Trans. JSASS Aerospace Tech. Japan
Vol. 16, No. 3, pp. 312-317, 2018
DOI: 10.2322/tastj.16.312

A Record Flight of the Hybrid Sounding Rocket HEROS 3

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(Received June 10th, 2017)

Hybrid rocket propulsion offers inherent safety during handling and launch operations at low cost. This makes it not only attractive for space tourism applications like SpaceShipTwo but also for sounding rockets and for educational activities with students. This has been successfully demonstrated by the HyEnD student project from the University of Stuttgart: On November 8th, 2016 at 10:30 a.m. the hybrid sounding rocket HEROS 3 was launched from the Esrange Space Center to an apogee altitude of 32,300 m (106,000 ft). This set a new altitude record for European student and amateur rocketry. Furthermore, this is a world altitude record for hybrid rockets built by students. It was successfully recovered with the drogue and main parachute being released. The rocket was powered by a 10 kN design thrust hybrid rocket engine with a paraffin-based fuel and Nitrous Oxide (N_2O) as the oxidizer. The combustion efficiency was verified to be above 97 % in ground tests. Liquid burn time in the flight was for 15 s with an additional combustion of gaseous N_2O in the blow-down mode of about 10 s. The rocket was 7.5 m long with an empty mass of about 75 kg. The rocket structure was made completely from light-weight carbon fibre and glass fibre reinforced plastic.

Key Words: Hybrid Rocket Propulsion, Sounding Rocket

1. Introduction

Hybrid Engine Development (HyEnD) is a student based project located at the University of Stuttgart, founded in 2006. In the years from 2006 to 2012, HyEnD focused on developing its own hybrid rocket engines in different scales from 250 N to 2000 N thrust.[1)] In 2012 the project Studentische Experimentalraketen (student experimental rockets) STERN, was initiated by the German Aerospace Center (DLR) and HyEnD applied for it with the Institute of Space Systems. The experience and knowledge of HyEnD in developing and testing hybrid rocket engines was the foundation to develop, construct and build its own experimental hybrid sounding rocket within the planed three years of the STERN project.

In September 2012 the rocket development began, starting from scratch. The previous experience with hybrid rocket engines was the basis for the project. Within the first year, the concept of the rocket HEROS (Hybrid Experimental ROcket Stuttgart) was developed. Simultaneously, a smaller demonstrator rocket, MIRAS, was initiated in order to test all subsystems in a smaller scale before the launch of HEROS in 2015. HEROS was targeted to have a thrust of 10 kN and an to reach altitude of more than 20 km. A smaller scale was applied for MIRAS, which reaches altitudes of around 2 km with a 500 N engine. This allows test flights of the rocket on German launch sites. Both MIRAS and HEROS use a hybrid rocket engine with a paraffin-based fuel and liquid N_2O as oxidizer. More than 150 hot-fire tests have been performed in the HyEnD project so far. Results of the 500 N engine development and the 10 kN engine are presented in.[2,3)] The design of the HEROS hybrid sounding rocket is presented in detail in.[4)] A lot of improvements were made to the design of the different subsystems during the development of the MIRAS demonstrator, which were applied to the HEROS rocket design until the end of the 2nd year. At that time, HyEnD also passed the Critical Design Review. The review board included experts from the DLR MORABA, the DLR Space Agency and the DLR Institute of Space Propulsion. Six reviews have been passed in total during the project. In early 2015 the MIRAS demonstrator rocket was launched successfully, proving that the baseline concept is working. In summer 2015 a 2nd flight of MIRAS was done before the launch campaign of HEROS in October 2015. All HEROS flights took place at the Esrange Space Center near Kiruna, Sweden. The first launch of HEROS 1 in October 2015 ended prematurely due to combustion instability and a burn-through of the combustion chamber. Low temperature N_2O was the cause of the failure. However, a project extension for one year with a failure analysis was granted. After the successful Failure Analysis Review, it was decided to build and then launch the slightly improved rockets HEROS 2 and 3. Next to the engine, more improvements were made with an advanced on-board measurement system, a new telemetry system and power control unit.

2. State of the Art of Hybrid Rocket Propulsion

2.1. Liquefying hybrid rocket fuels

Hybrid rocket engines have distinct advantages[5)] compared to classical solid[6)] or liquid propellant rocket engines.[7)] The interest in hybrid rocket engines is quite high, which is indicated by the number of publications during the last years. In comparison to solid rocket engines, their TNT-equivalent of zero offers safety advantages during storage and handling. These advantages lead to reduced total costs of such a hybrid rocket engine. Controllable thrust including shut off and restart capability are further advantages. Less pipings and valves due to only one liquid component introduce less complexity and reduced costs compared to liquid rocket engines. Applications especially in space tourism like SpaceShipOne some years ago clearly show the potentials of hybrid rocket engines. One of the disadvantages might be the use of polymeric fuels. These fuels, like Hydroxyl-terminated Polybutadiene (HTPB) or High-Density Polyethylene (HDPE), show relatively low regression rates, which results in the necessity for multiport fuel grains for high thrust applications. The multiport design increases the residual mass of unburnt fuel and thereby decreases the delivered specific impulse. Instabilities are also more likely with this type of design.

Liquefying hybrid rocket fuels were investigated in the last years. Cryogenic solid n-pentane showed regression rates 5-10 times higher than polymeric hybrid fuels.[8] Following these studies, tests were done at Stanford University with long chain hydrocarbons that are solid at ambient temperature.[9,10] These fuels are Paraffin-based and show a 3-5 times higher regression rate than polymers at similar mass fluxes. This is achieved by a different combustion mechanism. Paraffin fuels form a liquid layer on the fuel surface during the combustion.[9] It is expected that the low viscosity and low surface tension of the liquid fuel enable an additional mass transfer by entrainment of liquid droplets. The gas flow over the surface induces liquid layer instabilities, which produce the droplet entrainment.[11] Optical results of this entrainment process of low viscosity liquefying fuels are shown in.[12,13] Theoretical frequencies and wave-lengths of this entrainment process are evaluated in[12] and are compared with experimental results in.[14] Scale-up tests were done and confirmed that the theory is also applicable for engines at larger scale.[15] Recent tests with different Paraffin-based fuels and Gaseous Oxygen (GOX) showed an exponential relation between the liquid layer viscosity and the overall regression rate.[16,17] Numerical analysis of the liquid layer instability is given in.[18]

2.2. Recent and current programs

Hybrid rocket engines are in the focus of research at several institutions and universities world-wide. They are well suited for educational purposes with students due to their aforementioned inherent safety. Especially small-scale combustion experiments are widely available and described in detail in the literature. At larger scales, the number of experiments and available data is much smaller. Their good performance, depending on the chosen propellant combination, makes hybrid rockets attractive for small to medium scale sounding rockets. The throttling and restart capability are further advantages of hybrid rocket engines.

The biggest operational hybrid rocket engine was realized within the Hybrid Propulsion Demonstration Program in the United States.[19] The engine was based on HTPB and Liquid Oxygen (LOX) with a thrust of 250 klb. Sub-scale tests were successful while the full thrust engine still suffered from instabilities. Different flight tests have also been performed, with exception of SpaceShipOne, mostly with problems.[20] Recent efforts from NASA Ames, the Stanford University and the Space Propulsion Group Inc. (SPG) were aiming at developing the Peregrine sounding rocket in a joint program. It uses a hybrid rocket engine with N_2O and a Paraffin-based fuel to launch a 5 kg payload to an altitude of more than 100 km.[21] The development of the engine was challenging due to the occurrence of low frequency instabilities based on feed system coupling and acoustic instabilities.[22] The low frequency instabilities were partially related to the injection conditions of the N_2O, especially its vapor pressure.[23,24] The latest tests showed stable operation at high efficiency. In the last years, SPG developed a high performance hybrid rocket engine with LOX and Paraffin-based fuels as propellants.[25] Its application was proposed as an upper stage engine with an extrapolated vacuum specific impulse of 340 s. The technological challenges of combustion instabilities, which often arise with LOX hybrid rocket engines,[26] were said to be solved only by advanced combustion chamber and injector design and passive devices. In previous engines these instabilities were only solved partially by injecting pyrophoric liquids, which increased the complexity and decreased the inherent safety of hybrid rocket engines.[27–29] Often low-frequency instabilities can arise in hybrids[30] which are based on a coupling between thermal transients in the fuel grain and transients in the boundary layer. The JAXA in Japan is investigating a wide field of different hybrid rocket propulsion concepts.[31] This includes the work on a 5 kN swirling oxidizer flow hybrid rocket engine.[32] SpaceShipOne and SpaceShipTwo are still the most well-known examples of flight proven hybrid rocket engines. A sub-orbital hybrid sounding rocket is in development by the Norwegian company NAMMO.[33,34] The engine is using a HTPB fuel and Hydrogen Peroxide (H_2O_2) as oxidizer. The Jet Propulsion Laboratory is currently evaluating hybrid rocket propulsion as a technology for a Mars Ascent Vehicle.[35] It shall use a wax-based fuel formulation from SPG, which has a lower glass transition temperature than HTPB and a wide operating temperature range from -100 °C till 50 °C. Thereby, it is attractive for this application on the Mars where high temperature variations on the surface exist.

3. HEROS Rocket Description

The sounding rocket HEROS is shown in Fig. 1. Its main dimensions, components and subsystems are shown in Fig. 2. In addition to the rocket systems, a lot of work and effort has been invested in the Ground Support Equipment (GSE). It was used at Esrange to load or unload the oxidizer, supply the rocket with power while on launch pad, operate the on-board electronics, the cameras and provide a remote connection to the control room at the launch site.

4. HEROS 3 Flight

On November 8th, 2016 at 9:30 a.m. the hybrid sounding rocket HEROS 3 was launched from the Esrange Space Center to an apogee altitude of 32,300 m (106,000 ft). An on-board camera image is shown in Fig. 3 from the flight at apogee. Launch permission was given by the Esrange safety board after an extensive failure analysis of the HEROS 2 launch, where the telemetry connection was lost. The remaining launch window was open just until November 9th. The loaded oxidizer mass corresponds to a filling level of only about 70 % N_2O in the oxidizer tank. Moreover, the relatively flat launch angle of 80° further decreased the apogee altitude. This low angle was chosen by Esrange for increased safety during the launch, in order to let the rocket move away quickly from the launch site. Thereby, a significantly higher apogee is possible with HEROS 3, by loading more oxidizer and using a steeper launch angle. According to the wind measurements shortly before launch, the flight path calculations have been updated as well as the launcher settings. The trajectory of the flight is shown in Fig. 4. GPS data is

Fig. 1. HEROS rocket mounted on the launcher.

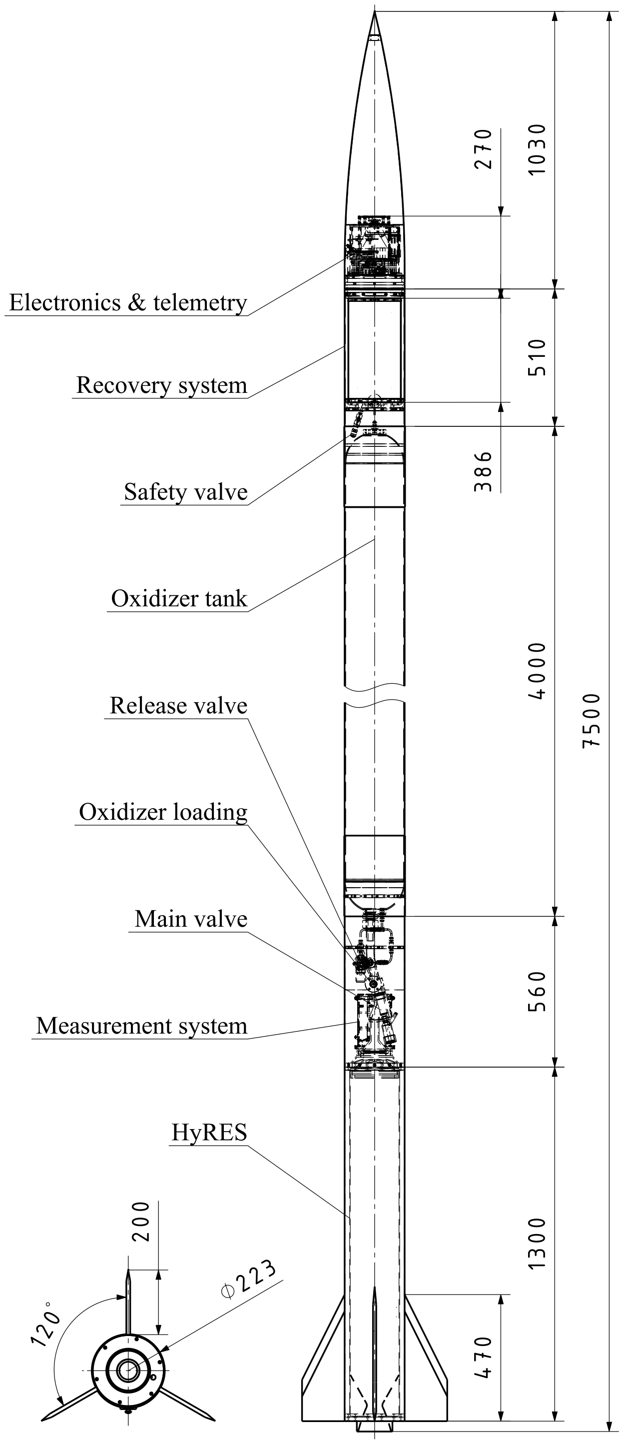

Fig. 2. Overview of HEROS rocket and its subsystems.

shown as well as the simulated trajectory from ASTOS.

Fig. 3. HEROS 3 on-board picture at 32,300 m apogee

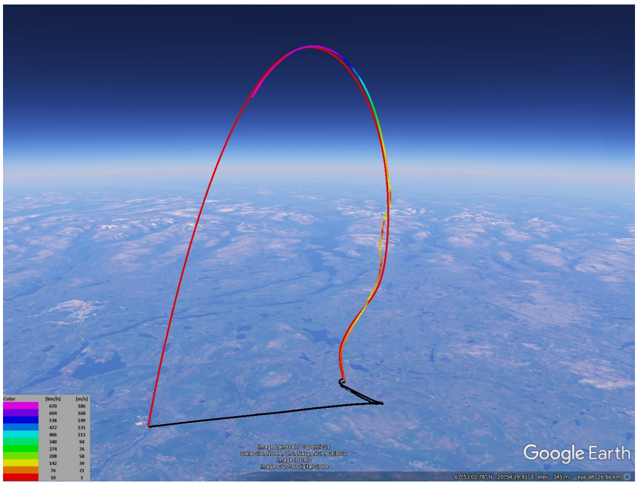

Fig. 4. HEROS 3 flight: Trajectory simulation (red) and measured GPS flight data (colored). Data shown in Google Earth.

4.1. Engine ground testing and verification

The flight trajectory has been calculated with the combustion efficiency from the ground tests of the engine. The simulation results with the ESPSS software were in very good agreement with the measurements of a blowdown test at M11.5, when a tank model with high enough resolution was used.[36] Figure 5 shows the simulation results for Test 19 in comparison with the measurements for the pressure. It is remarkable how well the tank pressure fits the real behavior. In the beginning the pressure in the tank is dropping faster, since the gas was warm at 30 °C and therefore the ullage was supercharged to 62 bar. The liquid N_2O had an initial temperature of 21.75 °C. Then, the oxidizer temperature is falling steadily as more and more N_2O vaporizes. Therefore the tank pressure drops. After 22.5 s the liquid N_2O is depleted and only gaseous oxidizer leaves the tank outlet. It depletes roughly 0.4 s later in the simulation. The hybrid rocket engine continues burning with the gaseous oxidizer flow until the main valve of the test bench is closed at 23.5 s. The simulated combustion chamber pressure is very close to the measured combustion chamber pressure. Due to the one dimensional discretization of the ESPSS component, the combustion processes in the chamber can be simulated in high detail. For example pressure drops over the pre-combustion chamber, fuel grain and post-combustion chamber can be included. The liquid oxidizer is simulated in two phase flow and the vaporization of the two phase fluid after injection is simulated along the fuel grain length.

Two chamber pressure sensors, one in the pre- and one in the post-combustion chamber, were used for the combustion efficiency calculation. When equilibrium conditions are assumed in the nozzle for the theoretical value, then a combustion efficiency of 97 % is achieved. This normally underestimates the real values. For frozen conditions, this value is even some percent higher. In reality, the results are expected to be between these two values[22]. The simulated combustion chamber pressure in Figure 5 uses also a combustion efficiency of 97 % and fits nicely to the experimental value. Additionally, the post-combustion chamber pressure also yields a lower, more conservative value of the efficiency, since it is lower than the pre-combustion chamber pressure.

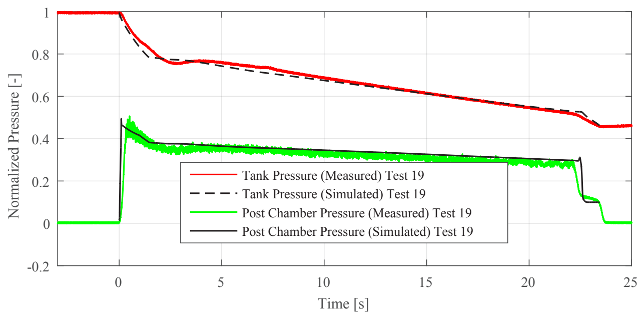

Fig. 5. Measured normalized combustion chamber and tank pressures of HyRES hot fire test 19 and comparison with simulated data

4.2. Flight data analysis of HEROS 3

All on-board measurements and sensors worked successfully and were analyzed after the recovery in detail. This includes data of the dedicated measurement system as well as the two redundant flight computers. The actual and the simulated flight trajectory is shown in Figure 4. GPS data was gathered during the rockets flight except the time frame between T+11 s and T+41 s. The COCOM Limit* of the GPS modules was exceeded during this period. The data of all GPS modules show good consistency. The measured apogee heights are within 15 m of each other. The rocket could be located and was recovered within two hours due to the maintained GPS log and telemetry link during the entire flight. The GPS height compared to the calculated height of the IMU data, as well as the rockets velocity are shown in Fig. 6.

The flight computer recorded IMU data consisting of acceleration along three axes as well as the rotation rates around the same. Using this data, the rockets attitude is calculated with a self-made MATLAB tool. The calculated yaw and pitch angles are plotted in Fig. 7, as well as the same angles according to the ASTOS simulations. It is clearly seen, that the simulated and measured results fit almost perfectly. This confirms the applicability of the used software tools.

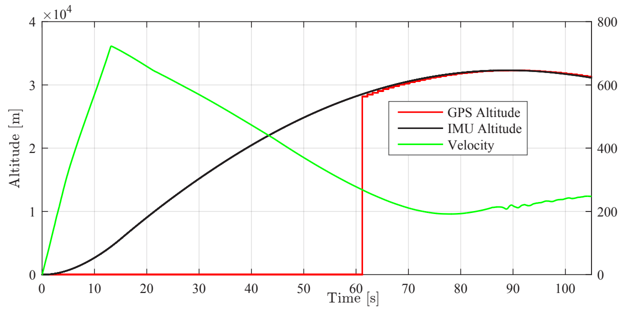

Fig. 6. GPS altitude, calculated altitude and velocity of the rocket.

The rocket acceleration along its three axes is shown in Fig. 8. The liquid thrust phase and acceleration until 15 seconds is seen clearly. Then, the acceleration is reduced due to the gas phase combustion of N_2O. The rocket is in free flight conditions, with very low residual accelerations after 40 s into the flight. Initially, the acceleration shows more vibrations up to 5 s. This is likely related to structural vibrations inside the rocket at the mounting structure of the sensor, since the combustion

* https://en.wikipedia.org/wiki/Coordinating_Committee_for_Multilateral_Export_Controls [retrieved 31st March 2017]

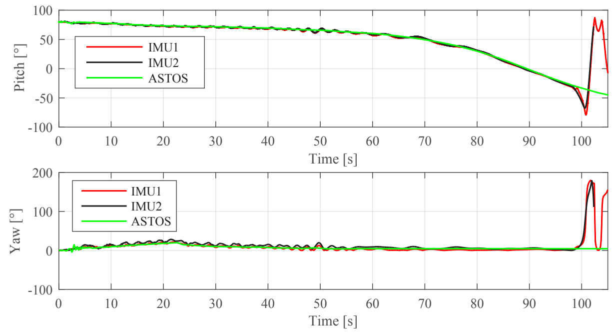

Fig. 7. The rockets flight attitude, calculated from the on-board measurements, and the corresponding simulation results from ASTOS.

chamber pressure data shows very stable combustion for the whole liquid burning time. The rocket is reaching supersonic velocity at around 5.5 s. This is also the time, when the oscillations are decreasing. The maximum rotation rate around the longitudinal axis is at 0.5 Hz at liquid N_2O burnout. After that time, the roll rate is decreasing steadily until the apogee at around 90 s. The roll rate decreases at 5.5 s at the time when supersonic velocity is reached.

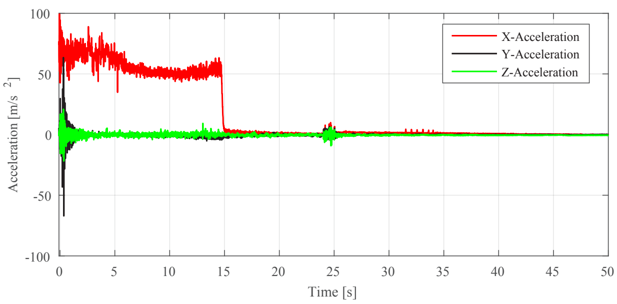

Fig. 8. Acceleration in rocket fixed coordinates.

5. Conclusion

Three HEROS hybrid sounding rockets have been developed, built and launched within just 4 years project time. The development involves the design of the complete rocket system, including the propulsion system, flight weight valve, rocket engine, tank, electronics, data acquisition, recovery system and rocket structure. This clearly shows the potential of hybrid rocket propulsion and hybrid sounding rockets. Moreover, the project enabled students to participate in the development and implementation of all the aforementioned systems, thereby providing them excellent hands-on experience in addition to their theoretical studies. Furthermore, a new world record for hybrid sounding rockets built by students has been achieved.

Acknowledgments

The HyEnD-STERN project was funded by the DLR Space Administration with funding from the Federal Ministry for Economic Affairs and Energy (BMWI) at the Institute of Space Systems at the University of Stuttgart, under the grant number 50RL1254 since September 2012. The experimental tests were performed in cooperation with the Institute of Space Propulsion at the DLR Lampoldshausen, test complex M11.5. The support of the DLR Lampoldshausen and its department of propellants is greatly acknowledged. The support and the software from ASTOS Solutions GmbH is greatly acknowledged. The authors would like to thank all the students, individuals, institutes and companies who supported the presented work in several manners. A special thanks to Dr. Thomas Wegmann at the Institute of Space Systems for his excellent administrative support.

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