Test Campaign of a 10000 N Hybrid Rocket Engine

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Abstract

A 10000 N hybrid rocket engine called HyRES (Hybrid Rocket Engine Stuttgart) is developed, built and tested by the student team Hybrid Engine development (HyEnD) at the University of Stuttgart within the DLR STERN program. It serves as the main propulsion system for the HEROS sounding rocket, which shall be launched from Esrange in Sweden. The rocket shall reach an altitude of at least 20 km, and this determines the engine thrust and burn time. HyRES is aimed to have a total impulse of over 100 kNs with a nominal burn time of 10-15 sec. The targeted combustion efficiency is more than 90 % in order to provide high performance for maximum flight altitude. HyRES is using a liquefying paraffin-based solid fuel and Nitrous oxide (N_2O) as oxidizer. The usage of liquefying fuels enables a simple single port fuel designs and a higher fuel utilization compared to low regression rate fuels like Hydroxyl-terminated Polybutadien (HTPB). The application of a self-pressurizing oxidizer permits a simple propulsion system with good performance, without external pressurization. The development and the test campaign of HyRES is described in detail. The main goals of the test campaigns are to achieve a high combustion efficiency of the hybrid rocket engine and provide stable operation with low combustion chamber pressure fluctuations.

1. Introduction

Hybrid Engine Development (HyEnD) is a student team located at the University of Stuttgart, since its foundation 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, [2]) was initiated by the German Aerospace Center (DLR) and HyEnD applied for it with the Institute of Space Systems. The gained experience and knowledge of HyEnD in ground testing hybrid rocket engines was the foundation to develop, construct and build its own experimental hybrid sounding rocket within the 3 years of the STERN project.

In September 2012 the rocket development began, starting from scratch. Except for the rocket engine, HyEnD had only little experience with the rocket systems including flight-weight propellant management, rocket recovery and flight electronics. Within the first year, the concept of the rocket called HEROS (Hybrid Experimental ROcket Stuttgart) was developed. Simultaneously, a smaller demonstrator rocket called MIRAS (Micro Rakete Stuttgart) 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 a maximum altitude of higher than 20 km. A smaller scale was applied for MIRAS. It can reach altitudes of around 2 km with a 500 N engine. This allows to test the rocket on German launch sites. Both MIRAS and HEROS use a hybrid rocket engine with a paraffin-based fuel and liquid nitrous oxide as oxidizer. More than 140 hot-fire tests have been performed in the HyEnD project so far. Results of the 500 N engine development are presented in [3], the design of the HEROS hybrid sounding rocket is presented in detail in [4]. A lot of the subsystems that will be used on HEROS could be built and tested in smaller scale for MIRAS. This includes the flight-weight rocket engine, the pyrotechnical valve, the oxidizer tank, the recovery system, the flight electronics and the Ground Support Equipment. During the development of the MIRAS demonstrator, a lot of improvements could be made to the design of the different subsystems which could be 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. 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 is planned before the launch campaign of HEROS in October 2015. It is planned to take place at the Esrange Space Center near Kiruna, Sweden. The latest project advancement was the successful Integration Progress Review in May 2015. A time line is given in Table 1.

Table 1: HyEnD-STERN project time line at University of Stuttgart

2006	Foundation of HyEnD
2008	First Hybrid Rocket Engine Test Campaign
Sept. 2012	Begin of STERN project at HyEnD
Sept. 2013	Begin of MIRAS 500 N engine test Campaign
Dec. 2013	**Preliminary Design Review**
Nov. 2014	Begin of HyRES 10000 N engine Test Campaign
Nov. 2014	**Critical Design Review**
Feb. 2015	1st launch of MIRAS
May 2015	**Integration Progress Review**
July 2015	*End HyRES test campaign*
July 2015	*2nd MIRAS launch*
Aug. 2015	*Completion of HEROS integration*
Sept. 2015	***Rocket Acceptance Review***
Oct. 2015	***Flight Readiness Review***
Oct. 2015	*HEROS launch*
Nov. 2015	*Post flight analysis*

2. State of the Art

Hybrid rocket engines at smaller scale 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 inherent safety. Especially small-scale combustion experiments are widely available and described in detail in the literature. At larger scale, the number of experiments and available data is much less. Their good performance, depending on the chosen propellant combination, makes them attractive for small to medium scale sounding rockets. The potential throttling and restart capability are further advantages of hybrid rocket engines.

At large scale, the biggest operational hybrid rocket engine was realized within the Hybrid Propulsion Demonstration Program at the United States [5]. The engine was based on HTPB and Liquid Oxygen (LOX) with a thrust of 250000 lb. Sub-scale tests were successful while the full thrust engine still suffered from instabilities [6]. Recent efforts from the NASA Ames, the Stanford University and the Space Propulsion Group 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 [7, 8, 9, 10, 11, 12]. The development of the engine was challenging due to the occurrence of low frequency instabilities based on feed system coupling and acoustic instabilities [11, 12]. The low frequency instabilities were partially related to the injection conditions of the N_2O, especially its vapor pressure [13, 14, 15]. The latest tests showed stable operation at high efficiency. In the last years, the Space Propulsion Group developed a high performance hybrid rocket engine with LOX and paraffin-based fuels as propellants [16, 17]. Its application was proposed as an upper stage engine where it should have an extrapolated vacuum specific impulse of 340 s. The technological challenges of combustion instabilities, that often arise with LOX hybrid rocket engines [18], were said to be solved only by advanced combustion chamber and injector design and passive devices. In previous engines these instabilities could only be solved partially by injecting pyrophoric liquids, which increased the complexity and decreased the inherent safety of hybrid rocket engines [19, 20, 21]. The JAXA in Japan is investigating a wide field of different hybrid rocket propulsion concepts [22]. A scale-up engine was set-up with Gaseous Oxygen (GOX) or LOX at 5 kN thrust and swirl injection. At Padua a hybrid rocket booster was developed with 50 kNs total impulse and a short burn time [23]. Space Ship One and Two are still the most well known examples of flight proven hybrid rocket engines. Recently the research at German universities in small sounding rockets with hybrid rocket engines has increased thanks to the afore mentioned DLR STERN program. It was initiated by the DLR Space Administration, in order to promote the interest of students and young professionals for launcher-systems and space transportation [2].

Concluding it can be seen that combustion instability can be a design challenge for these types of engines at increased scale, and a special focus is set on this point during the development program. In general, combustion instability was and still is a key element for all types of rocket engines: liquids, solids and hybrids.

3. Test Bench and Experimental Set-up

3.1 Hybrid Rocket Engine

An efficient and stable rocket engine is mandatory for a sounding rocket that shall reach high altitudes. A hybrid rocket engine was chosen for the HyEnD project due to its good performance and inherent safety. That makes it especially useful to work with in educational programs with students. The oxidizer is N_2O and a solid paraffin-based fuel is used. The surface of the paraffin forms a liquid melt layer during the combustion, due to the low melting point of paraffin. This liquid layer creates droplets from hydrodynamical unstable waves, which are increasing the regression rate of the fuel by a factor of 3 to 6, compared to classic hybrid rocket fuels like HTPB [24]. Detailed research regarding this kind of fuel was done in cooperation with the DLR Institute of Space Propulsion, Lampoldshausen [25]. The fuel of HyRES was designed for a high-performance in regression rate and mechanical properties. Furthermore, a lot of effort was put in the increase of the combustion efficiency. It can be low for hybrid rocket engines, if the combustion chamber design is not optimized. The reason for this is that the mixing of fuel and oxidizer doesn't happen directly after injection, but the fuel mass flow is distributed over the length of the chamber. This forms typically a layered flow structure where the fuel is on the outside while the oxidizer is in the core. To optimize this, different injectors, mixture ratios and combustion chamber layouts were investigated. Table 2 shows the key operational data of HyRES.

Table 2: HyRES key data

Property	Value
Nominal thrust	10000 N
Nominal burn time	15 s
Nominal mass flow	5-5.5 $\frac{kg}{s}$
Chamber pressure	30-35 bar
Solid paraffin-based fuel	15 kg
Combustion efficiency	>90%
Dry mass	20 kg
Length	1300 mm
Fuel diameter	175 mm

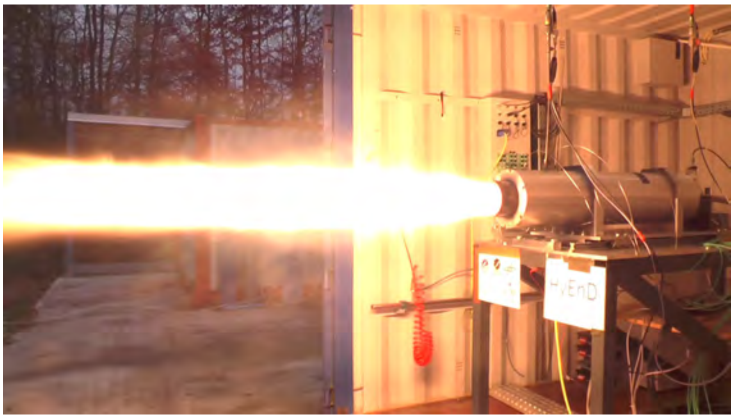

Figure 1: HyRES test at DLR Lampoldshausen test site M11.5

3.2 Measurements and Instrumentation

The measurement system consists of a National Instruments PXI system with different measurement cards for the respective sensors. The software was developed and programmed with Labview. The complete measurement system is installed separately in the rear part of the test container, in order to provide short cable lengths and adequate safety from the engine testing. The tests are conducted remote controlled from the M11.5 control room in safe distance from the test site. Table 3 shows the sensor list of the HyRES test campaign. These sensors enable the measurement and calculation of the most important values which are needed to characterize the engine performance.

Table 3: HyRES sensor list

Sensor	Manufacturer	Location	Frequency	Range
Load cell	Althen	Engine thrust	20 kHz	0-20 kN
Pressure	Kistler	Pre-combustion chamber	20 kHz	0-100 bar
Pressure	Kistler	Post-combustion chamber	20 kHz	0-100 bar
Pressure	Kistler	Injector	20 kHz	0-100 bar
Pressure	Sensortechnics	Pre-combustion chamber	1 kHz	0-70 bar
Pressure	Sensortechnics	Post-combustion chamber	1 kHz	0-70 bar
Pressure	Wika	Injector	1 kHz	0-100 bar
Pressure	Wika	Main oxidizer valve	1 kHz	0-100 bar
Thermocouple type K	Electronic-sensor	Several at combustion chamber wall	10 Hz	0-100 °C
Coriolis	Endress+Hauser	M11.5 N_2O feed system	≈10 Hz	0-14 kg/s

3.3 Test bench M11.5

The experimental tests with an engine of this thrust size needed to be done in a safe and adequate environment. Therefore a collaboration with the DLR Institute of Space Propulsion in Lampoldshausen was started for the test campaign. In 2012 the DLR Lampoldshausen started the design and construction of a new test bench M11.5, which is shown in Figure 2. It is especially dedicated to support educational tests with students, hybrid rocket propulsion at larger scale and new propellant combinations. It is an extension of the test complex M11 of the department of propellants.

Figure 2: DLR Lampoldshausen test bench M11.5

Figure 3: M11.5 oxidizer storage and gas supply

Two test positions are available for experimental set-ups in mobile containers. This allows student teams to assemble their experiment in a container with measurements and instrumentation at their university and then bring the container for the test campaign to M11.5. Here 2 supply lines for N_2O can be used for mass flow rates up to 5 kg/s. Additionally, several connections for N_2 auxiliary gas are installed, at different pressure levels. The whole N_2O and N_2 supply is installed at M11.5 in secure distance from the containers behind concrete walls, as shown in Figure 3. The media supply and test campaigns are run from a dedicated control room. Several positions are available for the control of a test run by the DLR, shown in Figure 4, and for the user experiments as shown in Figure 5. Several network connections and remote video surveillance complete the testing capabilities. The test bench is also used regularly for student workshops for the DLR STERN program, for Summer school events or for School Lab activities from the DLR Lampoldshausen, in order to provide hands-on experience for students during their education.

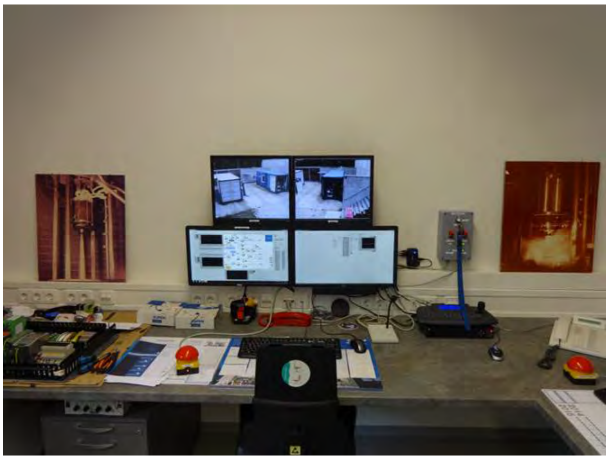

Figure 4: M11.5 control room: DLR position

Figure 5: M11.5 control room: User position

4. Results

The time for the HyRES engine development and the test campaign was rather limited, due to the short overall project time frame. Therefore, an extensive test campaign was realized with a sub-scale 500 N hybrid rocket engine. This enables a high number of tests at low cost and a short time between two tests. Currently 89 tests have been performed with this engine, including one flight demonstration with the MIRAS rocket. Several important results were achieved which could be used directly for the design of the scaled-up HyRES engine. Some of the most important results include the characterization of a wide number of different paraffin-based fuels. Their regression rate is characterized by their liquid viscosity [25]. The mechanical strength was optimized as well. Special care was taken concerning the stability of the combustion process. Combustion instability lowers the performance and increases the loads on the rocket structure and payload. In general, the injector and pre-combustion chamber configuration determine the stability of the motor. The post-combustion chamber is used to optimize the efficiency of the engine. Several different injectors were tested and their effect on efficiency was determined. Good and rapid atomization and vaporization of the N_2O was crucial for the stability as well as the efficiency of the engine. The post-combustion chamber was optimized to provide better mixing of the propellants and enable a high c^* efficiency. It is seen that a considerable pressure drop is measured between the pressure measurement of the pre- and post-combustion chamber. This must be taken into account carefully when evaluating the engine efficiencies and performance.

4.1 Scale-up concept

Some important results of the small scale tests with the 500 N MIRAS engine are presented herein. The tests were done at the same test facility, and if possible under similar operating conditions as in the 10000 N tests. Figure 6 shows one of the earlier tests. Strong oscillations are visible in both the injector pressure and the combustion chamber pressure. The reason for this behavior was found to be based mainly on improper atomization of the injector. A typical feed system coupled instability behavior is noticed, where the oscillations are also visible in the injector pressure measurement. The low injector pressure drop permits this instability. At the end of the burn time, it is seen that the oscillations stop suddenly. This is because the nozzle cracked at this time, and increased the effective throat diameter. This lowers the chamber pressure and increases the pressure drop, which stabilizes the combustion.

In contrast to that, Figure 7 shows one of the latest test runs with very stable combustion and high efficiency. The main difference to the previous test is, that an injector with improved atomization performance was used. Additionally it was seen during other tests, that a high vapor pressure of the N_2O in the combustion chamber also improves the stability. The reason is that N_2O is likely to flash vaporize, if the local pressure in the chamber is below the vapor pressure.

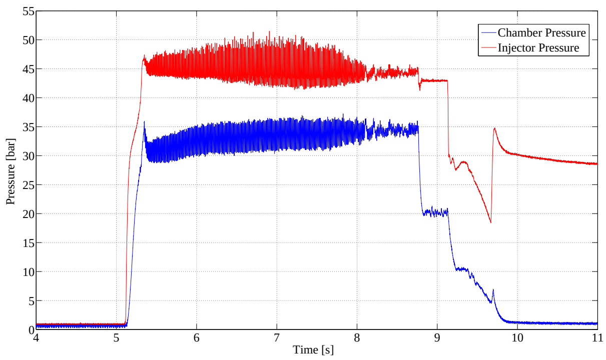

Figure 6: Pressure data of 500 N engine test 36

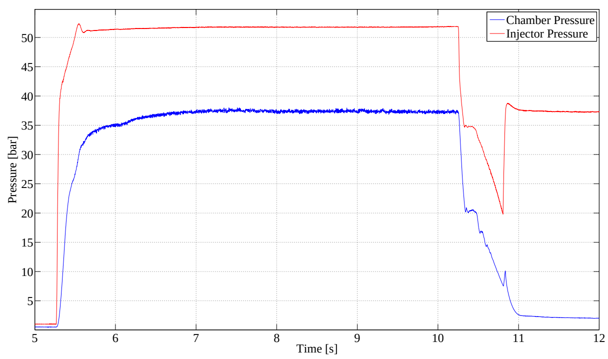

Figure 7: Pressure data of 500 N engine test 86

4.2 HyRES test campaign

The test matrix of the HyRES test campaign is shown in Table 4. 8 tests were done up to now. The performance of the engine and the operation of the test bench was gradually increased during the campaign. The first two tests showed a small initial drop in chamber pressure. This was identified to be caused by a too small pyrotechnical ignition charge and thereby was improved for the later tests. Test number 3 was done for 10 s to verify the thermal design of the engine. A modification in the post-combustion chamber was introduced in test 4 to increase the c^* efficiency. As a next step, the full mass flow injector was used for test 5 and later tests. During test 6 and 7 the engine was operated for the first time at its design conditions. The latest test 8 was at the design condition of the engine for a burn time of 12 s. This was realized with the latest upgrade of the M11.5 test facility with a 250 l volume N_2O run tank. The previous tests were limited in burn time due to a smaller tank.

Table 4: HyRES test matrix

Test no.	Configuration	Time	Comments
i-0	Igniter test	2 s	
0	N_2O Cold flow, 5 kN injector	3 s	
1	5 kN injector	5 s	
2	5 kN injector	5 s	Ignition improved
3	5 kN injector	10 s	Thermal design test
4	5 kN injector	5 s	Increased efficiency
5	10 kN injector, reduced chamber pressure	5 s	
6	10 kN injector, full pressure and thrust	5 s	Design conditions
7	10 kN injector, full pressure and thrust	3 s	Design conditions
8	10 kN injector, full pressure and thrust	12 s	Facility upgrade

Figure 8 shows the pressure and thrust measurements for test 8 . P_{cc1} and P_{cc2} are the measured pressures in the pre-combustion chamber and post-combustion chamber. The filtered thrust measurement signal is shown below. Both pressure and thrust show a steady-state behavior. The combustion chamber pressure signals are stable with very little oscillations.

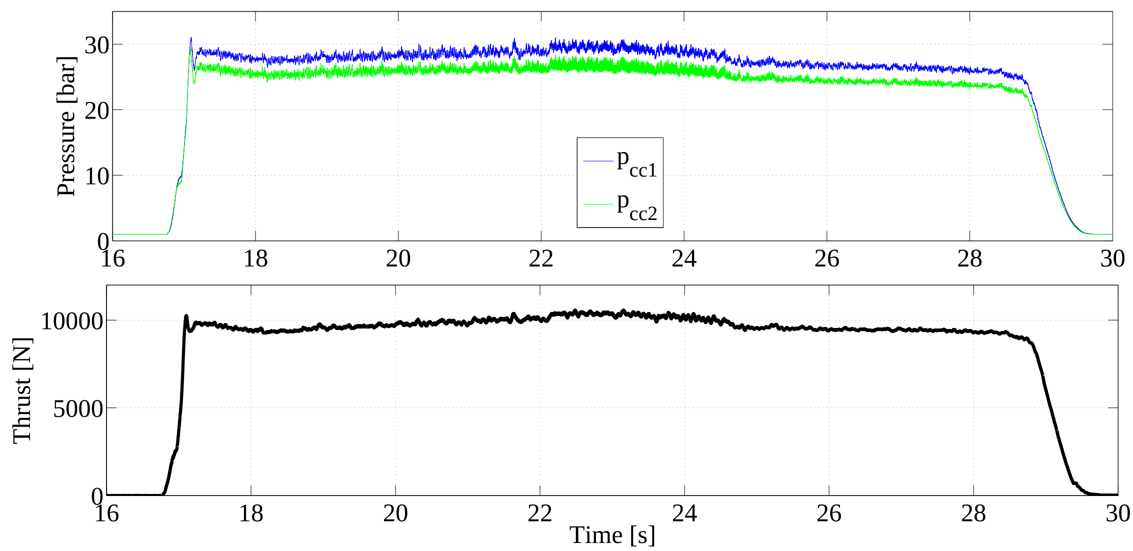

Figure 8: HyRES pressure and thrust measurement of test 8

5. Conclusion

The development, test campaign and optimization of a 10000 N hybrid rocket engine is described in detail. The design was based on a 2 step approach, with a small scale 500 N demonstrator engine which was used to gather experience and better understanding of the underlying physical combustion processes. This approach enables a high number of tests at small scale and low cost. The test campaign was targeted at the effect of the fuel composition, the injector configuration, fluid dynamic effects, combustion stability and efficiency. These results were analyzed and used for the design of the 10000 N scale-up engine. Up to now, 8 tests were done, where the performance of the engine was gradually increased up to the design conditions. The experimental results match closely the theoretical calculations. The most important requirements were achieved successfully: a stable combustion at high efficiency and a delivered total impulse of more than 100 kNs. This proves the applicability of this engine concept for the targeted launch date in October 2015.

6. Acknowledgements

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Abbreviations

DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
GOX	Gaseous Oxygen
HEROS	Hybrid Experimental Rocket Stuttgart
HyEnD	Hybrid Engine Development, DGLR student group
HyRES	Hybrid Rocket Engine Stuttgart
HTPB	Hydroxyl-terminated Polybutadien
LOX	Liquid Oxygen
MIRAS	Micro Rakete Stuttgart (demonstrator rocket)
MORABA	Mobile Raketenbasis (DLR sounding rocket division)
STERN	STudentische Experimental RaketeN (Student Experimental Rockets, educational programme of DLR)