The propulsion system of the ZEpHyR - ZARM Experimental Hybrid Rocket: A contribution to the DLR STERN Project by the University of Bremen

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Abstract
The ZARM Experimental Hybrid Rocket, is a contribution to the DLR-STERN project. ZEpHyR is powered by a hybrid engine designed to produce 1,8kN of thrust for 30s. Three propellant combinations were considered: paraffin-GOX, -LOX and -N_2O and analysed in a trade-off.
Following the trade-off a small sub scale engine (GOX/paraffin) was used to gain experience in grain design, regression rate analyses, injector design and additives (aluminium and titanium hydride). Data on start-up procedures and materials subjected to combustion chamber gases was gathered.
Using this data, a full scale engineering model is being manufactured and the paper concludes with the most recent progress in this effort.

1 Introduction

Hybrid propulsion engines are a specific group of bi-propellant engines in which one part of the propellants (usually the oxidiser) is present in liquid or gaseous form, while the other component (usually the fuel) is present in solid form. Hence the two components are separated by a phase difference and a hybrid propulsion concept can be seen as a mix of solid and all liquid propulsion systems [1][2].

Hybrid rocket engines have been known since the early days of space transportation as a possible space propulsion system and as early as the 1950s many different fuel and oxidiser combinations were tested. Despite this long history and their many intrinsic advantages such as safety (during manufacturing, handling, storage and operation), shutdown capability (as opposed to solids), ability to throttle, low cost (only one liquid handling system) and good performance (I_{sp} is in between solids and liquid-liquid systems) [1], they have only been applied in technological niches and never as main propulsion for a space transportation system until 21st of June 2004, when the hybrid powered SpaceShipOne reached an apogee of 109km on a suborbital trajectory [3].

The main reason for the scarce use of hybrid propulsion systems in space transportation applications, was the biggest drawback of hybrids - low regression rate. The regression rate in a hybrid signifies the velocity at which the burning surface of fuel recedes before the flame. This flame in hybrids is a diffusion flame, and hence the whole combustion process is diffusion limited [2]. This low regression rate in turn means that the fuel mass flow is highly dependent on a large surface area, if a large thrust is desired. With classical fuel this meant complicated multi-port fuel geometries, to fit as much surface area into the grain as possible. Nonetheless hybrid had a bad volumetric efficiency compared to solids and especially all liquid systems. This changed however with the discovery of high regression (up to a factor of 4 increase) rate fuels, such as for example paraffin [4]. The mechanism that enables these high regression rate is droplet entrainment from the liquid film surface into the combustion zone. Due to the high gas velocities in a hybrid, a liquid melt film of fuel becomes destabilised and develops small surface wave, of off which a spray of droplets is entrained into the flame zone, thereby increasing the regression rate significantly [4], [5], [6].

The fact that such a great increase in performance can be achieved with such a benign and simple fuel as paraffin is of great value to the project at hand. Not only can a small hybrid engine be produced with relative ease that is small, yet powerful, but also can this be achieved with a cheap main propellant that can be handled and cast easily in any University lab, with a minimum of safety requirements.

As such the current paper will describe the process of developing a hybrid engine that employs paraffin as its fuel, provides a thrust of about 1,8kN for 30s, so as to propel the ZEpHyR (ZARM Experimental Hybrid Rocket) rocket to an altitude of up to 20km.

2 Propulsion System Trade-Off

The choice of propellant was mostly done with performance (entrainment), safety and ease of handling in mind. As previously explained this lead to the easy choice of paraffin. The choice of oxidator was more involved however, the goal being maximum burnout altitude, with minimum system mass. Even with all non-toxic compounds excluded three choices still remain: gaseous oxygen (GOX), liquid oxygen (LOX) and nitrous oxide (N_2O). The first point of interest hence is the specific impulse of these three propellant combination options, which is shown in Figure 1.

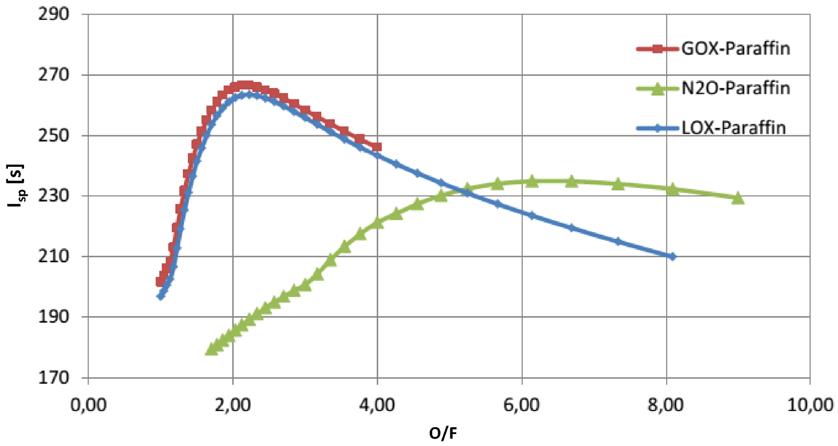

Figure 1: I_{sp} vs. O/F for the propellant options at 3MPa chamber pressure and 0,1MPa ambient pressure [7]

The data of Figure 1 was produced using the NASA CEA (Chemical Equilibrium with Applications) Code [8] that is based on the Bonnie J. McBride and Sanford Gordon FORTRAN code [9], [10]. It shows that the best option in terms of I_{sp} would be GOX, with LOX only insignificantly lower, while N_2O has an I_{sp} quite a bit lower and at a rather unfavourable mixture ratio (high O/F leads to a large tank for the oxidiser, for the same amount of fuel to be burned).

However a choice between these three options is also a choice between systems of sorts, since both GOX and N_2O would function in a blow-down mode, with N_2O being self pressurising. LOX in the other hand would require a pressurant. The system pressure traces can be seen in Figure 2 for LOX and N_2O. While the pressure in the LOX system is fully regulated from the high pressure of the pressurant tank, which must only remain high enough at the end of the burn to still support the minimum line pressure at the inlet to the injector, the case is quite different for N_2O. It is stored at critical conditions and room temperature. Upon engine ignition the tank will start to be drained, which in turn causes the pressure to drop. This will trigger the critical N_2O to boil and create more N_2O gas to re-pressurise the tank. The boil-off however causes a drop in temperature of the liquid N_2O, shifting the critical point to a lower pressure, thus re-establishing a balance through a combination of additional vapour volume and shifting critical point. In the case of this engine the required mass flow is so high that the boil-off and creation of vapour cannot keep up, causing tank pressure to drop significantly as can be seen in Figure 2. This in turn causes the chamber pressure to drop accordingly, reducing the thrust of the engine. This could only be avoided by supercharging the system with an additional pressurant tank, which negates all remaining mass advantages. Combined with the lower overall I_{sp} this means this type of system is not competitive.

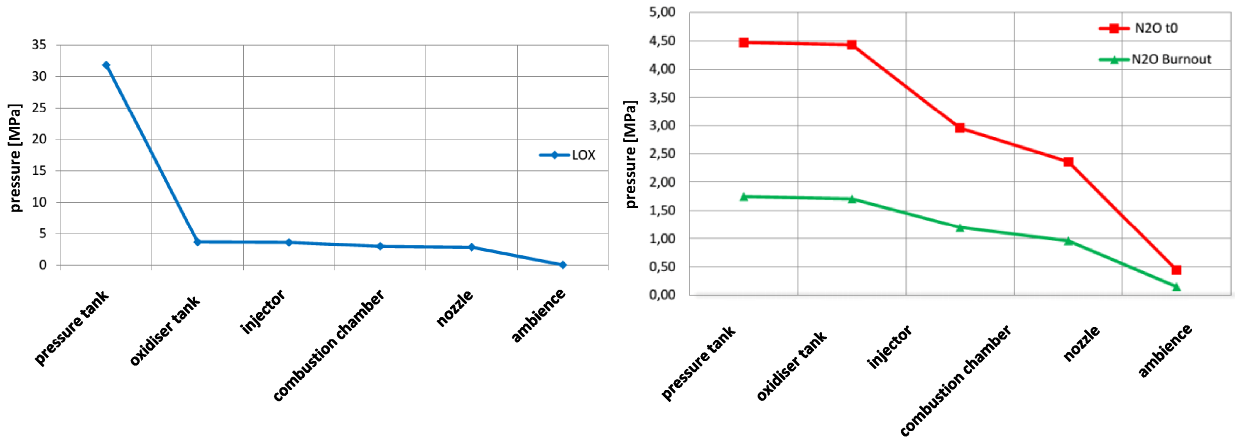

Figure 2 - System pressure traces for LOX and N_2O [7]

This leave the GOX and LOX systems for comparison. In order to get a realistic comparison for these two systems a simplified model was created, that incorporates tank volume and mass employing standard formulas for hoop stress and Barlow's formula. Factors of safety incorporated in the system ranged from 1.25 (combustion chamber) to 2 (oxidiser and pressurant tanks). Additionally, a simplified trajectory analysis was conducted that allows to calculate the burn-out altitude, by balancing force of gravity, thrust and drag (using an ISA atmospheric model) in a simplified vertical disturbance-free trajectory [7].

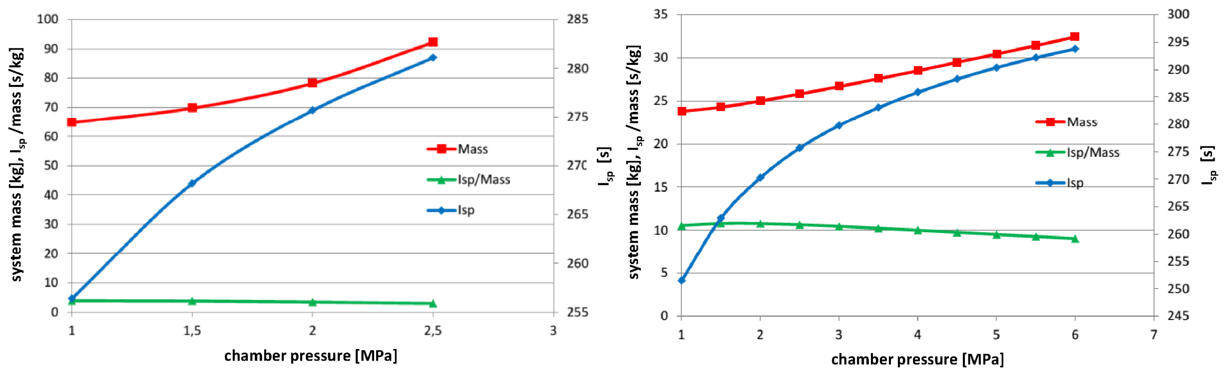

Figure 3 - Comparison of GOX/paraffin (left) and LOX/paraffin (right) systems [7]

Results of the trade-off are shown in Figure 3 and it can clearly be seen that at a targeted chamber pressure of 3MPa the LOX/paraffin system is significantly lighter than the GOX/paraffin alternative. The reason for this is the large mass of the tank. In order to accommodate sufficient GOX at a high enough pressure, the tank becomes prohibitively large. With these results of the trade-off study the system of choice for the ZEpHyR will be a LOX/paraffin pressure regulated engine. While this engine does provide the highest performance this comes at the cost of the highest complexity.

In order to reduce the risks of this system it was decided to use the existing test-stand and small experimental hybrid engine (paraffin/GOX), to verify as many characteristics of hybrid combustion as possible. The main engine of the ZEpHyR would in addition be built in two versions, the first one being a heavily instrumented and highly robust engineering model (EM), which is still much too heavy to fly. With the EM all states of operation of the engine, even highly anomalous ones with large instabilities and pressure fluctuations, can be tested without the danger of a catastrophic failure. Once the behaviour is fully characterised a much lighter and less instrumented flight version of the engine will be built to power the ZEpHyR.

3 Model GOX-Paraffin Test Engine

The small model GOX/paraffin engine used at the ZARM test facility can be seen in Figure 4. It was designed to be very flexible with easily exchangeable injector designs, fuel grain types and lengths (only the main wall cylinder has to be adapted), exchangeable nozzle and liners. In addition to this the engine can withstand pressures of up to 40MPa, thus allowing the engine to be run in unstable cases for test purposes. In the current configuration the engine produces about 80N of thrust for up to 10 seconds burn duration

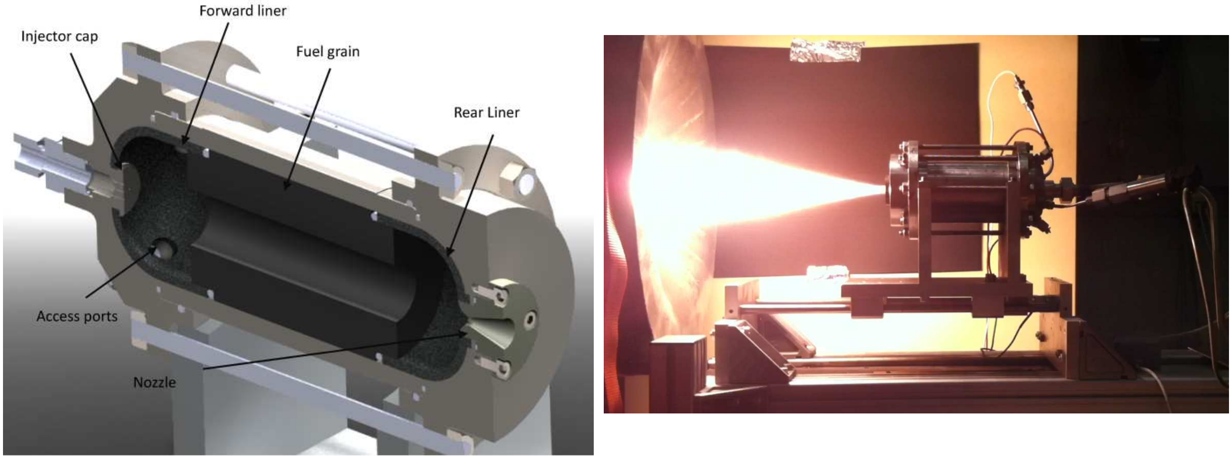

Figure 4 - GOX/paraffin test engine configuration (left) and in operation (right) modified from [11]

The pre-test program for the ZEpHyR main engine had the following objectives:

- Test different kinds of chamber pressure (1MPa - 3.5MPa)
- Verify and test different start-up procedures using the currently available resistive ignition system
- Verify and test fuel grain production methods and possible additives
- Test different kinds of injectors (four types, three chocked, one subsonic)
- Test different materials subjected to the flame, especially the nozzle

Most of these investigations were carried out by Drinkewitz [11] and the main conclusions of this work will be presented here.

As could be expected of a hybrid engine, which intrinsically allows for easy throttling, the engine could be run at various operating pressures without any problems, with the limitation that the correct start-up procedure and grain manufacturing technique must first found.

The effect of an incorrect start-up procedure can be seen in Figure 5. The left graph shows the chamber pressure smoothly rising to a pressure level of just under 0.5MPa, but once the ignition wire is activated the chamber pressure spikes causing the pressure to briefly rise to almost 250% of the nominal chamber pressure before settling. This type of instability must be avoided, since it is prone to damage not only the fuel grain, but in a flight engine could lead to much more serious damage. The right graph shows a smooth start-up procedure with a sufficiently damped small oscillation at the start of the engine. Hence, a good start-up procedure is vital for the correct functioning of the engine. The ability to throttle a hybrid can be used to the advantage of testing the EM of the ZEpHyR main engine, since the start-up procedure can be verified at initially low operating pressures and only if confidence in this procedure is high, can the engine slowly be throttled up to maximum power.

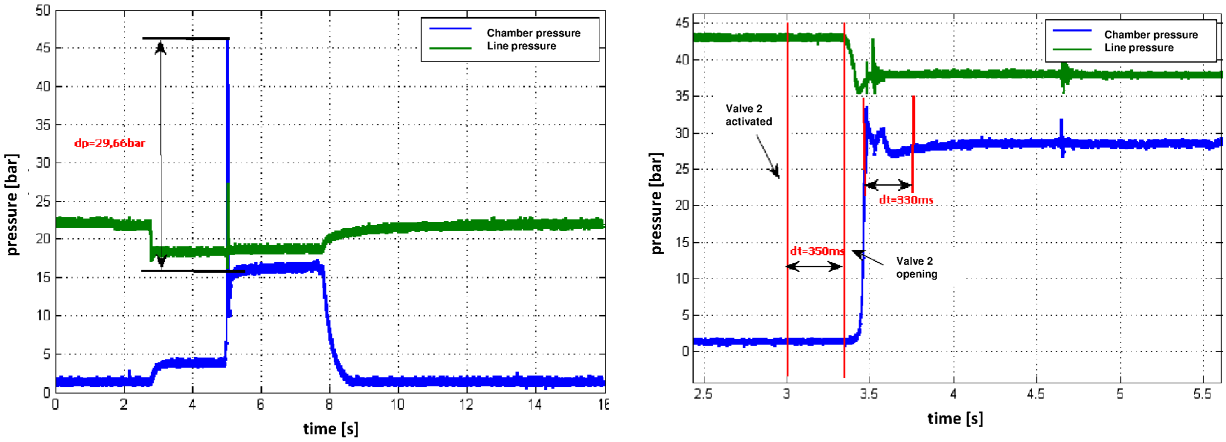

Figure 5 - Rough start-up (left), smooth (right), modified from [11]

Figure 5 (right) also shows a small instability at about 4.6s into the experiment. This instability is most likely due to small manufacturing effects in the fuel grain. In this case the effect on the chamber pressure is only minor, but only an investigation of the remaining fuel grain after the burn can ascertain if the problem was only locally contained.

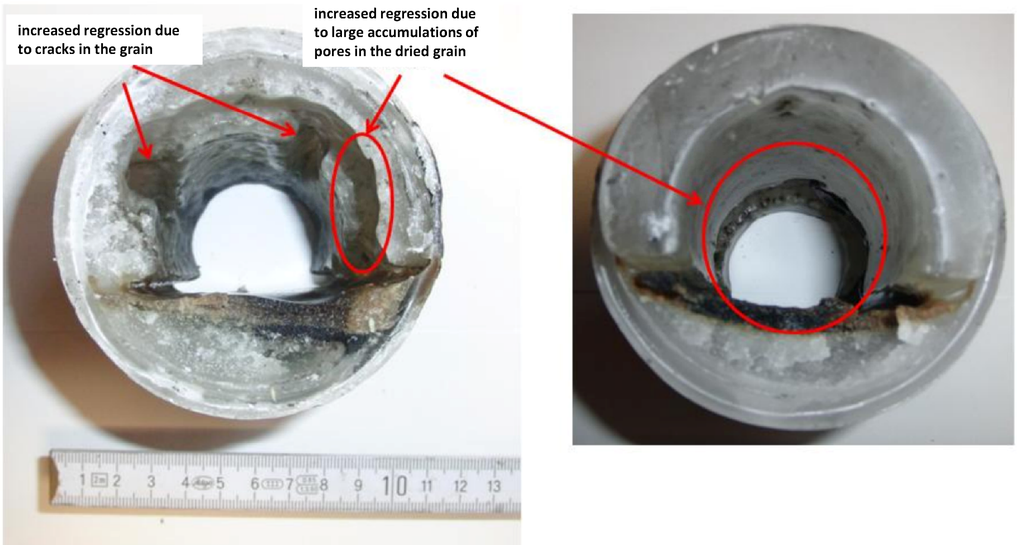

Figure 6 - Effect of imperfections in the fuel grain, modified from [11]

The effect of imperfections in the grain, which can cause pressure fluctuations can be seen in Figure 6. While the non-symmetrical flat pooling of the fuel at the bottom is a normal occurrence that happens due to residual heat only after the engine has been shut down, the marked channels and fractures in the fuel grain are not normal or desired. While this type of problem does not cause large changes in chamber pressure, as it would in a solid motor, it does present the danger of the flame zone prematurely reaching the chamber wall and causing local hotspots, that could endanger structural integrity.

The imperfections in the grain are due to the shrinkage (up to about 17% [12]) of paraffin during cooling. If the fuel grain is simply cast and left to dry, this shrinkage will cause cracks and pores in the grain, which then lead to uneven burning and regression behaviour. To avoid this the grain must be compacted during cooling, which can for example be achieved via a centrifuge or in the case of this engine via a pressurised cast with a cylinder that continually pressurizes the fuel.

In addition to the manufacturing procedure, two different additives namely aluminium wool and titanium hydride were tested with up to 5% mass fraction of the fuel [11]. The main goal was to shift the O/F and thus reduce the oxidiser needed for the same amount of impulse and possible even further increase regression rate. While some effect could be measured the results were inconclusive [11], most likely due to the small size of the engine and the tests will have to be repeated in the EM to verify both combustion stability and effectiveness of the additive.

In addition to the above tests and lessons learned for the start-up procedure and fuel manufacturing, different types of injectors where tested. While these results are not directly applicable to the EM, which will use LOX instead of GOX, they are nonetheless interesting from an engine combustion stability point of view.

In total four different injectors were tested, all of them having the same total area and mass flow, but in different configurations (the configurations can be seen in Table 1). Three of the injectors were designed with a chocked flow in mind (injectors 1-3) and one injector with a subsonic injection velocity. While injectors 1-3 automatically decouple the combustion chamber from the feed-system, this is not the case with injector 4. In order to ensure that the feed system is not coupled with the chamber, a chocked venturi was added to injector 4, about 27mm upstream of the injector holes. The decoupling is important for two main reasons, one is safety meaning that possible instabilities in the combustion chamber do not travel upstream into the feed system and a flashback is not possible. Secondly, this ensure similar measurement conditions as the feed system is not influenced by events in the combustion chamber, providing constant mass flow and flow conditions regardless of the chamber conditions.

Table 1 - Injector Configurations [11]

Injector Number	*Number of injector holes*	*Diameter of injector holes [mm]*	*Configuration / Comment*
1	1	1,7	One central hole (chocked flow)
2	6	0,7	Six holes arranged on an 8mm diameter (chocked flow)
3	5	1	One central hole and four holes arranged on an 8mm diameter (chocked flow)
4	6	2	Six holes arranged on an 8mm diameter (subsonic injection M<0.1), decoupled through a chocked venturi 27mm upstream

It was found that while the chocked high speed injectors did increase regression rate significantly [11], this seems to be a local phenomenon, with the highest regression rates near the re-attachment zone of the high speed jet in the grain. These findings agree with previous investigations by Carmicino [13]. It remains to be seen whether this phenomenon can be utilised in a larger engine to improve performance, as it seems likely that the effect is more detrimental than helpful, due to the localised nature of the increased regression rate, causing a premature depletion of fuel grain and consequently heating of the combustion chamber wall in the area in question. Further it was found that the high speed jet in the engine causes insufficient mixing in the aft combustion chamber and as such the ejection of un-burnt fuel through the nozzle. Evidence for this can be seen in Figure 7, which shows the exhaust plume of the engine with chocking and subsonic injection. The flame temperature in the subsonic in is higher (shift of O/F due to different oxidiser mass-flux) leading to more glowing soot and a brighter exhaust plume.

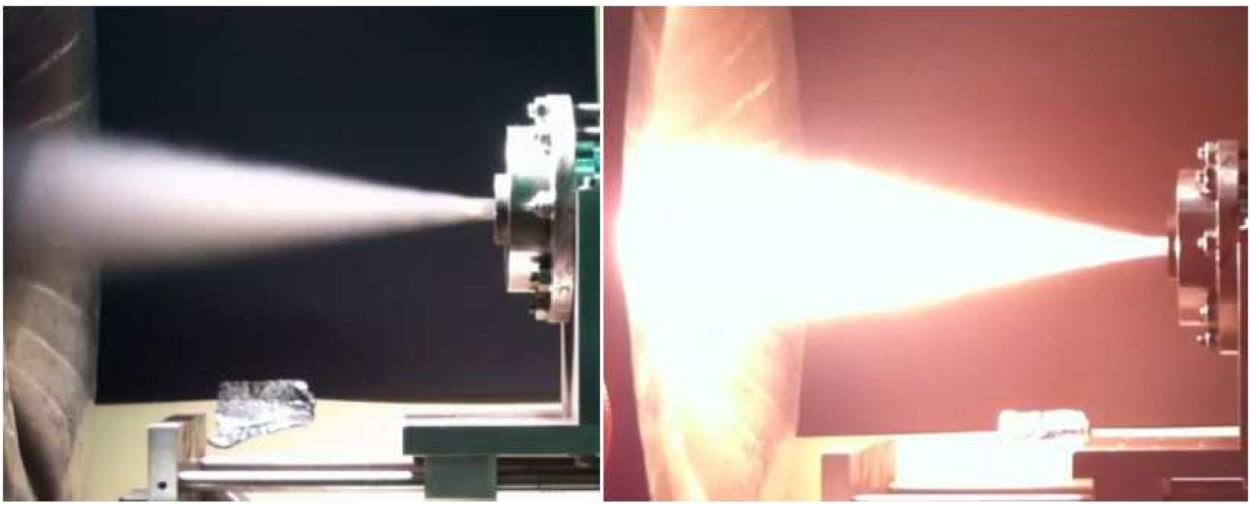

Figure 7 - Chocked injector (left), subsonic injector (right) [11]

Another important factor in the performance of hybrid engines is the material used to protect the parts of the engines that are subjected to direct contact with the high temperature exhaust gases. Unlike a liquid engine, most of the combustion chamber wall is covered with the fuel which carries all the heat away via ablation, which is the desired effect in the combustion chamber. The injector head of the combustion chamber is subject to some heat loading from the adjacent flame at the start of the fuel grain. This heat load is however mostly radiative in nature and the injected oxidiser has some cooling effect. This means that injectors and the forward lining only need a limited high temperature performance in in-line hybrid engines. In fact the injectors of this GOX/paraffin engine were manufactured from 7050 aluminium and experienced no degradation or problems. Thermocouples in this region registered temperatures on the order of 473K after about 8 seconds of firing.

The aft mixing chamber and nozzle however are subject to much higher heat loading as these also experience high forced convective heat transfer from the exhaust gases. Due to the nature of a hybrid engine and system complexity considerations, a regenerative cooling system (with the only readily available coolant being the oxidiser) was discarded as an option early on in testing. As such, this engine (and previous other engines) were tested with many different materials for these high temperature regions. Among them ceramics, high temperature steels, graphite and molybdenum. While ceramics and steels showed very poor resilience, often failing after less than three seconds, graphite performed much better. It had however two very significant drawbacks. Since it was made from compacted graphite powder the shapes that could be produced had to be fairly simple, which required more complicated mounting brackets and in addition especially thin parts were very sensitive to shock loading from both thermal shocks and pressure spikes in the engine. This caused shattering of the graphite parts, compromising the engine severely. Another problem was the slow sublimation of graphite at these elevated temperatures, leading to a slow drop in chamber pressure due to throat erosion.

Due to this another option was considered: pure molybdenum, which can be manufactured even in large wrought material badges, through a metal powder sintering process. This semi-finished material can then be easily manufactured to even complex shapes this threads etc. via conventional machining techniques. Molybdenum was used by the Stanford group in their experimental hybrid engine [14] and it was also tested as a nozzle material for highly corroding exhaust gases in solid rocket motors by NASA [15] (already in 1966). In the NASA paper three different solid fuels were tested and molybdenum performed very well with two of them, showing hardly any erosion or sensitivity to thermal shock. Only the highest temperature burning fuel lead to a catastrophic failure [15]. The burn duration of these tests was 30s - the expected maximum burn of the ZEpHyR engine. It was hence decided to use molybdenum in all further tests, limiting flame temperature to the expected maximum from the second hottest NASA solid fuel of about 3360K. Since then the new nozzle and chamber liners have accumulated well over two and a half minutes of cumulative firing time without any measurable degradation.

4 ZEpHyR EM-Engine

As a result of the trade-off studies and lessons learned from the tests with the smaller GOX/paraffin engine the overall internal geometry and performance parameters of the ZEpHyR engine can be fixed and the EM can be designed and built. The purpose of the EM engine is to test all expected operating conditions of the final flight engine and also venture beyond the normal flight envelope to gain experience with the engine when it approaches non-nominal conditions. The data from these tests is vital to the safe operation of the entire ZEpHyR rocket, as it will be the basis for the engine control software as well as the decision making process of the engine operators on the ground, when the vehicle prepares for and finally takes flight.

As such the EM is identical, from the point of internal geometry and overall performance such as thrust, mass-flow, pressure and temperature, to the later flight version, but is designed with much more safety margin (>10) and instrumentation. Table 2 summarises the main performance parameters of the engine.

Table 2 - Main performance parameters of the ZEpHyR main engine EM, modified from [7]

Parameter	*Value*
Initial port diameter [m]	0.04
Final port diameter [m]	0.14
Port length [m]	0.65
Propellant mass [kg]	≈ 20
Oxidiser mass-flow [kg/s]	≈ 0.5
Average I_{sp} [s]	≈ 270
Average thrust [N]	≈ 1800
Burn duration [s]	≈ 30
Maximum expected chamber pressure [MPa]	≈ 3.5

Figure 8 shows a CAD cut-away of the ZEpHyR main engine EM that is currently being manufactured. Its outer hull is a stainless steel cylinder with large wall thickness and two main end flanges. The pressure vessel is designed to withstand a pressure of 23MPa with a factor of safety 1.5, hence chamber pressure spikes of over 600% during testing can be safely contained.

The nozzle and post combustion mixing chamber are produced from a single integral part of molybdenum and it is possible to measure the outside wall temperature of this lining at eight locations around the circumference. A further four measurement points of temperature are integrated at the throat of the nozzle at 90° angle separation in four different depth, which should allow the exact determination of the thermal loading at the inside of the throat. This data is vital for the design of the flight engine, allowing the molybdenum lining to be reduced to a minimum in order to save maximum mass.

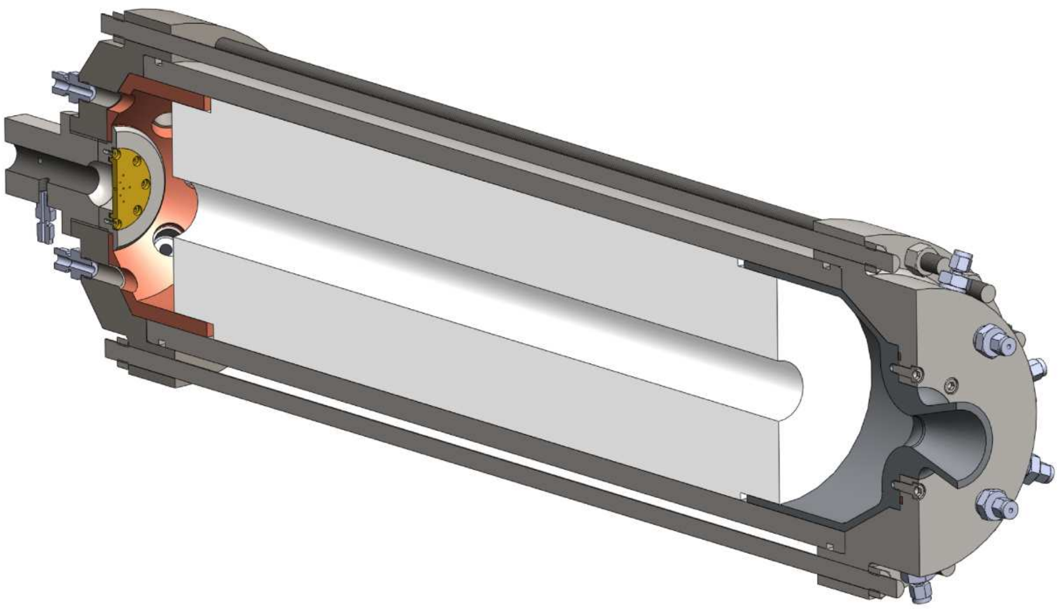

Figure 8 - ZEpHyR main engine EM, CAD cutaway model

The fuel grain is constrained in the chamber main pressure vessel by the rear molybdenum liner and the forward injector flange liner. It is made of copper in since the heat loading is not as critical here. In addition to this the copper allows for maximum heat transfer between the sub-cooled LOX and the flame zone at the entrance to the grain. The forward liner is contained in the injector flange which has another eight access points into the combustion chamber, allowing for the measurement of pressure and temperature at different locations and also the insertion of different ignition systems into the engine. Currently the ignition system is envisioned to be a propane, oxygen pre-burner. For the flight engine this ignition system will be inserted through a lance through the nozzle into the engine and will remain on the launch-pad to save weight. This is fully sufficient since no restart capability is required after launch.

The injector assembly is a stainless steel manifold that has two access points, one for temperature measurements of the LOX just before injection and another access mount for a high speed pressure transducer. This pressure transducer can also be used to measure and diagnose any adverse pressure fluctuations that travel upstream from the combustion chamber into the feeding system and can be used to initiate an emergency shutdown if required. The second part of the injector manifold is a simple adapter system made of stainless steel to hold the injector plate fabricated from brass. The injector plate will most likely be the most critical part during initial engine testing. The first configuration of injector holes is a circularly arranged showerhead. The data from the small GOX/paraffin test engine will be of some help here, but according to Kuo et. al [4] it is vital that only gaseous oxygen reach the fuel grain. This means the atomisation and vaporisation of the LOX during ignition and operation of the engine must be closely monitored. Large hybrids (much larger than the ZEpHyR main engine) suffered serious instability issues, due to not meeting this requirement. If the fuel grain becomes flooded with LOX, the flame zone will be disrupted and the burning fuel surface area will vary significantly causing a change in chamber pressure that can lead to unstable pressure fluctuations [4]. Since the exact mode of this instability is very difficult to predict a-priori, depending heavily on the spray breakup and droplet formation processes, which cannot be reliably predicted, only testing will answer this question. This is the main reason why the engine was designed to withstand high pressure fluctuations, allowing for the testing of many different injector plate configurations to find the optimal injection properties, without endangering test engine integrity, even if high amplitude instabilities should be encountered.

Currently all parts of the engine are being manufactured as well as all ancillary equipment, such as the casting die. At the writing of this paper the injector assembly was complete and can be seen in Figure 9. It shows the two access points for the thermocouple and pressure transducer, as well as the showerhead injector plate. Once the injector flange and the test-stand are complete the entire assembly will be water flow tested.

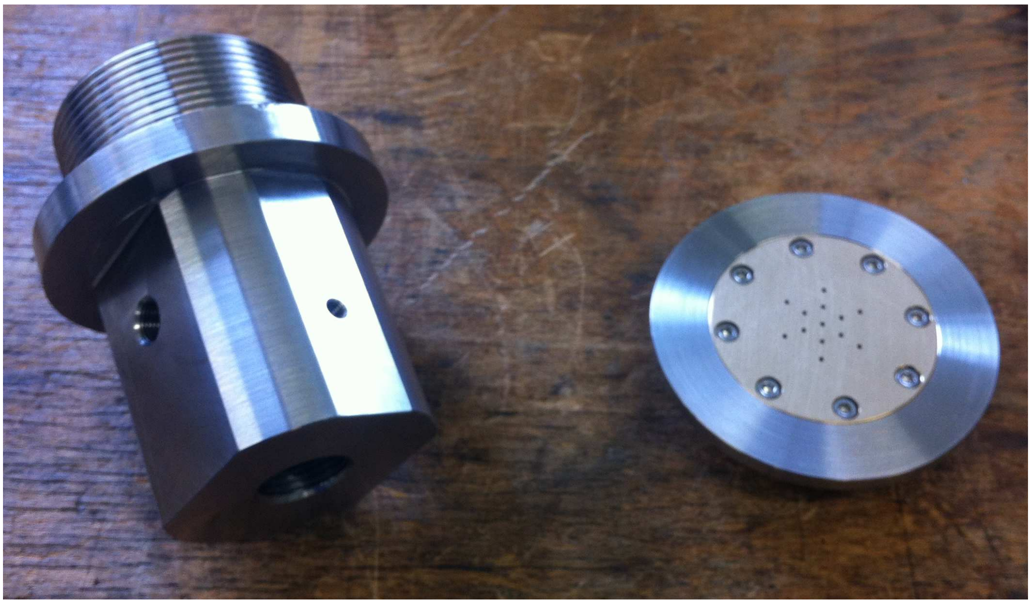

Figure 9 - ZEpHyR main engine EM injector assembly with showerhead injector plate

4.1 Test-stand

The test-stand is an upgraded version of the current GOX test-stand at ZARM and a schematic of it can be seen in Figure 10. It shows the current test facilities (red box) and the upgrades, which are currently being installed. In addition to the gaseous oxygen system a LOX system is added. The liquid oxygen is produced on site in order to reduce the amount stored at any one time to an absolute minimum, necessary for a single test only. The LOX is produced by means of condensation of GOX in a pressure vessel submerged in liquid nitrogen. Once a sufficient amount has been produced, the GOX feed into the tank is terminated and the LOX tank is pressurised to the required operating pressure using N_2 gas. The LOX is then feed into the engine via several valves (eliminating a failure in open mode) and measurement points such as a venturi, pressure and temperature transducers. As additional safety features a non return valve and a cavitating venturi will be installed to hinder any combustion instability pressure spikes from travelling into the feed system.

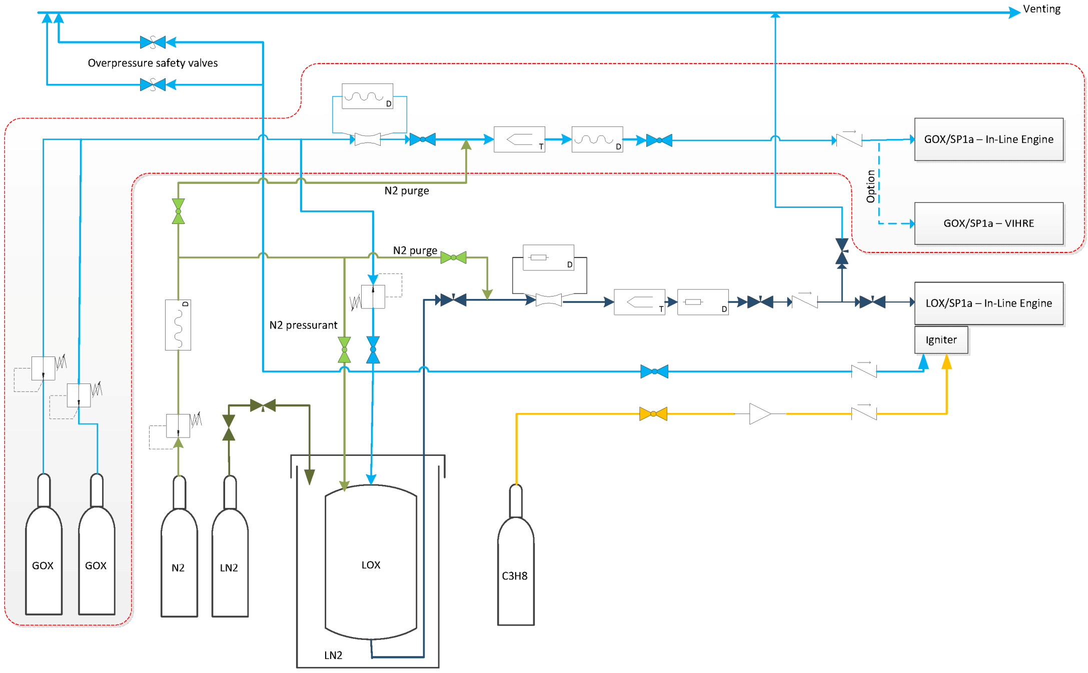

Figure 10 - Current test-stand at ZARM (red boxed region) and upgrades to LOX operation

In addition to pressurisation the N_2 system can also be used to purge the entire system prior and after testing to remove any contaminants and/or remaining oxygen, providing a safe and inert system at all times.

The test-stand itself is completely remotely operated (from the point of commencement of LOX production) and is contained inside an explosion proof room at the ZARM combustion lab, with a large exhaust gas channel to the outside to vent the gases from the engine firing. The exhaust channel is equipped with a water nebulising system to cool the exhaust plume and provide some fraction of noise control.

5 Conclusion

The current paper presents a work in progress - the design and construction of the ZEpHyR main engine EM. The engine is a highly instrumented and pressure proofed version of the later flight engine, providing about 1,8kN of thrust for 30s firing time. The propellant used in the engine is paraffin and the oxidator is LOX, operating at a maximum combustion chamber pressure of 3.5MPa.

The current paper describes the trade-off between three different propellant combinations, namely paraffin with GOX, LOX or N_2O both from a rocket systems and propulsion system point of view. The conclusion of the trade-off is that the best propellant oxidiser combination for the system at hand is paraffin LOX.

In preparation for the design and testing of the ZEpHyR main engine EM, a smaller GOX/paraffin test motor was used and several tests with different fuel grains and injectors were conducted. The main findings of these pre-tests was that a crack free casting of paraffin fuel is vital and can only be achieved through compensating shrinkage during the cooling process. In this instance this compensation was done by drying the die under high pressure condition. The injector study showed that while chocked injectors can increase regression rate, this comes at the cost of localised increases that might endanger structural integrity due to uneven thermal loading of the chamber wall. Also it is unclear how these results transfer to a liquid oxygen injector.

Finally, the finalised design of the main engine EM is described and the current progress in construction of the engine and test-stand is described. Many of the findings of previous test engine firings such as start-up procedures and material choices where incorporated in the design and testing of the engine will commence later this year.

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