: 2nd International Conference on High-Speed Vehicle Science Technology, 11–15 September 2022, Bruges, Belgium.