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ZEpHyR - ZARM Experimental Hybrid Rocket: Results of the Propulsion System Tests and Flight of a Small LOX/Paraffin Powered Sounding Rocket

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Abstract

The ZARM Experimental Hybrid Rocket (ZEpHyR) was a small sounding rocket developed under the DLR STERN (Student Experimental Rockets) project. Its development started in 2012 as a small technology pathfinder rocket to prove the feasibility of using a LOX (Liquid Oxygen) and paraffin hybrid motor in a flight configuration and culminated in the launch of the rocket from Esrange Space Center in Sweden on April 16th 2016. This paper shows results of the engine test campaign from engineering model to flight model including flight data providing hands-on experience from the whole development cycle.

1. Introduction

In recent years hybrid rocket engines have seen an increase in attention and development manly stemming from improvements in regression rate, eliminating poor volumetric efficiency as one of the drawbacks of hybrid engines. The improvements in increased regression rate were achieved by employing the entrainment process, which was first discovered and described by Karabeyogulo et. al. [1, 2].

Entrainment of the fuel into the diffusion flame in a hybrid engines combustion chamber requires a fuel, which forms a molten layer and has a low viscosity and surface tension. The fuel of choice is often wax, as it exhibits the right properties, while being safe and easy to handle. However, wax is seldom used in pure form and is blended with additives to improve mostly its mechanical and radiation absorption properties and tailor the regression rate to the needed value.

As such wax was chosen as the basic ingredient for the fuel of the ZEpHyR's main engine and several trade-off studies led to the conclusion that liquid oxygen (LOX) would be the preferred oxidator [3]. In addition to performance characteristics this combination also fit well in the general framework of the STERN project. Its main purpose was to increase awareness in STEM (Science Technology, Engineering and Mathematics) subjects and encourage young graduating engineers to pursue a career in space transportation systems. As such the combination of a wax/LOX hybrid engine allowed the participating students to learn many aspects of rocketry such as cryogenics, solid fuels, pressurization systems and the many other disciplines involved in building a functioning rocket engine, while still being relatively safe.

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2. Overview of the Engine

The following table summarises the design performance characteristics.

Table 1: ZEpHyR main engine performance characteristics

Parameter	Data
Average thrust	1875 N
Burn duration	25 s
Sea level I_{sp}	264s (theoretical) / ≈ 225s (measured)
Total Impulse	≈ 46800 Ns
Oxidiser tank pressure	5.0 MPa
Combustion chamber pressure	3.5 MPa
Average O/F	1.8
Propellant	Paraffin wax blend
Oxidiser	LOX
Pressurant gas	Helium
Igniter	Pyrotechnic

The engine operated at a nominal chamber pressure of 3.5 MPa and an average mixture ratio of O/F 1.8. The flame temperature was calculated to reach values of up to about 2850 K using the NASA CAE code [4]. This resulted in a calculated thrust of about 1900 N at an average sea level I_{sp} of 264 s (calculated).

In order to develop the engine a two model philosophy was employed. First an engineering model (EM) was designed and constructed. This engine had a structural safety factor in excess of 10, allowing for combustion chamber pressure spikes of more than 40MPa. In addition this engine was highly instrumented with up to 16 thermocouples and three pressure transducers. This was done to allow testing of the engines characteristics even in off-nominal conditions, such as combustion instabilities. In addition the engine allowed for easy adaptability of the main components such as pre-and post-combustion chamber, nozzle and to a limited extent the fuel grain.

The EM was used to tune the engine and discover any discrepancies in the actual operation of the engine, when compared to theory.

The second model, a flight model (FM) was designed at a later stage and incorporated all the lessons learned from the EM as well as a much lighter combustion chamber. Its production would only start after the EM had achieved stable operation for several runs. The highest pressures encountered during the final stable EM runs would be the design pressure of the FM and it in turn was then designed with a safety factor of 1.5. The internal geometries of the EM and FM were kept as identical as possible (i.e. injector, per- and post combustion chamber, grain and nozzle dimensions and volumes), so as to avoid any unknown behaviour when transitioning between the two models.

The FM was then tested three times, a short burp-test of 5 seconds and two full duration burns of 25 s each, to qualify the engine for flight. After the tests the engine was thoroughly inspected and then refurbished for the flight in Esrange.

Figure 1 shows a comparison between the two engine models. The EM was designed using high strength stainless steel and hat a wet mass (including grain) of more than 112 kg. In order to facilitate many test sequences the EM was fitted with a copper thermal protection jacket on the injector side. It provided the necessary capacitive cooling capacity. In addition it was at least in part actively cooled by being in contact with the LOX streaming into the

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injector. The grain was housed in a cotton phenolic liner (not shown) that provided the necessary mould during spin casting and also a precise shape for the low tolerance fit with the combustion chamber. The nozzle of the EM initially was constructed of molybdenum, providing high temperature resistance and high capacitive cooling capabilities. This type of nozzle could be used for short duration testing of up to 10 s burn duration, while exhibiting not appreciable degradation. It was hence very useful for rapid initial testing cycles. Longer duration firings however lead to significant damage (cracking and melting) as the capacitive cooling capabilities where exhausted. Hence for the longer duration tests this nozzle was replaced with a cotton phenolic and graphite inlay composite nozzle, which was also used for the flight model.

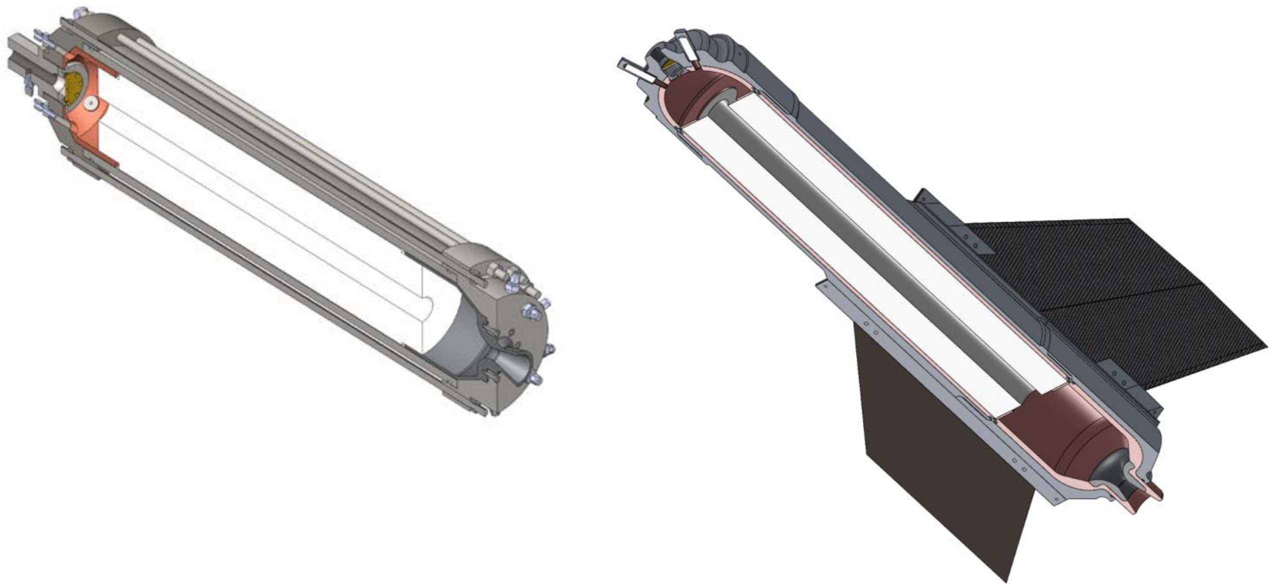

Figure 1: EM of the engine (left) and FM of the engine (right)

The flight model as shown possesses the same internal fuel grain and chamber geometry as the EM but was tuned for minimum mass. As such the final testing runs of the EM were used as benchmark for possible expected pressure spikes and were used to parameterise the CAD (computer aided design) model of the FM. The FM was manufactured from aluminium and also possesses the attachment points for the fins of the rocket as an integral part to the main combustion chamber pressure vessel, further reducing the mass. Additional mass is saved by replacing the pre-combustion chamber copper liner with a cotton phenolic one. In addition the igniters are visible in the image, two of which are used for redundancy purposes. While these modifications made the FM a rather complex part to produce – it was manufactured from a single shaft of aluminium in a multistep turning and milling process – it did reduce the wet mass of the engine including fins to about 33 kg.

3. Overview of the test stand

The engine test stand was an upgrade of the previously available small scale test stand at ZARM (Centre for Applied Space Technology and Microgravity). While the small initial test stand used GOX (gaseous oxygen) as its main oxidiser, it now needed LOX (liquid oxygen) capability. This upgrade was done over a period of several months and yielded a test stand capable of the performance characteristics displayed in the following table.

Table 2: Engine test stand capabilities

Parameter	Data
GOX supply	max. 0.3 kg/s for 70s @ 6 MPa
LOX supply	max. 1 kg/s for 30s @ 5 MPa
Ancillary gases	He and N_2 at up to 6 MPa

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	LN_2 for chill-down and testing
Water deluge system	11 m³/hr supply for cooling (max. 3.5 min duration)
Maximum thrust level	10 kN
DAQ	Dedicated DAQ system with up to 10 kHz sampling on more than 20 channels as well as dedicated control and safety systems

One unique fact about the test stand is its ability to produce the LOX required for the test – no LOX is stored for longer than a single test sequence. This was achieved by using liquid nitrogen to liquidise gaseous oxygen from standard 20 MPa 50 liter cylinders. This technique increased safety as no large quantities of LOX would be stored and reduced cost as a full duration test only required about 15kg of LOX, hence large storage facilities would be inefficient (most LOX would be lost to boil-off in between tests). Figure 2 shows the test stand with the EM engine installed, ready for testing.

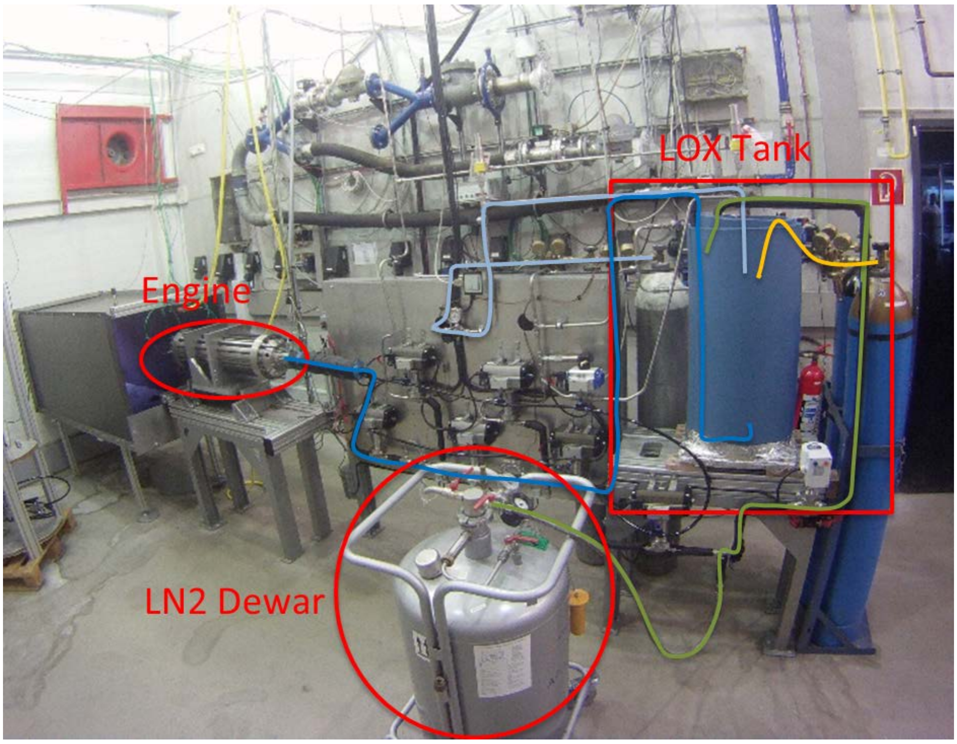

Figure 2: Test stand (light blue – GOX supply, dark blue – LOX supply, yellow – He supply, green – LN2 supply)

4. Test Campaign

The following section describes the test campaign for the ZEpHyR main engine. The goal of the campaign was twofold. First to establish the differences between the theoretical engine design and an actual engineering test model and secondly once stable operation was achieved to qualify a flight model of the engine. As such the test campaign was mostly concentrated on the EM tests, while there would only be three FM tests to verify that no unexpected instabilities had occurred in the transfer from engineering to flight model.

4.1 EM Test Campaign

The first test of the engine was conducted on November 4th of 2014 and was meant to be a typical short "burp – test" of the engine. As this was the first test of the engine and test stand using LOX it was decided to lower the chamber pressure significantly to only 1 MPa and limit the firing duration to 5 seconds. Prior to this test several cold – flow and chill-down tests were performed using LN2 to verify the correct operation of the setup. The reduced chamber

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pressure would significantly reduce the performance of the engine and shift the O/F to a very rich setting, but it would verify that the igniters could start the engine.

The EM Test campaign foresaw three testing stages to achieve stable operation. Figure 3 shows test data gained during these blocks.

The first block of tests increased gradually the firing duration from 5s to the nominal 25s by constant chamber pressure (75% p_{cmax}). This block's objective was to qualify basic functional, performance, design and operational requirements as well as to improve the EM test campaign's sequence, i.e. Shut-Down Sequence after the 1st test. The shutdown sequence of the first test was not optimised as can be seen in Figure 3 (top left). The test should have lasted only five seconds, at which point a marked reduction in chamber pressure can be observed. However, due to the untested shutdown sequence, significant quantities of residual LOX from the test stand were purged through the engine leading to the shown erratic pressure trace. As a consequence the shutdown sequence was reworked leading to much smoother shutdown in the following tests.

The second block iteratively increased the chamber pressure by constant firing duration of 10s, 15s and 20s. As a stable operation was achieved for one pressure level the tests have been restarted at a low pressure level and a longer firing duration. Its objective was to qualify the EM's nominal performance characteristics (Table 1) see 4th and 16th Test.

The third block tested different LOX injectors at 80% nominal chamber pressure and 66% of the nominal firing duration. The objective of this block was to minimize combustion instabilities (Figure 3) by increasing the EM's performance (see Test 19th).

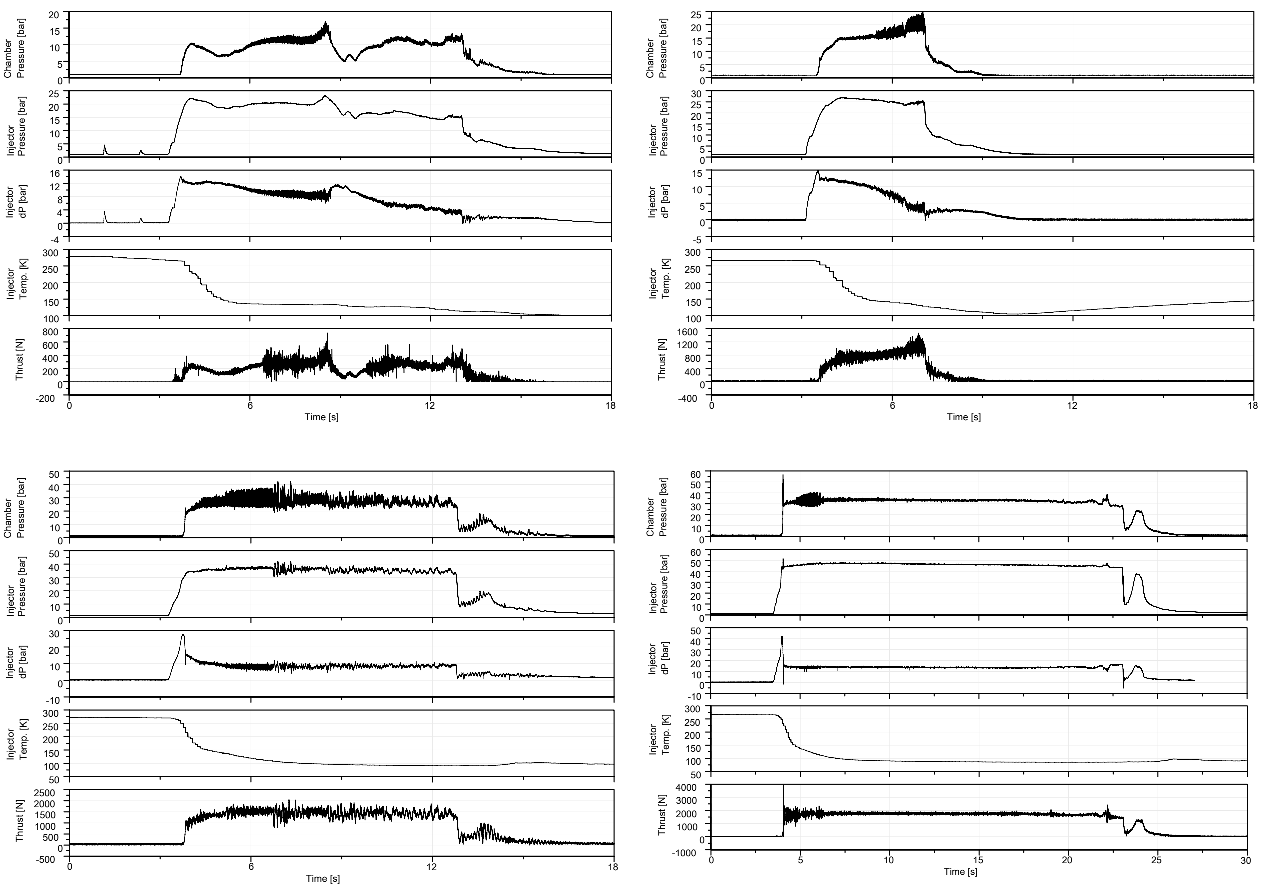

Figure 3: ZEpHyR EM test data – 1st burb-test (top left), 4thtest (top right), 16th test (bottom left), 19th test (bottom right)

Figure 4 shows the frequency analysis of the EM's combustion instabilities (from the tests performed shown in Figure 3) using a Fast Fourier Transformation (FFT). The amplitudes of the analysis have been normalised to be able to compare the results, as the intervals (firing duration & sample rate) of each tests were different. All tests showed

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similar major anomalies occurring at about 400 Hz in the medium frequency spectrum. Tests 16th and 19th showed both a frequency shift of the 400Hz to a higher frequency with increasing firing duration. This frequency shift can be explained as a function of the O/F shift together with an increasing chamber diameter with increasing firing duration but cannot be completely explained, with the available data and thus will be subject for further analysis. It is clearly visible that the efforts of improving the injector in the last test block (see test 19) led to a much reduced instability that also dissipates as the test progresses. This is in stark contrast to the strong prevailing instability seen in the 16th test. The injector was modified from a simple showerhead to an impinging type injector improving atomisation. It is thus the hypothesis that the 400 Hz instability stems mostly from interactions of insufficiently atomised LOX with the fuel grain surface. The improved atomisation of the colliding injector of test number 19 limited this instability to the first few seconds of the burn, where the port diameter is still fairly small and hence initially only allowing for a short time for the LOX to atomise. Once the port diameter increases, this problem becomes less pronounced and the instability fades.

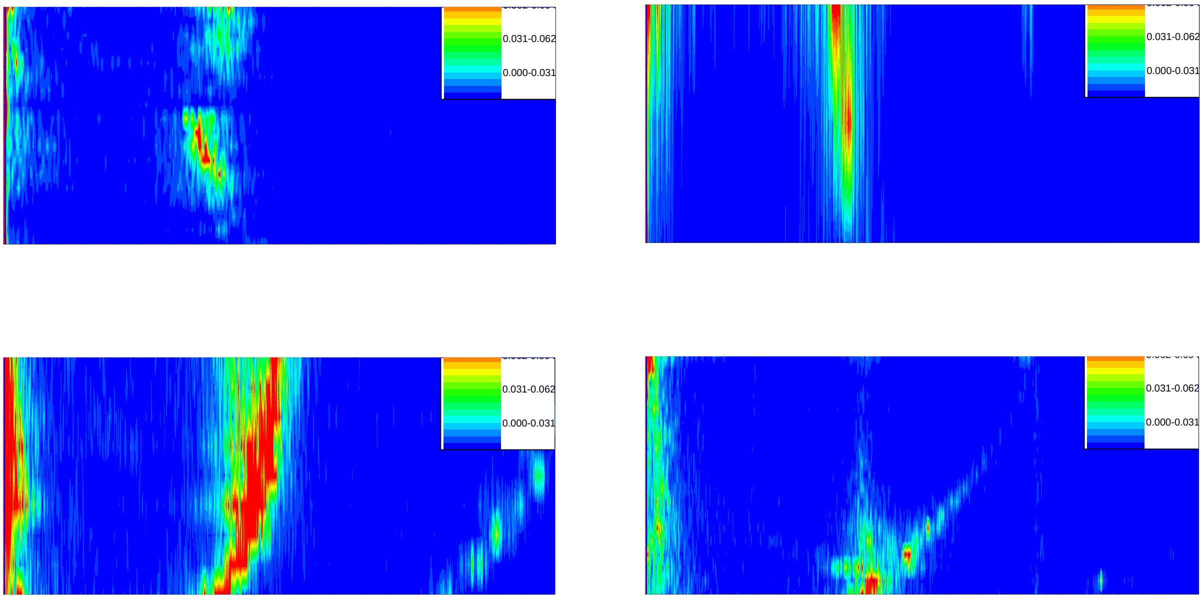

Figure 4: ZEpHyR EM Combustion chamber pressure instability analysis – 1st burb-test (top left), 4th test (top right), 16th test (bottom left), 19th test (bottom right)

4.2 Engine Improvements

Figure 3 and Figure 4 show the progression from the first hot test to the final longer duration EM tests. The contribution of the various different improvements can clearly be seen leading to a stable operation of the EM. The three main improvements are:

(1) Adaptation of the engine's starting sequence reduced a pressure peak at start, which could cause in the worst case a loss of the engine.

(2) Improvements in the paraffin grain production using a customised spin-casting process as well as carbon black additives to darken the grain. The carbon black prevented the grain from randomly liquefying below the upper melt layer. Without the carbon black thermal radiation could penetrate further into the grain and cause random pockets of molten wax – leading to random pressure spikes and instabilities. In addition, the spin casting technique reduced the tendency for voids and defects and thus also leads to an improved performance with less random instabilities.

(3) For 10 different LOX injector configurations water spray tests have been conducted to analyse their spray and impingement patterns. Further the water spray tests were used to select only the most promising configurations for block 3 to minimize costs and time for the hot firing tests. Test 19th used a like-on-like impingement injector with an optimal $l_0/d_0 = 2$ [5] setup which showed for the EM the best performance data minimizing combustion instabilities.

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4.3 FM Test Campaign

Once the EM test campaign showed stable operation several tests similar to test number 19 were conducted and the maximum pressure peaks (including slightly off–nominal start–up) were tracked. These then defined the minimum pressure that must reliably sustained by the FM, which in turn parametrised the final FM CAD model (wall thickness). Once built this engine was then subjected to three qualifications tests. The results of the two final tests (the first was just a short test to verify the correct engine start-up) are shown in the following graphs.

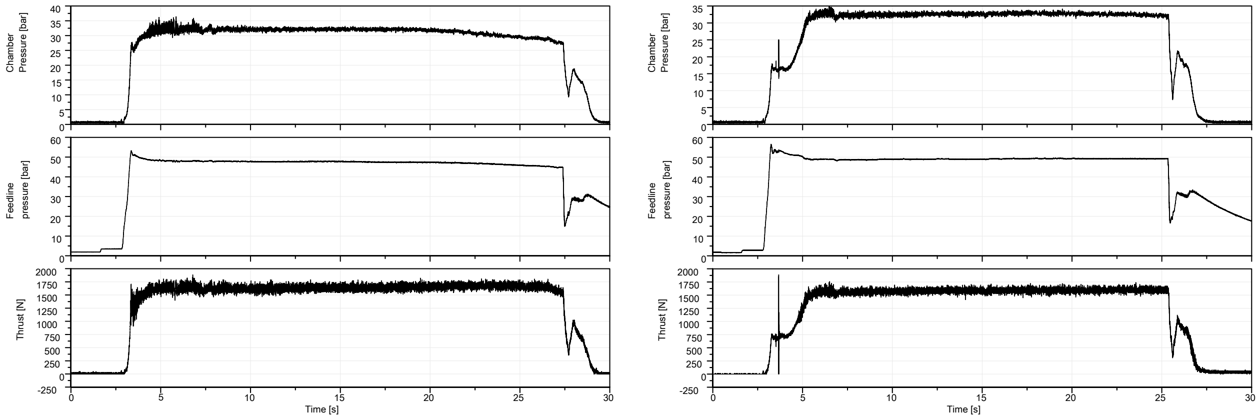

Figure 5: ZEpHyR FM test data – 2nd qual. test (left), 3rd qual. test (right)

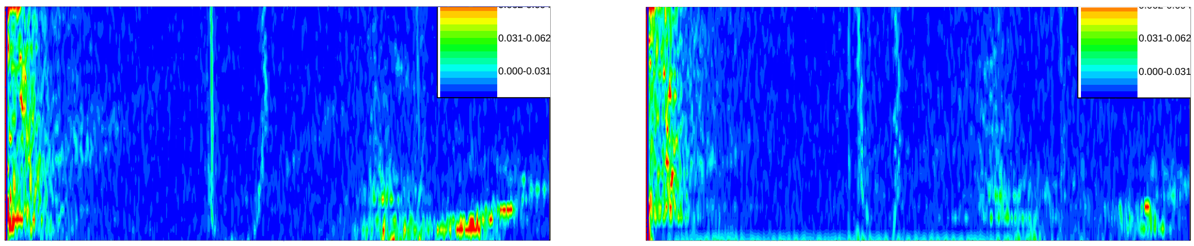

Figure 6: ZEpHyR FM Combustion chamber pressure instability analysis – 2nd qual. test (left), 3rd qual. test (right)

Figure 5 and Figure 6 show the characteristic plots for the engine. This is less data as the instrumentation on the flight engine was reduced to a minimum due to mass, power and data acquisition constraints on the rocket. Nonetheless it can be seen that the engine functions as expected; only exhibiting the previously observed 400 Hz instability at the start (not so much in the 3rd qualification test due to the slow start-up with off-nominal chill-down). Interestingly, two new slight instabilities appeared in the FM at 190 Hz and 230 Hz. The exact cause of these is currently unknown, but since there were very small adjustments in the pre- and post-combustion chamber volumes due to the slightly adapted outer geometry of the engine, this might be the cause of these instabilities. Further research here is ongoing to isolate the cause for a future iteration of the engine. In addition the engine shows the typical ILFI (Intrinsic Low Frequency Instabilities) common in many hybrids and which are still subject of active research [6]. None of these instabilities were critical for the flight of the rocket or integrity of the engine and hence the engine was declared ready for flight.

5. Flight of the Rocket

The launch of the rocket occurred on the 16th of April 2016 in the Esrange test range in Sweden. It reached an altitude of just over 1500 m above sea level. Due to the experimental nature of the rocket and non-favourable wind conditions the rocket had to be launched with a launcher elevation of only 75° leading to a very flat and suppressed trajectory and high lateral velocities at apogee. This in turn overloaded the parachute recovery system and the rocket followed a ballistic trajectory. As such the on board computer which was situated in the rockets nosecone was damaged beyond repair / data recovery upon impact and only the telemetry downlink was available. While the downlink did contain all vital engine data-streams the framerate in the downlink was only 1 Hz.

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As can be seen in Figure 7 the engine pressure data does behave as expected leading to about 5 MPa pressure in the tank and about 3.5 MPa chamber pressure. Interestingly the pressure build-up in the combustion chamber took longer than expected, which can be explained with the also slowly rising pressure in the LOX tank due to the limited responsiveness of the pressure regulation system between helium and LOX tank.

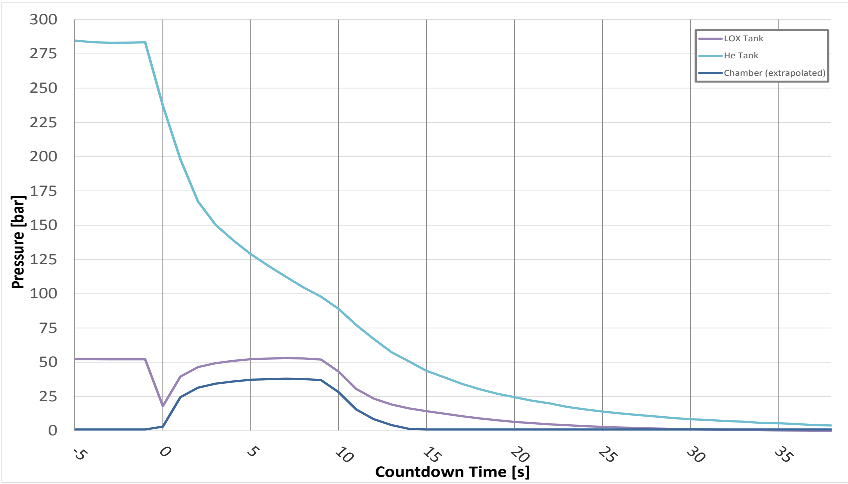


Figure 7: Telemetry downlink engine and tank pressure data

The engine however shuts down prematurely by almost 15 s which is significant considering the planned burn duration of 25 s. It was later determined that the cause for this was a low LOX load of the tank of only 30-40% due to a malfunction of the LOX fill level detection during tanking. This is something to be improved in the next generation of this rocket – planned for flight in 2020.

Table 3: Visual Camera exhaust plume analysis (start-up)

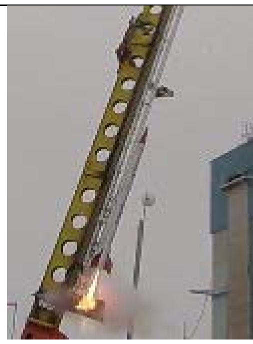
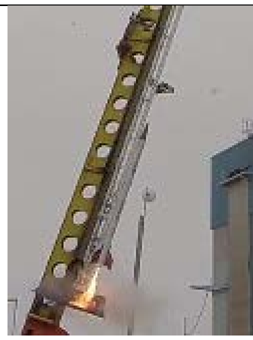
(a) Engine Ignition Sequence (Pulsing due to start-up)			
			
T+0.00 s	T+0.03 s	T+0.06 s	T+0.09 s
			
T+0.12 s	T+0.15 s	T+0.18 s	T+0.21 s

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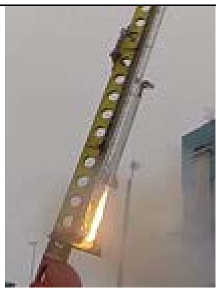
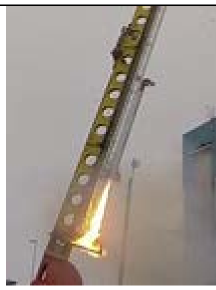
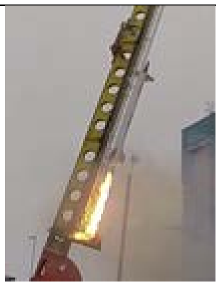
Table 4: Visual Camera exhaust plume analysis (steady state)

(a) Engine reached steady state			
			
T+0.83 s	T+0.86 s	T+0.89 s	T+0.92 s
			
T+0.95 s	T+0.98 s	T+1.01 s	T+1.04 s
			
T+1.07 s	T+1.10 s	T+1.13 s	T+1.16 s

Since the data of the sensors in the rocket was only available at 1 Hz, it was decided to investigate the initial functioning and start-up of the engine using a 33 fps camera that was positioned to observe the launch sequence. This visual inspection of the exhaust plume, while not sufficient to directly measure the initial instability observed during testing, would provide some insight into the actual behaviour of the engine during launch. Consistent with the data acquired by the on-board system, the engine does only slowly reach steady state operation (see Table 3 and Table 4). The initial start-up shows instances of mainly unburned wax being ejected by the engine. This is again consistent with a very low O/F caused by the slower than expected pressurisation of the flight tank. This has to do with the starting sequence of the engine. The LOX tank could not be fully pressurised prior to ignition since the main oxidiser "valve" in this case is a burst – disk. Due to volume and mass restrictions it was not possible to place an active valve downstream of the LOX tank and upstream of the injector. Instead a 2 MPa burst disk was installed in the line. It would keep the LOX inside the tank during tanking and would burst to permit flow into the engine once the tank pressurisation valve between the LOX and helium tanks was actuated at which time the two engine igniters would also be activated. This had the advantage of minimal mass and no need for a complex cryogenic valve on-board of the rocket. However, higher burst-pressures than the one indicated here were not possible in order to prevent an engine hard-start. Once in steady state the engine does seem to operate as expected, showing a stable plume and steady acceleration.

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6. Conclusion

This paper summarises the results of an extensive test campaign to produce the first flight version LOX – paraffin hybrid engine in Europe. Initial instabilities in the operation of the engine were overcome by adapting the fuel grain and injectors among other small adjustments. This led to an engine that operated stably for up to 25 s of burn duration during the final flight model qualification burns.

During the flight the engine did perform normally once it reached steady state operation. The start-up of the engine was slower than expected from the test data due to a slow reaction of the tank pressurisation system and the engine only burned for about 8-10 s due to an off nominal LOX load. Nonetheless, the engine did prove the concept of a small LOX / paraffin hybrid capable of flight and now sets the basis for a second generation of engine that is currently in development. This engine is planned to reach about 5 kN of thrust and will be the main engine for a second generation of the ZEpHyR with a planned launch in Esrange in 2020.

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