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From Lampoldshausen to Space: DLR Spin-off *InSpacePropulsion Technologies* and the Development Status of Green Propellant Thrusters Based on H_2O_2 and N_2O

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1. Abstract

The German Aerospace Center's Institute of Space Propulsion in Lampoldshausen has more than a decade of experience in green propellant research and green propulsion hardware development. Over time, thrusters and propulsion hardware were developed in-house and the TRL of the hardware was increased step by step. Currently, the two most promising technologies are: the HyNOx bipropellant technology, based on nitrous oxide and hydrocarbon fuels, as well as the hypergolic HIP_11 technology. To commercialize the two propulsion technologies, a DLR spin-off called InSpacePropulsion Technologies will be founded in summer 2023. The preparation of the spin-off is currently funded by the Helmholtz Association and DLR. This paper gives an overview on the development of the two technologies and their development status.

2. Introduction

The propulsion system of a spacecraft is an essential component for the success of many missions. State of the art propellants, such as hydrazine-based fuels or oxidizers based on oxides of nitrogen are highly toxic. Hence, they pose a danger to the personnel who have to handle these propellants during different stages of the preparation of a mission. For safe handling of these toxic substances, the personnel have to wear heavy protective equipment (so-called SCAPE suits), which leads to time consuming procedures and high costs. Furthermore, in Europe, hydrazine is subjected to the REACH regulation. In 2011 it was added to the candidate list as substance of very high concern [1]. Thus, the use of this substance could be banned in Europe [2]. To overcome the danger for the personnel and the environment, to avoid costly handling activities and to anticipate potential political restrictions regarding conventional propellants, several alternative, so-called green propellants were developed in the last decades [3–14]. The development and investigation process of green propellant technologies always goes hand in hand with the development of suitable thruster and propulsion system hardware. So new propellants need: a) compatible system components, such as tanks, valves, tubes b) thrusters with appropriate injection, ignition and cooling systems as well as chamber geometries which are suitable for the used propellants.

2.1. Green Propellant developments

Several candidates exist to substitute conventional toxic propellants and first propulsion technologies were already flown in space. The most mature alternatives to monopropellant hydrazine are fuel blends which contain an energetic ionic liquid (as e.g. ammonium dinitramide, ADN or hydroxylammonium nitrate, HAN) dissolved in a fuel and water. Examples for these kinds of propellant blends are LMP-103S [15, 10], ASCENT (formerly known as AFM-315E) [16, 17] or SHP163 [5]. These blends offer a higher performance compared to hydrazine as a monopropellant, but require costly, temperature resistant combustion chamber materials and resistant catalysts. Due to these limitations, upscaling of thrusters operating with ADN or HAN seems to be a challenging task as e.g. a ADN and HAN thruster with thrust classes larger than 1 N are still under development [18] and were not flown yet. Also, hydrogen peroxide (H_2O_2) and nitrous oxide (N_2O). can be used as monopropellant. As with ionic liquids, H_2O_2 requires a catalyst to decompose into water steam and oxygen. However, contrary to energetic ionic liquids, preheating of the catalyst is not strictly necessary to initiate the reaction, although from a catalyst lifetime point of view it may be required. The adiabatic decomposition temperature is strongly dependent on the concentration of HTP used, with a maximum of about 945°C for 98%wt. [19, 20]. Due to the benign temperatures, a much wider range of materials could serve as construction material for thrusters in comparison to energetic ionic liquids. A disadvantage of hydrogen peroxide next to the considerably lower I_{sp} is the

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sensitivity towards any form of contamination. For concentrations above 63%, contamination of H_2O_2 can induce a runaway decomposition reaction. The risk of a runaway reaction is one of the reasons that the space industry is highly divided on the use of H_2O_2 as propellant, often sparking debates on the issue [21]. Besides that, hydrogen peroxide is compatible with only a limited number of materials. This makes long-term (in-space) storage challenging. At the same time, there are examples of successful long-term storage under varying conditions [22].

N_2O can be used as a monopropellant or gaseous propellant in cold-gas systems. When exposed to a catalyst, it exothermally decomposes into N_2 and O_2, resulting in temperatures of about 1640°C [9]. Its I_{sp} is not as high as hydrazine, but higher than monopropellant H_2O_2. Furthermore, it has a wider range of storage temperatures than hydrazine. N2O can be stored as liquid at room temperature and a moderate high pressure of about 50 bar [23]. However, its storage density is very low, about 25% lower than that of hydrazine. It has a high vapour pressure, which makes self-pressurisation of the tanks possible. At the same time, heavier tanks are required to store the propellant [24].

Regarding bipropellants, green solutions require an alternative oxidizer to the commonly used dinitrogen tetroxide (N_2O_4 or NTO), but), but liquid storable oxidizers for space propulsion applications are rare. Possible oxidizers are highly concentrated hydrogen peroxide (H_2O_2) and nitrous oxide (N_2O). Hydrogen peroxide is a widely used substance in a variety of industrial applications. As it decomposes to water and oxygen, no toxic vapours are occurring during development, test and qualification of propulsion hardware. The toxicity is significantly lower compared to the conventional oxidizer NTO. The second oxidizer candidate, nitrous oxide, is non-toxic, easily available and gaseous under atmospheric conditions. Nevertheless, nitrous oxide can be liquified under ambient temperatures via pressurization. At 20°C the vapour pressure of N_2O is approximately 50 bar, so if stored in liquid state, the high vapour pressure can be used in self-pressurizes propulsion systems.

The high number of propulsion systems under development may lead to a more diversified chemical propulsion technology pool.

2.2. Activities of DLR's Institute of Space Propulsion in Lampoldshausen

DLR's Institute of Space Propulsion conducts research on green propellants for space propulsion applications for more than a decade [25, 26]. Especially the satellite and orbital propulsion department has experience in testing ammonium dinitramide fuel blends [27–30], nitromethane-based propellants [31, 32], hydrogen peroxide [33, 34], nitrous oxide based monopropellant blends and nitrous oxide based bipropellants [35–39]. Furthermore, hybrid rocket engines were tested and developed [40, 41] and scramjet research is conducted [42, 43]

Based on many years of research, two green propellant solutions, namely the HyNOx and HIP_11 technology, proved their potential to substitute the conventional toxic propellants. These technologies have reached a maturity and technology readiness and first products can be brought to the space market. To commercialize the research and transfer products into the market, the DLR employees Lukas Werling and Felix Lauck are founding the spin-off company InSpacePropulsion Technologies. The HyNOx technology (HyNOx means "hydrocarbons with nitrous oxide") offers a high specific impulse (up to 300 s), non-toxic components, self-pressurized propulsion systems, easy handling and very low cost. Initial products are bipropellant thrusters between 1 and 200 N of thrust and associated propulsion systems. A 1 N and 22 N HyNOx thruster were developed and tested in more than 1000 tests under ambient and vacuum conditions. Furthermore, a 5 N thruster and a 200 N thruster are currently under development.

HIP_11 is a patented hypergolic propellant with hydrogen peroxide as oxidizer and an ionic liquid-based fuel. This technology features low toxic components, hypergolic ignition, comparable performance to conventional hypergolic propellants, reduced costs for handling, operation, and testing. Currently, a 40 N thruster is extensively tested and a 200 N class thruster is under development.

3. Propellant and propulsion system development

The following section gives a general overview of the two prospective propulsion technologies and their development history.

3.1. The HyNOx technology

In 2014, the development of the HyNOx propulsion technology started at DLR [44]. The HyNOx propellant uses nitrous oxide as oxidizer and a light hydrocarbon as fuel. As already mentioned, nitrous oxide has a vapor pressure of approximately 50 bar at ambient temperatures. Due to this high vapor pressure, N_2O can be used in a self-pressurizing propulsion system without the need of an external pressurization system or infrastructure. Light hydrocarbons, such as ethane (C_2H_6) or ethylene (C_2H_4) have vapor pressures of a similar level. Therefore, they are suitable to be used as self-pressurized fuels together with nitrous oxide. This principle allows simplicity and reduced costs, since no

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additional components for a pressurization system are needed. Further, nitrous oxide, ethane or ethylene are widely available substances, which are applied in several industrial processes and therefore offer low cost.

The initial investigation on HyNOx were focused on premixed oxidizer-fuel blends [45, 46, 35, 37, 47, 48]. These fuel blends offer the same system simplicity as a monopropellant, but provide the performance of a bipropellant. However, a main challenge of premixed fuel and oxidizer propellants are their sensitivity and the possibility of ignition if sufficient energy is available. Moreover, a flame can propagate from the combustor upstream the injector and lead to an ignition of the propellant in the feeding system. Such a flame flashback must be avoided in any case [49, 47]. Extensive research was conducted on flame arresters, assuring the quenching of the flame and hindering it entering the feeding system [50]. Another challenge of HyNOx propellants is provision of a sufficient cooling [35]. Research on the performance of a mixture of nitrous oxide and ethylene and ethane was conducted [38]. In the frame of an ESA project, firings with liquid premixed propellant tank were demonstrated [39, 51].

Based on the experience with nitrous oxide fuel blends, research in nitrous oxide bipropellants was started. Based on a hydrocarbon screening, ethane was chosen as fuel. The development focused on the regenerative cooling concepts, optimization of injector and combustion chamber geometries. In an iterative process, several demonstrators were tested and the TRL was increased step by step. Now, several thrusters reached a level of maturity, which makes them attractive to the market. In the following sections some key achievements of the current demonstrators are presented.

3.2. The HIP_11 technology

In the frame of a PhD project, novel hypergolic fuels with highly concentrated hydrogen peroxide (up to 98%) were investigated. A screening for suitable fuel candidates was performed, focusing on commercially available room temperature ionic liquids [52]. This kind of substances are liquid salts with a melting point below room temperature. Due to their composition of anions and cations, ionic liquids do not have a vapor phase at ambient temperature. This significantly facilitates handling and increases the safety compared to conventional propellants.

Based on the screening, a selection of promising ionic liquids was made. These ionic liquids were tested on their hypergolic performance with hydrogen peroxide in a so-called lab-scale drop test [52–55]. This procedure allows the initial evaluation of the hypergolic behaviour of the two substances. After several fuel candidates were identified in drop tests, the ignition under more thruster like conditions using injectors was studied [56, 57]. The most promising fuel candidate was successfully hot fired in a battleship thruster [34]. Further achievements will be presented in the subsequent sections.

4. HyNOx: status of the thrusters and propulsion systems

Based on system studies [58] the HyNOx propulsion technology offers significant advantages for smaller, lighter spacecraft. Based on this assessment, the HyNOx technology seems to be most suitable for thrust classes in between 1 and 200 N. Nevertheless, the US company Launcher also developed a Nitrous Oxide/Ethane propulsion systems for its orbital transfer vehicle with a thrust classes of 1100 N [59]. Furthermore, Impulse Space recently qualified its 22 N Thruster called Saiph [60] and develops a 800 N thruster called Rigel [61].

DLR’s HyNOx thrusters are supplied with gaseous nitrous oxide and ethane while liquid feeding is under investigation. The thrusters feature a regenerative cooled thrust chamber to allow thermal steady-state operation, which makes it possible to conduct thrust manoeuvres which are not limited by a maximum impulse bit of the engine. Since oxidizer and fuel are both self-pressurized, the thrust level is adjustable and a throttle range from 35 up to 200% intended for every thruster by thermal control of the propellant tanks. Additionally, pulse mode operation allows for precise impulse manoeuvres. The ignition and operation of the thrusters was demonstrated for a wide range of propellant mixture ratios so that the corresponding propulsion system can either be designed for maximum volume- or mass specific impulse. Figure 1 shows the current family of the HyNOx thrusters in the 1 N, 5 N, 22 and 20 N and 200 NN class. Due to the throttability of the thrusters, the entire thrust spectrum from 0.35 N up to 400 N will be available.

In addition, propulsion systems for different satellite sizes are under development. Thus, starting from CubeSats all spacecraft can be equipped with a suitable system.

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Figure 1: 1 N, 5 N, 22 N and 200 N HyNOx thrusters. The 200 N thruster has a polymeric nozzle extension for demonstration of the full size.

4.1. HyNOx 1 N Thruster

Figure 2 and Figure 3 show the operation of a 1 N HyNOx thruster at atmospheric pressure and in a vacuum at DLR's M11 test facility. In both environments, steady state and pulse mode operation were demonstrated. A throttling range of 30 to 120 % and repeatable pulses with a minimum impulse bit of 0.1 Ns were demonstrated in vacuum as well.

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Figure 2: HyNOx 1N Thruster steady state firing under atmospheric conditions

Figure 3 : HyNOx 1N thruster firing in a vacuum

Figure 5 shows the pressure and temperature data during a 60 s test run where the thruster reaches thermal steady state operation under vacuum conditions at a chamber pressure of 7 bar. The chamber temperature shown is measured at the convergent part of the combustion chamber, whereas the temperature labelled “injector” is measured at the upstream end of the chamber. Both temperatures are measured on the outside wall of the thruster. The curve shows that the temperature is steady at a value of about 830°C. The demonstrated I_{sp} efficiency for the steady state operation in a near vacuum is 85 %. To the authors knowledge, that is the world’s first 1 N thruster operating with nitrous oxide and fuels which reaches thermal steady state and allows burn times as long as propellant is supplied..

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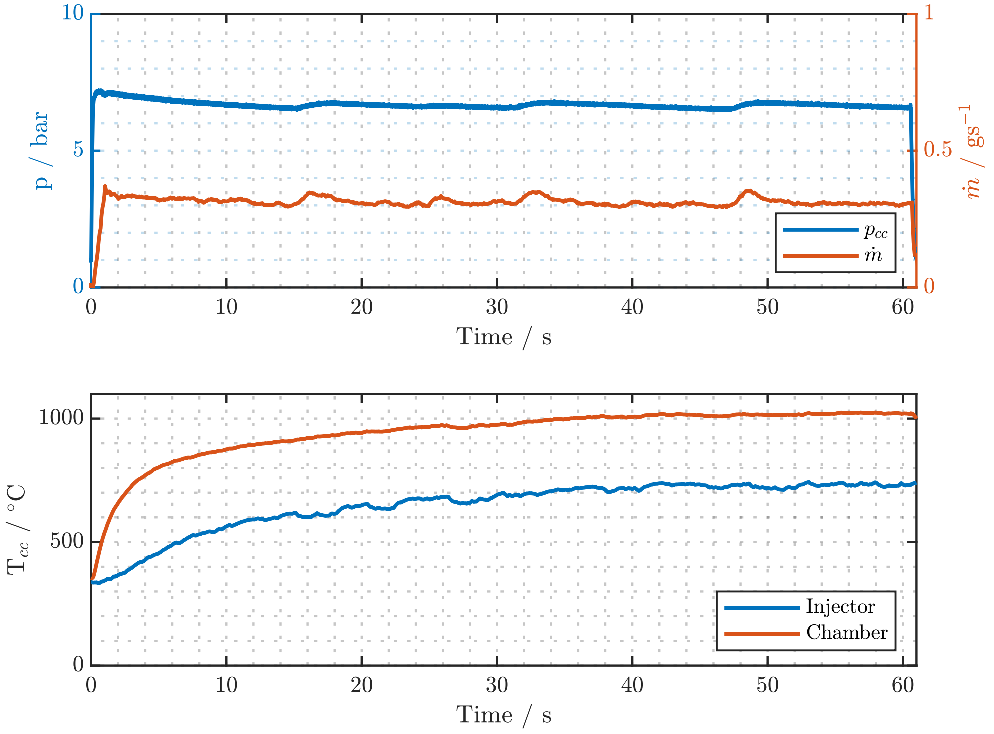

Figure 4: Steady-state test of the 1 N HyNOx thruster under atmospheric conditions

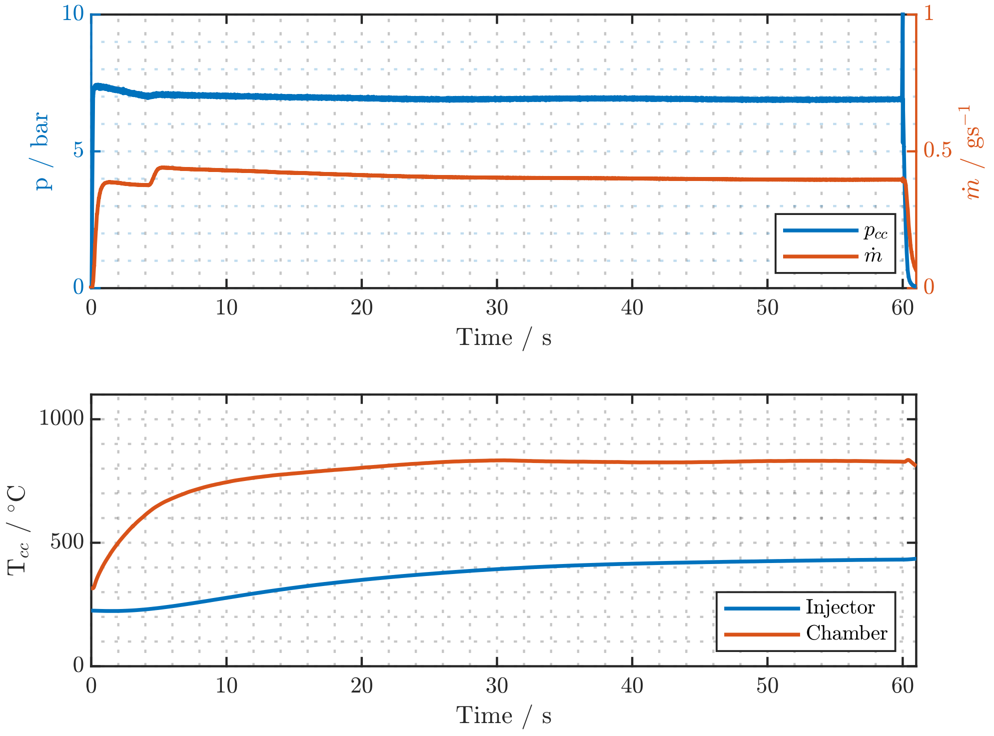

Figure 5: Steady-state test of the 1 N HyNOx thruster in vacuum

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Table 1: HyNOx 1N operating characteristics

	Value	Status
Thrust (nominal)	1 N	
Thrust Range	0.3 – 1.2 N	demonstrated
Specific Impulse (nominal)	up to 270 s	calculated (from measured combustion efficiency)
Chamber Pressure (nominal)	7 bar	demonstrated
Minimum Impulse Bit (Hot Gas)	< 0.1 Ns	demonstrated
Single pulse firing time	1 minute (vac) 3 minutes (atmospheric)	demonstrated
Propellant Throughput	1 kg	demonstrated
Cumulated on-time	> 40 minutes	demonstrated
Nozzle Expansion Ratio	100:1	adjustable
Maximum Pulse Frequency	5 Hz	demonstrated

A new iteration of the 1 N thruster due to be tested in the fall of 2023 is expected to increase the performance, and should allow steady state operation with an even higher I_{sp}.

4.2. HyNOx 1 N Cubesat propulsion module

A complete Cubesat propulsion module for 12 U Cubesats using the 1 N HyNOx thruster is currently under development. It has a size of 4 U and will feature a mostly additively manufactured tank and structure. Furthermore a 1 U propulsion module will be developed.

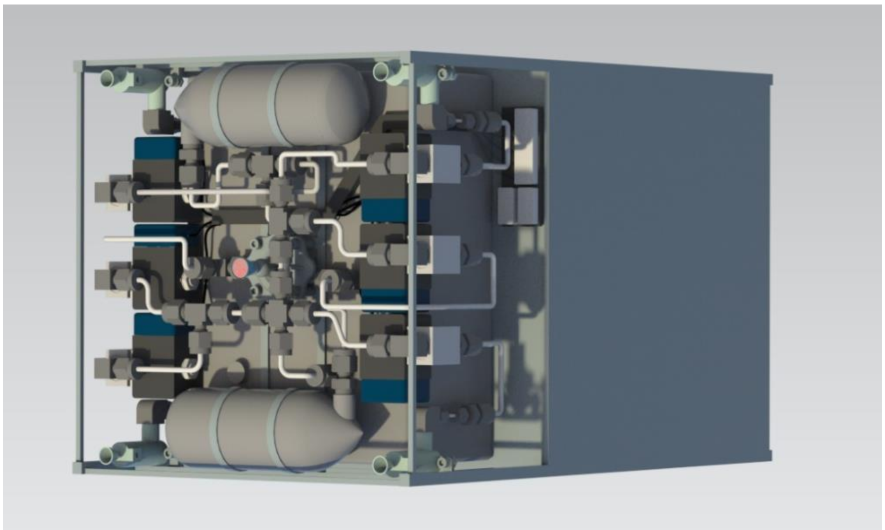

Figure 6: Preliminary rendering of the 4 U breadboard propulsion module, currently under development

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4.3. HyNOx 5 N Thruster

The 5 N HyNOx thruster, depicted in Figure 7 was recently designed and manufactured. By the time of publishing this paper, the thruster awaits the first hot firings. The thruster is of a similar design as the 1 N thruster already described, with a nominal chamber pressure of 7 bar and an expansion ratio of 100:1. Thus, a similar performance is expected. The first tests of the 5 N HyNOx thruster are planned in August 2023 at DLR in Lampoldshausen.

Figure 7: The 5 N HyNOx thruster currently awaiting testing

4.4. HyNOx 22 N thruster

The 22 N thruster was the first HyNOx thruster which was developed from scratch at DLR. For the current thruster design, a cumulated on-time of more than 1 hour and more than 20 kg of propellant throughput were demonstrated. Figure 8 shows the HyNOx 22 N thruster with integrated flow control valves as well as temperature and pressure interface for health monitoring. Figure 9 shows a the thruster in thermal steady-state operation under vacuum conditions.

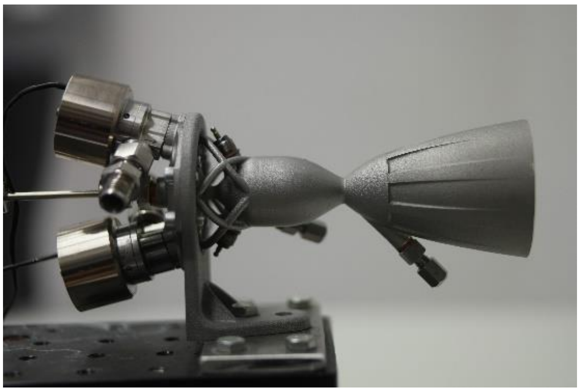

Figure 8: HyNOx 22 N thruster side view

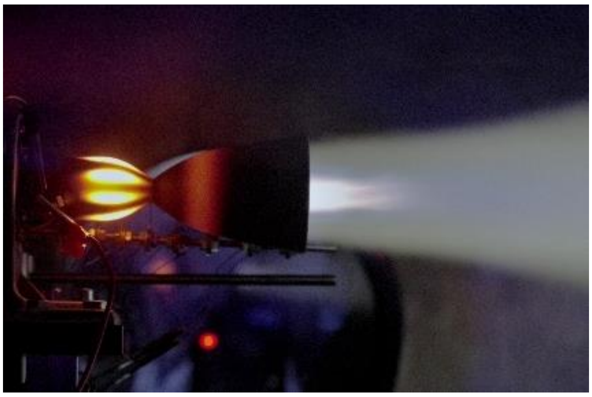

Figure 9 : HyNOx 22 N thruster steady state hot firing under vacuum conditions

Hot fires longer than 7 s and thus a sufficient chamber heating result in a combustion efficiency of more than 95%. The vacuum specific impulse and thrust were calculated using the determined combustion efficiency and the thrust coefficient calculated with NASA CEA [20] assuming a frozen flow at the throat and 2% nozzle losses. The average specific impulse is 290s at the nominal thrust level of 22 N, see Figure 10. Thrust measurements during vacuum tests confirm the I_{sp} calculations from the atmospheric testing.

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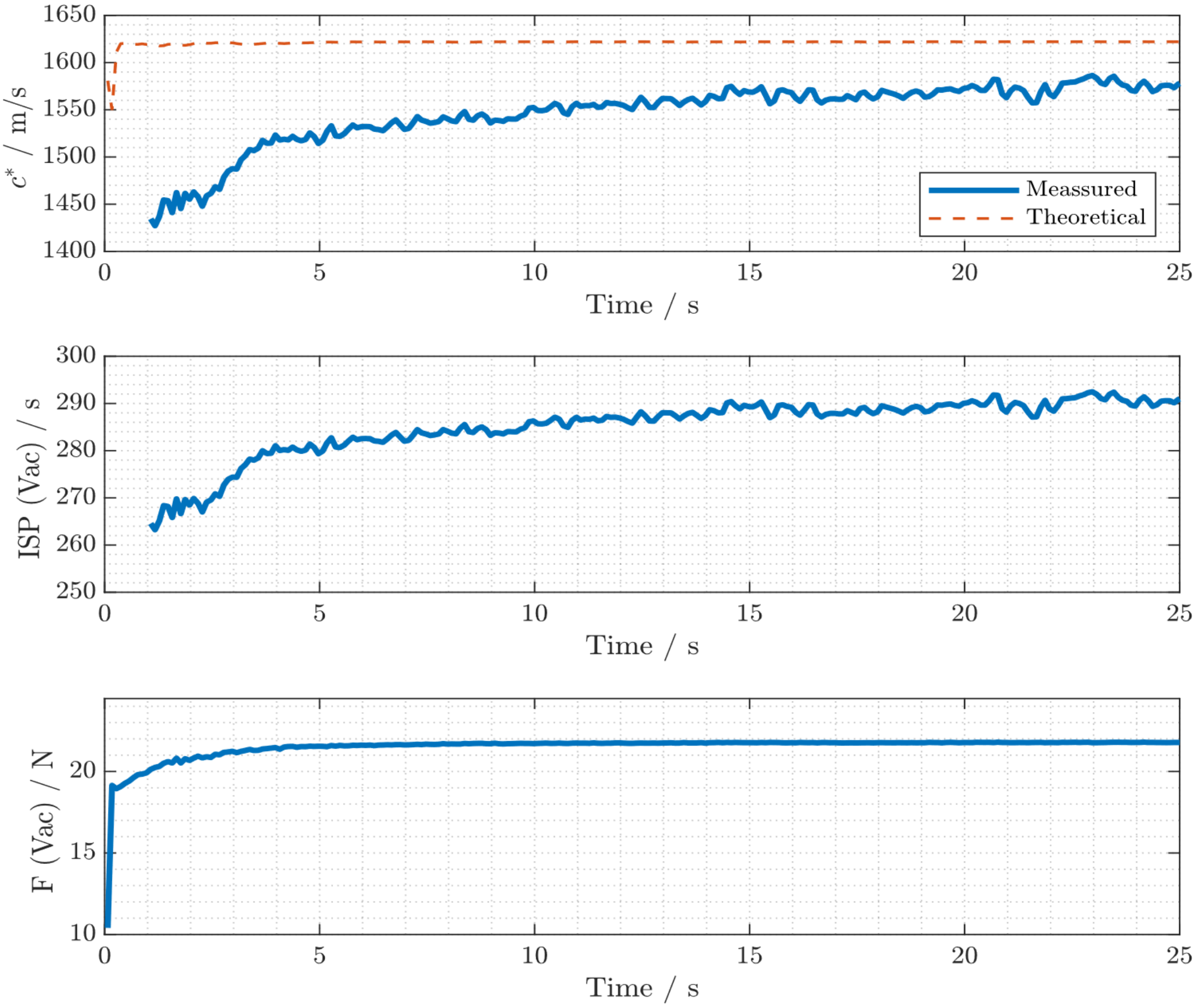

Figure 10: Efficiency characteristics at nominal operating conditions

Furthermore, the operation under thermal steady-state conditions for a wide range of mixture ratios (6 – 20) and thrust levels (14-30 N) was successfully demonstrated under atmospheric conditions. Figure 11 shows the temperature profile of the thruster during an atmospheric firing. The thruster was operated for 900 s and established a thermal steady state operation approximately after 40 s. Within the scope of the ESA project GreenRAIM, further testing of steady-state operations under vacuum conditions is currently completed. Figure 9 shows a vacuum firing of the 22 N thruster. Thermal steady state operation under vacuum conditions was demonstrated at 18 N of thrust.

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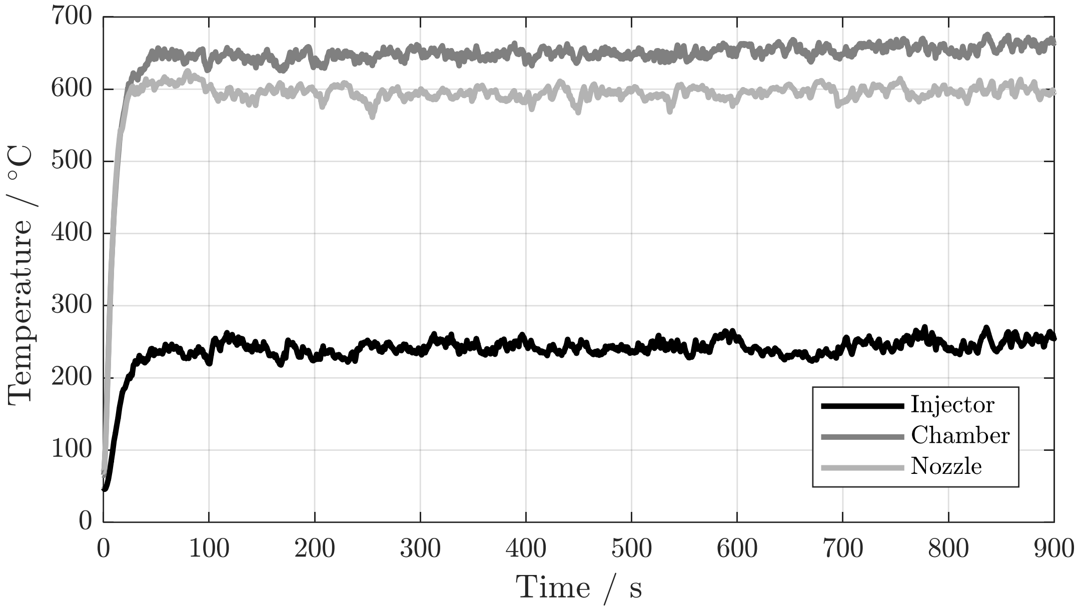

Figure 11: Steady-State Operation of 22 N Thruster (atmospheric conditions)

Moreover, pulse mode capability was demonstrated under atmospheric conditions and in vacuum. The minimum ON-time is 75 ms, with a total impulse bit lower than 1 Ns. In order to achieve separated pulses, for the current design a minimum Off-time of at least 225 ms was needed. Alternatively, the thruster can also be continuously fired with short valve off-times (25/50 ms) in order to achieve a throttling effect. The high reproducibility of the pulse mode operation is shown in Figure 12, which is an overlay of 10 pulse firings with 125ms ON-time.
Table 2 summarizes the thruster's specifications and performance.

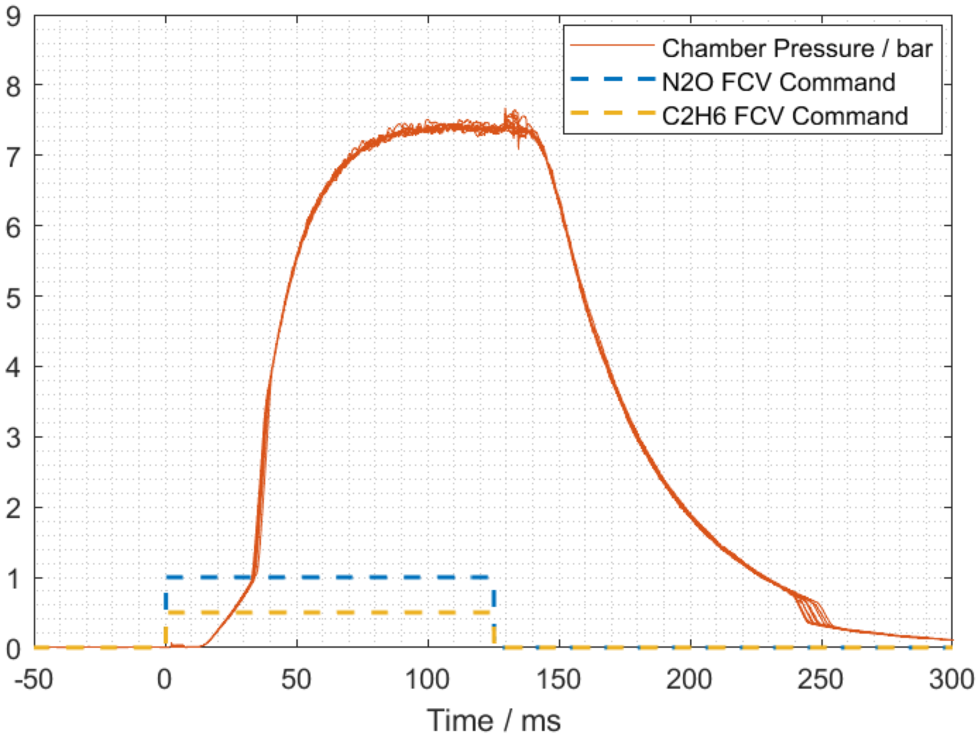

Figure 12: Pulse mode operation in vacuum, 10 pulses, 125 ms ON-time 125 ms OFF-time

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Table 2 HyNOx 22N Operation Characteristics

	Value	**Status**
Thrust (nominal)	22 N	
Thrust Range	44 – 7.7 N	qualification target
Specific Impulse (nominal)	290 s	calculated (from measured combustion efficiency)
Chamber Pressure (nominal)	6 bar	demonstrated
Minimum Impulse Bit	< 1 Ns	demonstrated
Single pulse firing time	> 15 minutes	demonstrated
Propellant Throughput	20 kg	demonstrated
Cumulated on-time	> 60 minutes	demonstrated
Nozzle Expansion Ratio	100:1	adjustable
Maximum Pulse Frequency	5 Hz	demonstrated

4.5. HyNOx 200 N Thruster

The latest developments include a 200 N HyNOx thruster, which is shown in Figure 13. The thruster is an upscaled version of the 22 N thruster and will allow steady state firings and pulse mode operation. It is designed for more than 1000 re-ignitions, pulses down to 200 ms ON-time and single pulse firing times of more than 15 minutes. The thruster will be throttable in between 70 N and 400 N, depending on the supplied mass flow. First hot fires are forseen in August 2023 at DLR’s test facilities.

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Figure 13: HyNOx 200 N thruster without nozzle extension

5. HIP_11: Status of the thrusters and propulsion systems

5.1. HIP_11 40 N thruster

The HIP_11 propellant is based on an ionic liquid fuel and highly concentrated hydrogen peroxide (up to 98%). The theoretical I_{sp} of the propellant is 315 s at an O/F of 3.9 (NASA CEA, chamber pressure 10.35 bar, expansion ratio 330, frozen at throat). This is 5% less than the conventional combination MMH/NTO at the same chamber pressure conditions (334 s). Nevertheless, the density specific I_{sp} of HIP_11 is about 10% higher than the density I_{sp} of conventional MMH/NTO combinations.

After the identification of a suitable hypergolic fuel candidates, tests with a 40 N battleship thruster were used to evaluate the performance of the HIP_11 propellant. The design of the corresponding thruster is described in [34].

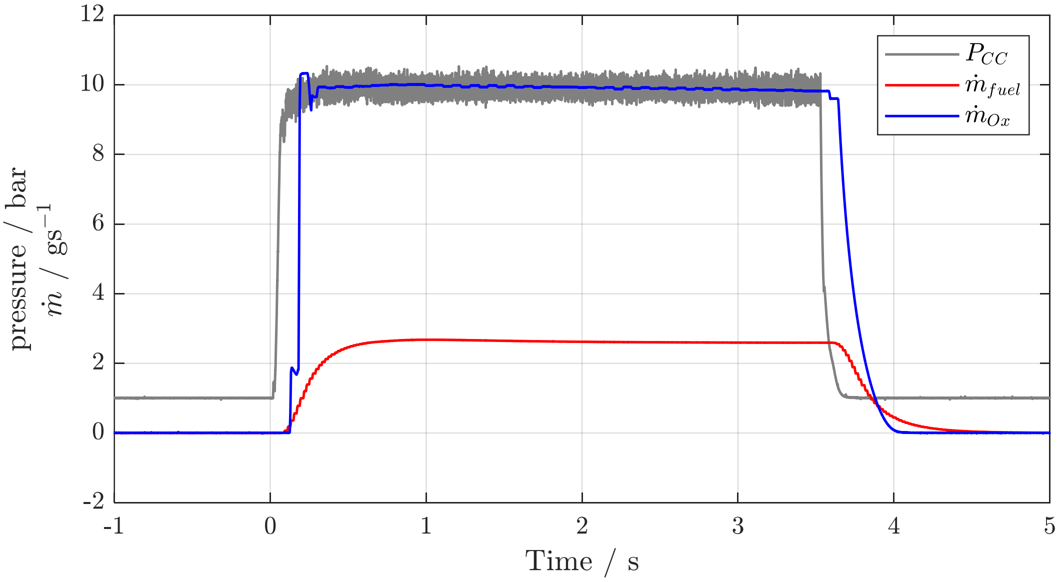

Figure 14: Measurement data of HIP_11 test with the 40 N battleship thruster

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Figure 14 shows the pressures and mass flows during a test run with the 40 N HIP_11 battleship thruster. As propellant, the ionic liquid with a copper additive and 97 % hydrogen peroxide was used. At 0 s fuel and oxidizer valve are commanded to open for 3.5 s. The supply pressure was set to achieve a nominal chamber pressure of about 10 bar at an O/F of 3.8. After the valves open, a smooth pressure rise inside the combustion chamber can be observed. The pressure increases to a steady level of about 9.9 bar. The following values are average values analysed in the window from second 3 s to 3.5 s. The combustion chamber pressure in the analysis window is 9.9 bar. The corresponding mass flows in the steady phase of the test run are 9.8 g/s for the oxidizer and 2.6 g/s for the fuel, which results in an O/F of 3.8. The calculated c* for this test is 1492.3 m/s. The c* efficiency of this test compared to the theoretical c* value calculated with CEA and the actual operating condition is 94.4%. The chamber pressure fluctuation assessed with the root-mean-square is 0.2 bar. Figure 15 shows a snapshot of the firing.

With the demonstrator, combustion efficiencies up to 96 % were demonstrated. Further, steady state operation up to 5 s and reliable pulsing down to 50 ms ON time confirmed. The ignition in vacuum condition was validated as well.

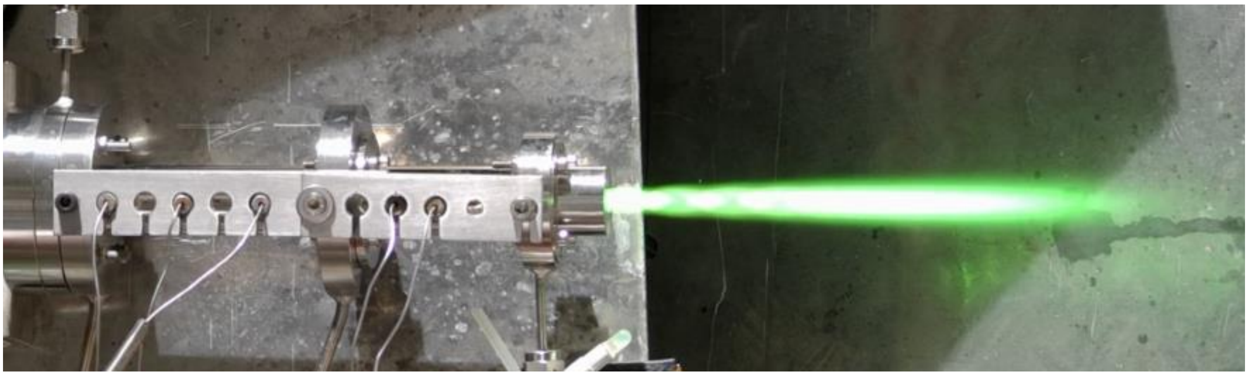

Figure 15: HIP_11 40 N Battleship thruster hot firing

5.2. HIP_11 200 N thruster

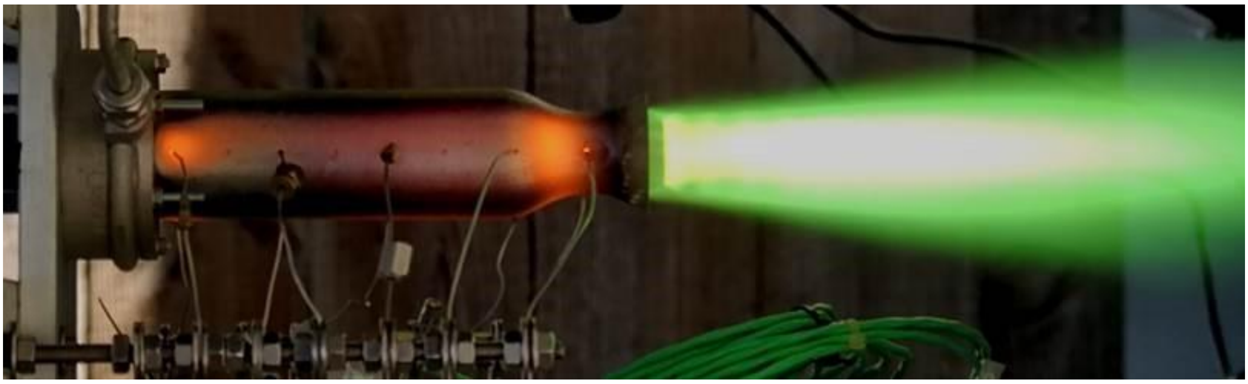

Figure 16: HIP_11 200 N Film cooled battleship thruster hot firing

Beside the 40 N HIP_11 battleship thruster, a additive manufactured 200 N battleship thruster was developed and tested. With this thruster a screening for different film cooling configurations is conducted. Due to the high optimum oxidizer to fuel mixture ratio of HIP_11 (ROF=3.9), a surplus of hydrogen peroxide is available and used as cooling fluid. The injector has two parts, a central injection element and a film cooling element. The injection elements are supplied from two separated oxidizer lines, to assess the influence of different cooling mass flows. The central injector operates in fuel rich conditions. Together with the cooling film, the thruster is operated at global ROF of 4. Currently, an investigation is ongoing of different injector and film cooling configurations. Up to now, reliable and smooth hypergolic ignitions of the thruster were observed. A cooling effect of the hydrogen peroxide film was verified and pulses down to 50 ms ON-time were demonstrated.

6. Conclusion

Based on initial system studies [62], the two propulsion technologies HyNOx and HIP_11 complement each other in a perfect way. The HyNOx technology is a low-cost and robust solution best suitable for spacecraft masses below 500 kg. The HIP_11 technology is a highly reliable solution and has advantages for lager spacecrafts with masses in the

order of several 100 kg and above. HyNOx thrusters were developed and successfully hot fired under ambient and in vacuum conditions in the 1 N and 22 N thrust class. In addition, 5 N and 200 N HyNOx thrusters were manufactured and are currently awaiting the first hot fires. HyNOx thrusters will be available Q4 2023 and an in-orbit demonstration of a whole propulsion system is planned for 2024.
HIP_11 currently has a slightly lower TRL, but at the end of 2024 first HIP_11 products will become available and an in-orbit demonstration is planned for 2025.

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