DOI: 10.13009/EUCASS2019-682

Advancing Europe's Hybrid Rocket Engine Technology with Paraffin and LOX

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Abstract

Hybrid rocket engine technology has been advanced enormously at European universities, research institutions and companies in the last decade. New fuels like paraffin-based mixtures have been developed in order to increase regression rate which enables more compact engine designs with high thrust density. With this, the application of hybrid rocket motors has become feasible in several fields like sounding rocket and smallsat launch vehicle propulsion systems. The start-up HyImpulse is developing a paraffin-based hybrid rocket engine with 75 kN thrust in order to power a hybrid propulsion sounding rocket and smallsat launch vehicle. To reach a design of a high performing launch vehicle, it was identified as crucial to choose the best performing oxidizer for hybrid rocket applications: Liquid oxygen. HyImpulse has successfully developed a 10 kN hybrid rocket motor using paraffin-based fuels and liquid oxygen.

1. Introduction

The history of developing hybrid rocket engines in Lampoldshausen spans over a decade by now, which is presented in Table 1. In 2006 the student team "Hybrid Engine Development" (HyEnD) was founded at the nearby located University of Stuttgart. HyEnD started developing and testing the hybrid rocket engines based on paraffin fuels. This ultimately led to the initiation of basic research on hybrid rocket propellants at the DLR Institute of Space Propulsion within the propellants department. The test bench M11 was the central point of the developments since 2011. In cooperation between the DLR Institute of Space Propulsion and the University of Stuttgart it was possible to develop a robust paraffin-based fuel, which was used in 2015 in the HyRES engine, a hybrid rocket engine using nitrous oxide and paraffin-based fuel to generate a thrust of 10 kN over more than 15 s burn time. This rocket engine, developed by the student team HyEnD led to a student world record for hybrid sounding rockets, when the rocket HEROS 3 reached an altitude of 32.3 km in 2016. In the year after, the researchers at DLR Lampoldshausen initiated the development of a hybrid rocket engine using paraffin-based fuel and liquid oxygen as the oxidizer, to further increase the performance. The paraffin-based fuel has been constantly improved over the last years and various papers and articles have been published[1, 2]. The ultimate goal of this research was to create a propulsion system for both sounding rockets and small launch vehicles. Also other applications have been investigated in system studies[3, 4, 5]. This development led to the founding of the start-up HyImpulse Technologies GmbH in Lampoldshausen. HyImpulse started the development, manufacturing and testing of the conceptualized HyPLOX 10 kN engine, which is using liquid oxygen as the oxidizer. Liquid oxygen offers a higher performance than nitrous oxide, as the specific impulse is more than 10% higher. This allows the development of more powerful rocket engines for the use in orbital launch vehicles. Liquid oxygen has also a higher density as nitrous oxide and a much lower vapor pressure, which makes it possible to develop a launch vehicle with low tank pressures, in order to create a light-weight design. In February 2018 HyImpulse began the test campaign of the HyPLOX 10 engine. The use of liquid oxygen in hybrid rocket motors brings some differences compared to nitrous oxide regarding injection & vaporization behavior, ignition energy and therefore a complete redesign of the combustion chamber was necessary. By successfully developing a 10 kN LOX / paraffin-based hybrid rocket engine, this is the largest engine of its kind in Europe, putting HyImpulse at a unique position in the market of hybrid rocket propulsion.

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Table 1: History of Hybrid Engine Development in Lampoldshausen

	2006	Foundation of the student team HyEnD at University of Stuttgart
	2008	First Hybrid Rocket Engine Test Campaign of HyEnD
	2012	Begin of basic research at the DLR Lampoldshausen propellants department
	2013	Begin of STERN project at HyEnD and University of Stuttgart
July	2015	End of test campaign of 10 kN nitrous oxide / paraffin engine "HyRES"
October	2015	Launch of HEROS 1
Oct./Nov.	2016	Launch of HEROS 2 & 3 with altitude record 32.3 km
	2017	Concept Phase for Small launch vehicle with Hybrid Propulsion
February	2018	Begin of test campaign of 10 kN LOX / paraffin engine "HyPLOX 10"
March	2018	Founding of HyImpulse Technologies GmbH
January	2019	Begin of testing light weight (CFRP) hybrid rocket engines in small scale
Autumn	*2019*	*Begin of test campaign 75 kN LOX / paraffin engine "HyPLOX 75"*
Winter	*2020*	*Launch of the Sounding Rocket SR75*

2. State of the Art

The previous state of the art was presented in our paper at EUCASS 2015 about the test campaign of a nitrous oxide (N_2O) hybrid rocket motor [6]. Recent highlights in the hybrid rocket propulsion area were the successful launch of the student rocket HEROS 3 in 2016 [7] using nitrous oxide and a paraffin-based fuel and the launch of the Nucleus rocket of Nammo in 2018 with hydrogen peroxide (H_2O_2) and a HTPB-based fuel. These two launches proved further the capabilities of hybrid rocket systems, to offer low-cost and yet high performing propulsion systems. The research on hybrid rocket engines is continuing around the globe, e.g. at JAXA the active mixture ratio control of hybrid rocket motors is investigated, in order to increase the overall performance of hybrid rocket engines [8]. NASA is investigating the application of hybrid rocket motors with special paraffin-based fuels for the Mars ascent vehicle [9]. Next to some established industry players like The Spaceship Company or Nammo, more and more start-ups worldwide are working on hybrid rocket propulsion for smallsat launch vehicles, others for orbital propulsion systems. The propellant choices are spread amongst these companies, which are shown in Table 2. However, although many companies worldwide have started developing rocket systems using hybrid propulsion, none of the actors have entered the commercial operation of their system. Concerning the development of hybrid rocket engines using liquid oxygen, only a few companies have advanced this technology. Amongst the European companies, HyImpulse has realized the first 10 kN thruster with stable performance over more than 10 s burning time using liquid oxygen as the oxidizer. Figure 1 illustrates the specific impulse of different oxidizers using paraffin-based fuel with the name "PB-5%". With liquid oxygen the specific vacuum impulse has its maximum at about 362 s. An ideal calculation of the specific vacuum impulse of LOX and RP-1 results in 363 s for the same conditions. Hydrogen peroxide (95% concentration) has about 10% lower specific impulse, while nitrous oxide is about 12% lower. In the diagram it is also shown, how the optimal mixture ratio is different for the oxidizers. LOX has a quite low optimal mixture ratio, which is not optimal, as it means, the fuel geometry needs to be longer. However, a positive side-effect of this is that less oxidizer needs to be fed to the engine.

Table 2: Start-up & established companies active in the hybrid rocket propulsion field

Name	Country	Business	Fuel	Oxidizer
HyImpulse	Germany/EU	SR, 500 kg LV	Paraffin-based	LOX
Nammo	Norway	SR, <150 kg LV	HTPB	H_2O_2
The Spaceship Company	USA	Suborbital manned	polyamide	N_2O
Space Propulsion Group	USA	Orbital	Paraffin-based	LOX and others
TiSpace	Taiwan	SR, 300 kg LV	HTPB	N_2O
Gilmour Space	Australia	SR, 400 kg LV	3D-printed fuel	H_2O_2
Rocket Crafters	USA	LV	3D-printed ABS	N_2O
T4I	Italy	Orbital propulsion	Paraffin-based	H_2O_2
Space Forest	Poland	Sounding Rocket	Paraffin-based	N_2O
Space Link	Slovenia	Sounding Rocket	Paraffin-based	LOX
Equatorial Space Ind.	Singapore	65 kg LV	Paraffin-based	LOX

SR = Sounding Rocket, LV = Launch Vehicle

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So it is a trade-off, which can be different for several applications. The mixture ratio shift is steeper for LOX than for nitrous oxide or hydrogen peroxide, which makes an optimal engine design a bit more challenging. A small deviation from the optimal mixture ratio reduces the specific impulse already notably.

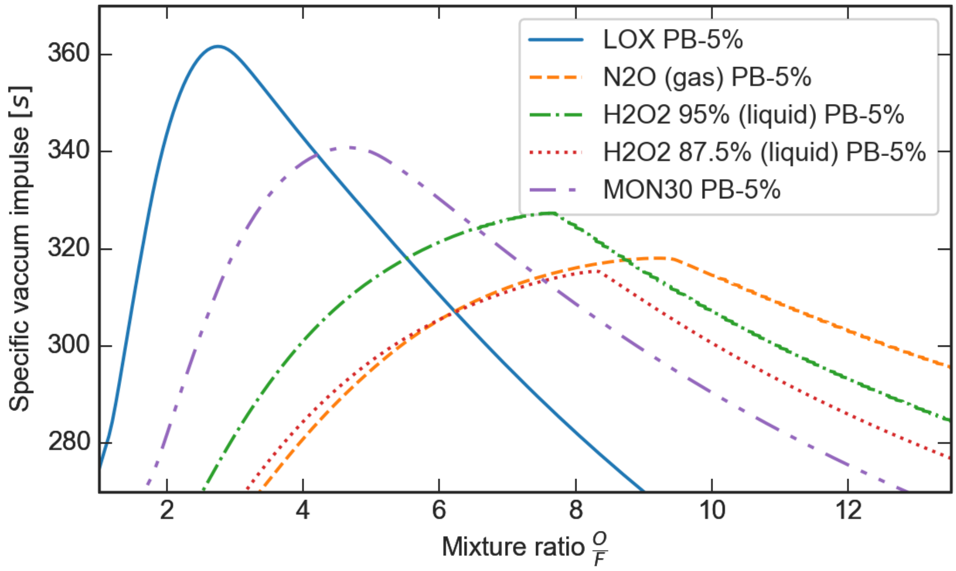

Figure 1: Specific vacuum impulse comparison for 15 bar and ϵ = 60 [10]

The selected propellants liquid oxygen and paraffin-based fuel offer distinct advantages:

- Very high specific impulse, same like LOX/Kerosene liquid rocket motors.
- Simple combustion chamber design, as no multiport geometry is necessary for the fuel grain.
- Versatile system, usable on many systems like sounding rockets, small launch vehicles, strap-on boosters, kick stages or upper stages.
- High safety for the whole propulsion system, increasing mission flexibility and reducing overall costs for manufacturing, development, assembly, campaign preparations or transport.

3. Design of the Hybrid Rocket Engine

3.1 Overall Combustion Chamber Design

Compared to a hybrid rocket engine using N_2O as the oxidizer, the HyPLOX 10 design which is utilizing LOX, is completely new and advanced. However, the main advantage has remained unchanged: The paraffin fuel is a single port design with a simple hollow cylinder. This is a major advantage compared to classical polymeric fuels in hybrid rocket engines, like HTPB, which needs a complex fuel grain design like a wagon wheel shape. This is always connected to large fuel residuals at the end of the burn time, which are almost zero for a paraffin-based fuel. Some of the key data of the engine are listed in Table 3. Figure 2 shows a picture of a test conducted at the M11.5 test bench of DLR Lampoldshausen.

3.2 Ignition and Combustion Stability

The motor is ignited by a small amount of conventional solid rocket propellant. The igniter needs to provide enough energy to heat up the solid fuel as well as the initial liquid oxidizer mass flow. Other than that, the ignition system is very simple, robust and low-cost, which overall strengthens the low-cost approach of the engine design. HyImpulse has solved the known problems with low frequency instabilities in hybrid rocket motors using liquid oxygen by developing a unique technology without adding any external heater or dangerous pyrophoric liquids like triethylaluminum (TEA)

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Table 3: HyPLOX 10 key data

Property	Value
Oxidizer	LOX
Fuel	Paraffin-based
Nominal thrust	10 kN
Nominal burn time	10-12 s
Nominal mass flow	3.8 $\frac{kg}{s}$
Mixture ratio	2.4-2.7
Chamber pressure	30 bar
Solid paraffin-based fuel	15-18 kg
Combustion efficiency	>95%
Expansion ratio	5-8
Fuel diameter	175 mm

Figure 2: Engine Test of HyPLOX 10

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and triethylborane (TEB). A similar system has been developed in the past by Karabeyoglu et al. but the information was proprietary [11]. Therefore HyImpulse developed its own system. Like discussed by Karabeyoglu et al.[12] hybrid rocket engines can suffer from low frequency instabilities caused by either the coupling of the combustion chamber and the feed system of the liquid oxidizer or the typical boundary layer combustion behavior of the internal flow. The feed system coupling is especially strong for liquid oxygen, as it has high enthalpy demands to vaporize from its cryogenic state. This causes the so-called vaporization lag of the oxidizer after the injection into the chamber. The vaporization lag can lead pressure oscillations with peak to peak values of as much as 50% of the mean chamber pressure. With the afore mentioned, developed system the feed system coupling of the hybrid rocket engine with liquid oxygen has been solved and the combustion is stable over the whole burn duration. In the past, the problem of the instability caused by injection of cryogenic oxygen has been mitigated differently. For example the American Rocket Company (AMROC) has developed a 1 MN hybrid rocket motor in the 1990s. They used continuous injection of TEA and TEB[13] over the whole burn duration of the engine. TEA and TEB are pyrophoric liquids, which ignite at contact with oxygen. Therefore they are very hazardous materials and can cause severe accidents, if they get in contact with oxygen or air. This compromises the concept of high safety and low-cost operations as well as low system complexity when using hybrid propulsion technology and was therefore not an adequate solution to the LOX vaporization issue. Another approach was shown in the US Patent Number 5,794,435 from 1998 by Jones from Lockheed Martin: A small hybrid rocket motor using gaseous oxygen is used to vaporize the liquid oxygen core flow. By this, the main hybrid rocket combustion chamber is basically supplied with gaseous oxygen, which decreases the risk of low-frequency instabilities. However, this system adds complexity to the rocket engine, as one or more small combustion chambers need to be integrated in the injection system and a gaseous oxygen supply is needed as well. The developed injection system by HyImpulse doesn't include any additional component and therefore does neither increase system complexity nor introduce hazardous materials.

3.3 Fuel Grain, Insulation and Nozzle

The fuel grain of the HyPLOX 10 engine is a simple hollow cylinder cast from HyImpulse's proprietary fuel, which has been developed and improved in 2018 and 2019 based on prior work. This fuel offers a high regression rate, tailored to the exact needs of the hybrid rocket motor design, a high mechanical strength and is completely safe, as it contains no ingredients which are harmful to health or environment. The insulation material used in the engine is a light-weight composite based on phenolic resin, which is easy to manufacture and can come in different shapes. The nozzle is made from a graphite insert, surrounded by insulation material and reinforced by structures. One of the next development steps of the engine is to develop a flight-weight 10 kN hybrid rocket motor using composite materials for the whole combustion chamber except for the LOX dome and injection system. Since the next step is to develop a 75 kN engine with a length of about 3.5 m and a diameter of 0.7 m, only with light-weight composite structures a flight-weight engine can be achieved.

4. Measurement and Instrumentation

A measurement system of National Instruments has been used together with the software LabVIEW. The oxidizer mass flow has been measured with a coriolis sensor, as well as calculated with the pressure measurements over a calibrated orifice. The pressure is recorded at several points with high frequency sensors, e.g. at the injector, in the combustion chamber in front and in the back of the paraffin fuel grain. The LOX temperature was measured with a thermocouple at the injector cavity. The paraffin mass is determined before and after the test, in order to calculate fuel consumption and an average regression rate.

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5. Test Results

The test campaign of the HyPLOX 10 engine comprises over 50 tests from a few seconds burn time up to 11 seconds, which is almost the maximum burn duration of the engine. Figure 3 shows a plot of the pre-combustion chamber (before the paraffin fuel grain) pressure normalized with the mean pressure during test 4. It shows the typical pressure oscillations for a feed system coupling characterized by its low frequency and high amplitude. During the more than

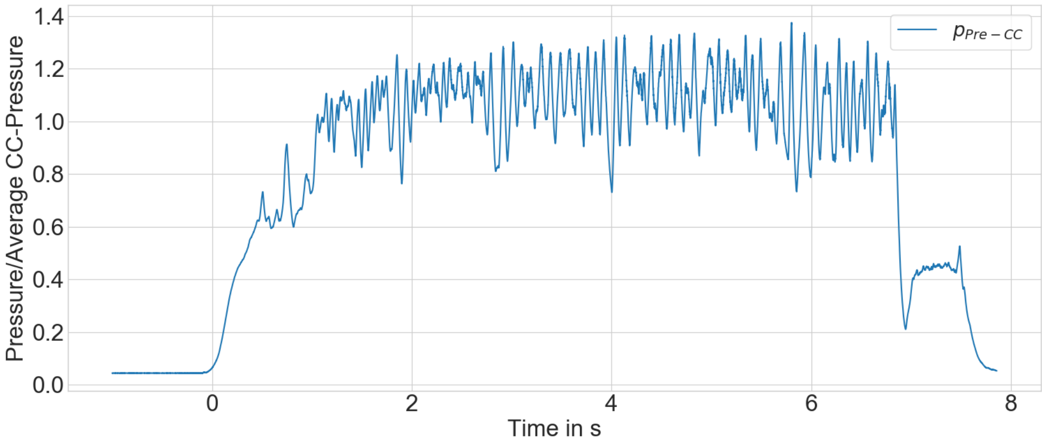

Figure 3: Combustion chamber pressure of test 4

50 tests, different set-ups of the injector system and the combustion chamber internal design were tested in various configurations, until an effective and stable injection and chamber design was reached. The result of this iterative development progress is made clear in Figure 4, which shows the normalized pressure of test 51. The low frequency instability has been removed. The chamber pressure is very stable over time and only dropping a few percent towards the end of the burn, caused by the changing fuel mass flow when the fuel port is opening up. Figure 5 depicts the

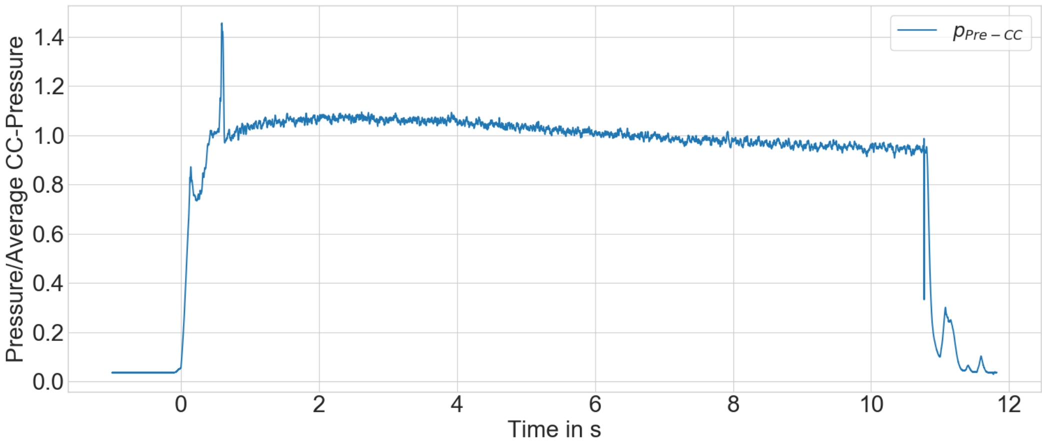

Figure 4: Combustion chamber pressure of test 5

mass flow measurement of test 51 of the coriolis sensor as well as the calculated curve using the pressure data of the calibrated orifice.

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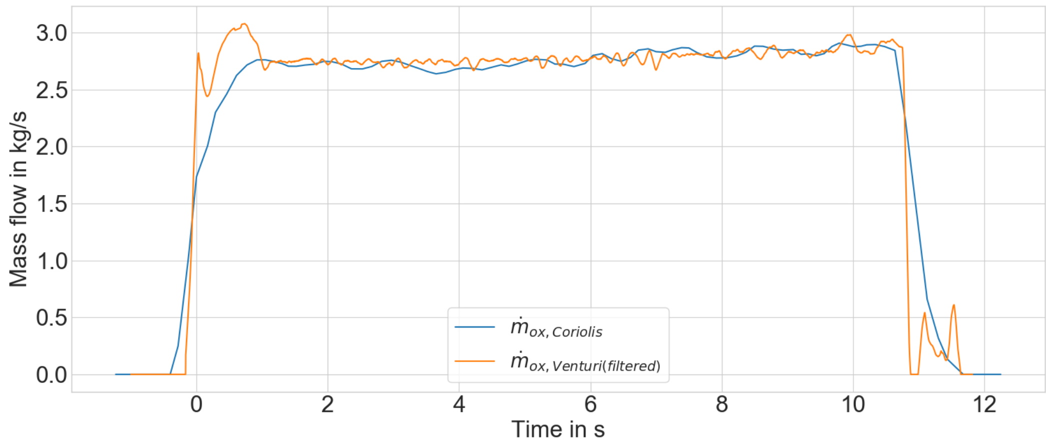

Figure 5: Mass flow measurements of test 51

6. Future plans

The next step in the hybrid rocket motor development at HyImpulse is to scale the engine up to a thrust of 75 kN at sea level with 30 bar chamber pressure. This larger engine will have a burn time of up to 70 seconds. At the same time a composite material casing is developed, which will allow to produce a flight-weight engine of the 75 kN engine, test and qualify it until fall 2020. This engine will then be used to produce a sounding rocket, using one single combustion chamber and a pressure-feeding system for the liquid oxygen. The sounding rocket will be able to carry 350 kg of payload to an altitude of 200 km on a suborbital trajectory. The design concept of the sounding rocket "SR75" is shown in Figure 6. The figure illustrates the size of the hybrid rocket motor, oxidizer tank and pressurization tank. The overall length of the sounding rocket will be about 15 m with a diameter of 0.7 m. The same engine design, with a higher

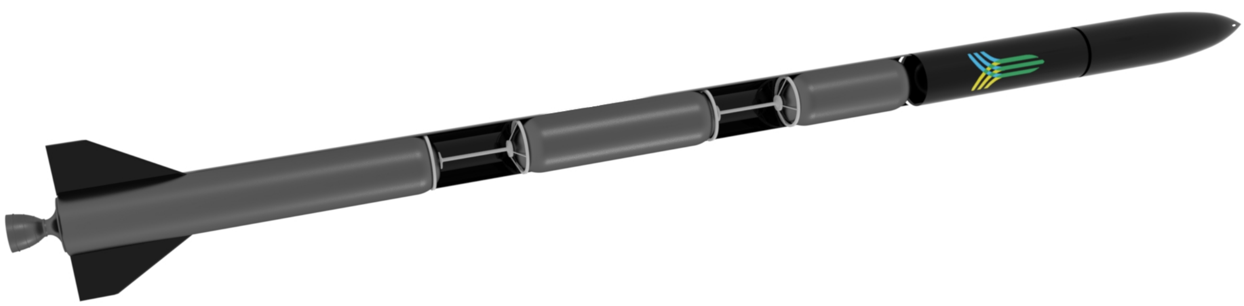

Figure 6: Sounding Rocket Concept by HyImpulse using the 75 kN hybrid rocket motor

operating pressure, will be also used on a smallsat launch vehicle. The first stage of the launch vehicle will comprise 7 engines of this larger class and the second stage will use additional 4 of the same engine, with a larger expansion ratio. A third stage will use a smaller hybrid rocket motor to inject a maximum payload of 500 kg into low Earth orbit. The launcher design proposed by HyImpulse is presented in Figure 7. This launcher will use turbopumps to feed the liquid oxygen into the hybrid rocket combustor. Using a safe and high performing propellant combination for the propulsion system enables a well-designed and optimized smallsat launch vehicle. The first and second stages share a very similar propulsion system, where only the number of engines and turbopump units and the nozzle expansion ratio is changed. Therefore, the production of the launcher will benefit from serial production effects once the launch rate reaches the targeted 10 launches per year. The plans of HyImpulse have been presented in more detail in an Acta Astronautica Article [14]. The hybrid rocket motors of HyImpulse will reach a very high TRL with high thrust levels in the next two years, which will also allow to transfer the technology to other areas like orbital propulsion, rocket booster or kick stages.

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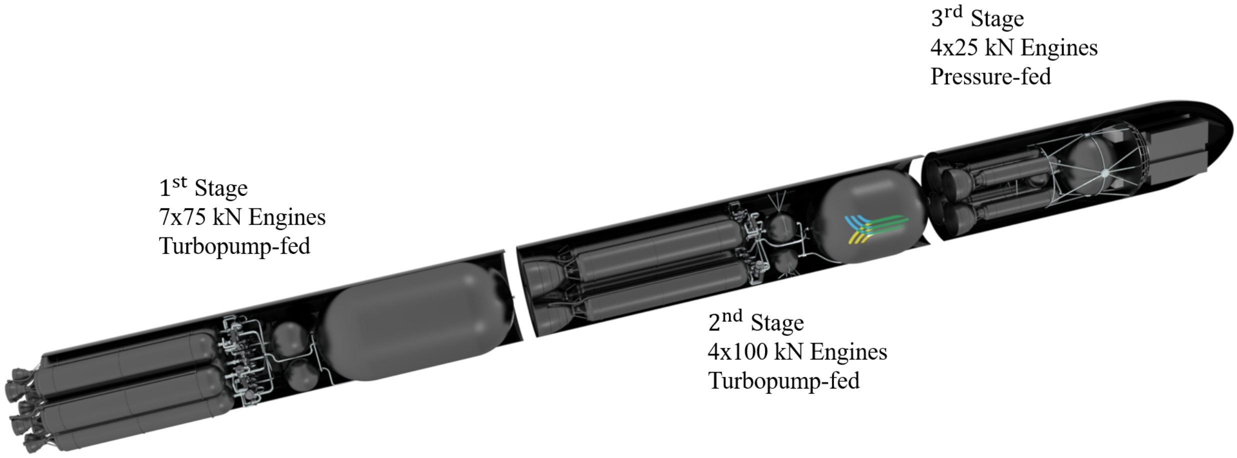

Figure 7: Launcher Concept by HyImpulse using Paraffin-based hybrid rocket motors with LOX

7. Conclusion

HyImpulse is developing hybrid rocket technology based on liquid oxygen as the oxidizer and paraffin-based fuel and has successfully built and tested a 10 kN rocket engine at the DLR test facilities at Lampoldshausen. With this state-of-the-art hybrid rocket technology, HyImpulse offers a competitive propulsion system for smallsat launchers and sounding rockets. The paraffin-based fuel enables high regression rates, which makes it possible to develop compact hybrid rocket engines with a cylindrical fuel port. Liquid oxygen offers the highest specific impulse, and the combination of both propellants is without hazardous impacts on health or environment. The technical difficulties of injection and vaporization of liquid oxygen have been solved by HyImpulse using a proprietary technology, which does not involve expensive subsystems or dangerous additional liquid propellants. The test campaign was highly successful and the next step is the scale-up from 10 kN to 75 kN thrust level with a burn time of up to 70 seconds. This engine will be the largest hybrid rocket motor in Europe and will power the sounding rocket and smallsat launch vehicle which HyImpulse will develop in the coming years.

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