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Advanced Propellants for Space Propulsion – A Task within the DLR Interdisciplinary Project "Future Fuels"

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Abstract

The project "Future Fuels" combines research in several institutes of the German Aerospace Center (DLR) on the production and use of synthetic fuels for space, energy, transportation, and aviation. Within the sub-project "Advanced Rocket Propellants" (TP5) three promising advanced green propellant systems were under investigation with regard to applicability and efficiency in rocket engines. They are liquid methane / liquid oxygen, liquid mono- and bipropellants consisting of light hydrocarbons and nitrous oxide, and green gelled propellants. This publication gives a short description of aims and results of the space relevant sub-project TP5 within the four years of the project term, but also a very short insight in the other parts of the cross-sectional project Future Fuels.

1. Introduction

Advanced and synthetic fuels and propellants are a decisive building block for the successful implementation of the German energy transition (Energiewende). These carriers allow to store energy in a simple, flexible, efficient and sustainable way. They are also powerful guarantors of future mobility in a vast range: as fuels for road vehicles, trains and ships as well as for aircrafts and rockets. Not only for earth-bound activities, but also for in-space and space propulsion, advanced propellants and propulsion systems are necessary for future sustainable space activities and a reduced environmental footprint.

The development process of rocket propulsion systems is no longer affected only by the demand for better performance properties like higher thrust, enhanced specific impulse and/or increased velocity gain. Instead, requirements are coming more and more into focus, which have been rated up to now as secondary [1,2]. These include amongst others a free and versatile thrust variation capability, simple handling and storage characteristics, low toxicity and health hazard risks both for propellant and exhaust flow species, improved safety in handling and use, environmental friendliness, reusability, and strategies for upgrading and decommissioning under the above-mentioned aspects. Furthermore, mission scenarios are getting more and more complex and existing propulsions systems with conventional propellants are not able to fulfil all of the envisioned demands of contemplated missions.

Thus, green rocket propulsion is a keystone for a sustainable future of space and in-space propulsion and for living in space. Intense and increasing efforts are conducted in the last decades to develop and test propellants and propulsion systems with better safety, handling and environmental characteristics, while performance characteristics should be equal to or if possible even better than conventional propellants, see e.g. [3,4].

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Within the sub-project "Advanced Rocket Propellants" (TP5) three promising advanced green propellant systems are under investigation with regard to applicability and efficiency in rocket engines. The work with three different propellant system candidates aims on different mission scenarios and tasks, whereas performance, low costs, environmentally friendliness, and safe handling characteristics are essential. The three selected promising propellant system candidates within this sub-project are: liquid methane / liquid oxygen, liquid mono- and bipropellants consisting of light hydrocarbons and nitrous oxide, and green gelled bipropellants. The work within the four-year collaborative cross-sectional research project "Future Fuels" started at the beginning of the year 2018 and ended in December 2021.

This paper gives a short overview on the conducted work and obtained results within in the sub-project TP5 "Advanced Rocket Propellants", whereas a very short insight in the other sub-projects of Future Fuels will be presented. Furthermore, this paper shall serve as introduction to the other papers and the presentations in the pre-arranged Special Session: "DLR Future Fuels Project" at EUCASS 2022 at Lille, France.

2. Short overview cross-sectional project "Future Fuels"

Fuels produced from renewable sources are an essential part in reaching our climate goals. Cross-sectoral applications cover a broad range from the global energy (power, heat) to the mobility and transport systems (road, sea, air and space). The objective of project Future Fuels [5] and its successor NeoFuels is to employ the multidisciplinary strength of the German Aerospace Center to embark on the transformation of our energy supply from a fossil to a regenerative fuel economy. The subprojects of Future Fuels cover the research fields space propulsion, aviation and road transport as well as the application of fuels as chemical energy carriers in the power supply system.

In the research field of space propulsion, the project covers the advancement of fuel systems liquid methane / liquid oxygen, nitrous oxide / ethane and gelled ionic liquid / H_2O_2 with their specific application purposes. As this research field is the main focus of the remaining article, a more detailed discussion will be given in the following sections.

In aviation, the main focus of the project is the development application of fuel design strategies and corresponding investigation of novel sustainable aviation fuels (SAF). Within this subproject, methods and tools were developed to evaluate and optimize SAF to cover the ambiguous chain from fuel molecules to climate effects. The effects of various fuel compounds or compositions on pollutant and contrail formation from real jet engines were investigated in ground and airborne test campaigns [6-8]. A highlight within these test campaigns were the tracing flights, of measurement planes following an Airbus A320 flying with SAF. One key result here is the finding that the application of low aromatic SAF can significantly decrease soot formation from jet engines by 50% to 70% [6]. These results are linked directly to SAF evaluations that are performed by the DLR SimFuel platform, which enables the simulation and evaluation of new, alternative and future fuels.

Within the topic of ground transportation fuels, the effects of oxymethylene ethers (OME) as a synthetic fuel blending component in gasoline and diesel fuels on the pollutant formations were investigated [5,9,10]. Thereby, a focus was set on the experimental investigation as well as the numeric modeling of combustion characteristics of OME and their technical application. Within the subproject especially soot reduction potentials from these oxygenated species were demonstrated [9,10].

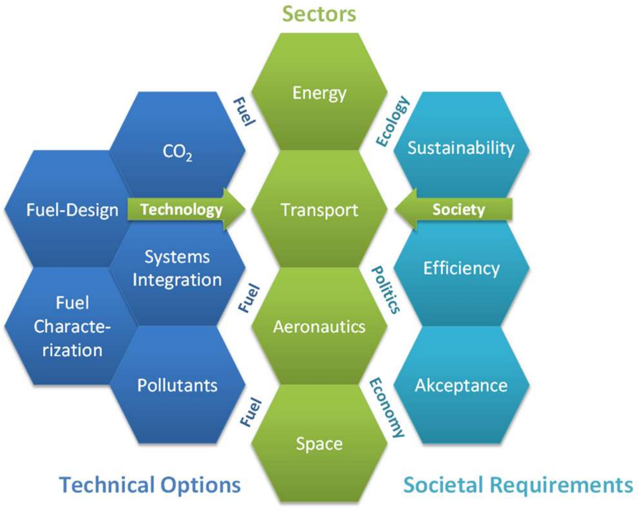

Figure 1: The holistic approach of the DLR project "Future Fuels".

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In the field of chemical energy carriers, the production of syngas — a key intermediate product for the production of synthetic liquid fuels — was investigated via electro-chemical high temperature electrolysis routes [11] as well as via solar-thermal routes [12]. As a highlight, both processes were beneficially coupled to supply the high temperature electrolysis with steam produced from solar power [11]. The liquid energy carriers will most likely be produced in decentralized facilities. These synthetic fuels can be further upgraded to achieve fuel specifications for different transport systems. Additionally, these fuels can be utilized for power re-conversion to support future fluctuating power supply, for electrical grids that heavily rely on power generation based on unsteady solar and wind power. To enable an efficient local low power class re-conversion of liquid fuels in gas turbines, new burner concepts were investigated. Within this project, a novel jet stabilized burner concept was developed, allowing a fuel flexible, liquid fuel combustion with low pollutant emissions for low power classes [13,14].

The insights into the multidisciplinary research topic are combined for a wholistic evaluation of feasible fuel production and utilization routs in terms of techno-economic, socio-economic analyses and eco-balances as well as technical fuel assessments [5]. Overall, the project Future Fuels and its successor NeoFuels contribute to tackling the challenges modern sustainable fuels and promotes the inevitable replacement of fossil fuels with renewable, sustainable, synthetic fuels.

3. Sub-project TP5 “Advanced Rocket Propellants”

The objective of the sub-project TP5 was

- to show and elaborate the potential of the three investigated propellant combinations,
- to develop and understand their combustor processes and
- to develop model combustion chambers with ceramic materials,
- with the task to advance the technology development in direction to a commercial development, and to provide results for industry.

The investigated propellant combinations were:

Table 1: Investigated propellant combinations in sub-project TP5.

			Propellant system type	**Main work package**
1	liquid methane / liquid oxygen	LCH4/LOX	bipropellant	HAP 5.1
2	light hydrocarbons / nitrous oxide	C_2H_6/N_2O, C_2H_4/N_2O	mono- and bipropellant	HAP 5.2
3	gelled ionic liquid / hydrogen peroxide	EIL/H_2O_2	gelled bipropellant	HAP 5.3

Within this complex task area three DLR institutes with different areas of expertise worked in a close collaboration. They were Institute of Space Propulsion, Institute of Combustion Technology, and Institute of Structures and Design. These propellant combinations were investigated in three main work packages (HAP 5.1 – HAP 5.3). Short descriptions and main highlights are given in the next chapters. A presentation of progress in sub-project TP5 was jet given at the EUCASS conference in 2019 at Madrid, Spain [15].

4. Liquid methane / liquid oxygen (LCH4/LOX)

The cryogenic bipropellant combination liquid methane / liquid oxygen (LCH4/LOX) is currently deemed to be one of the most promising bipropellant combinations for the development of new generations of launcher propulsion systems. Compared with hydrogen, methane theoretically enables multiple cost reduction possibilities including reducing the tanks size, allowing for simpler turbo pumps, and simplifying the ground support infrastructure by decreasing the requirements for cooling. Methane also lowers the combustion temperature enhancing durability of the combustion chamber and thereby its reusability. Compared with hydrogen, methane qualifies as a storable fuel for long term missions and offers an increase of the specific impulse of approximately 50 s in comparison to conventional storable propellants (e.g. MMH/NTO). In order to increase the technical understanding of methane combustion, various topics have been under investigation within the Future Fuels programme by DLR.

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4.1. Investigation of physical chemical properties of LCH4 and LNG

The development of methane rocket engines requires consideration of phase transition behavior of pure methane and of its natural gas mixtures to guarantee safe storage of liquid methane or LNG and pumping through valves, fuel pump, engine manifold and cooling channels of the combustion chamber, allowing then use of cost-effective LNG instead of pure methane, available only from a limited number of sources and countries.

Therefore, relevant physical chemical properties of liquified methane (LCH4) and of cheaper liquefied natural gas (LNG) with its impurities carbon dioxide, nitrogen, hydrogen and smaller hydrocarbons are investigated. Phase diagrams of the pure substances and its mixtures were calculated for pressures up to 100 bar with the NIST Reference Fluid Thermodynamic and Transport Properties database program REFPROP® by using reliable equation of states for each purpose. Detailed information of some parts of this work, especially the influence of carbon dioxide in methane on characteristic points of their phase diagram is given in Ref. [16], and was presented 2021 at the virtual Space Propulsion 2020+1 conference.

4.2. Experimental ignition delay time validation data for development of an optimized kinetic model for rocket combustion application

For validation of an optimized kinetic mechanism ignition delay times of diluted methane/oxygen mixtures were measured in a high-pressure shock tube at DLR Stuttgart. Diluted stoichiometric methane/oxygen mixtures were investigated at initial pressures of 16 and 32 bar and initial in a preignition temperature range between 900 K and 2000 K. Either pure carbon dioxide or a mixture consisting of 2/3 water and 1/3 CO_2 were taken as diluents. The dilutions were chosen between 1:2 and 1:4 (a dilution of 1:1 denotes the undiluted CH_4/O_2 – mixture).

As diluent the products of complete methane combustion, i.e. water, carbon dioxide and mixtures of them were used to investigate their effects on the ignition behaviour of methane/oxygen. Due to the operation of the shock tube as “tandem”-tube (the driven section is subdivided into a buffer gas and a reactive gas section similar to a “constraint reaction volume” approach), also low diluted methane/oxygen mixtures could be ignited without triggering detonations behind the incident shock front. Nevertheless, the maximum achievable pre-ignition temperature T_{init} behind the reflected shock front is limited due to the reactivity of the mixture at the conditions behind the incident shock.

As example, the ignition delay time measurement of a CH_4/O_2–mixture diluted with a mixture of 2/3 H_2O and 1/3 CO_2 are shown in Figure 2.

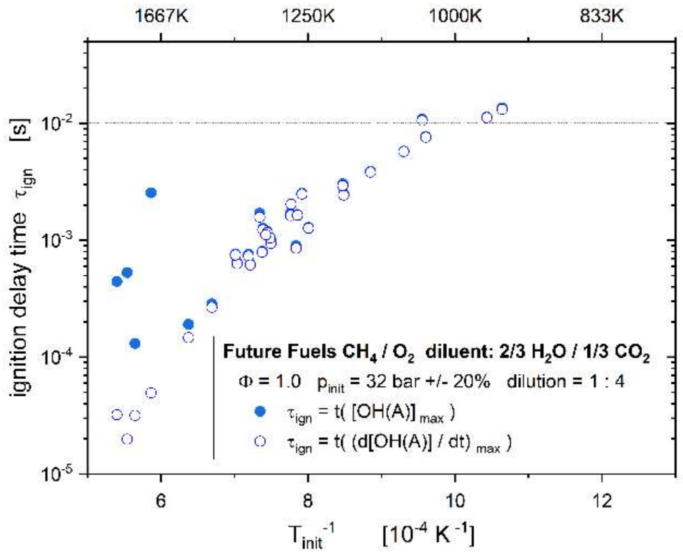

Figure 2: Results of experimental determined ignition delay times τ_{ign} (symbols) of a CH_4/O_2 mixture diluted 1:4 with a diluent mixture consisting of 2/3 H_2O and 1/3 CO_2. At already high initial temperatures, the use of the time of the peak OH(A)-Emission is foiled by the thermal excitation of OH(A) after ignition.

More details of ignition delay time measurements and the results of measurements of different methane/oxygen mixtures with carbon dioxide dilution are given in Ref. [17,18] and of methane/ethane mixtures with carbon dioxide and addition of water are shown in Ref. [19].

4.3. Development of an optimized chemical kinetic model

Details on development and validation of an optimised chemical kinetic model for the combustion of fuel mixtures of syngas and natural gas are given in Ref. [20]. These data, and all validation targets, are also available from DLR Webpage https://www.dlr.de/vt/mechanisms.
For rocket applications only, a smaller reaction model with further reduced number of species and reactions more suitable for large time consuming CFD simulations, is under development.

4.4. CFD Simulations of methane combustion in rocket application

Within the Future Fuels project, the current capability of DLRs TAU-Code for simulating methane combustion inside rocket engines was assessed. The knowledge gained during the project shall enable us to perform a high-fidelity full 3D RANS simulation of the DLR combustion chamber BKN presented in the next chapter.
In order to gain experience for simulating methane combustion, a simple gas/gas combustion test case was investigated. The widely used reference test case of the TUM [21] was chosen, as it allowed the comparison with various other groups simulating the same test case [22]. The need for an improved Finite Rate combustion model in order to include pressure dependent reaction rates was identified during this work [23].
Next, the REST-HF10 numerical test case was simulated, investigating the influence of a modulated mass flow on the combustion process. The methane mass flow rate mas modulated by ± 10 % at a frequency of 5 kHz. The computational domain itself was a single coaxial injector and a hexagonal combustion domain with no wall interaction and a pressure boundary of 100 bar. For the cryogenic injection conditions the Soave-Redlich-Kwong equation of state was used while combustion was modelled using a flamelet approach. For further details see the dedicated paper/presentation by Horchler et al as part of the REST session at EUCASS 2022 24]

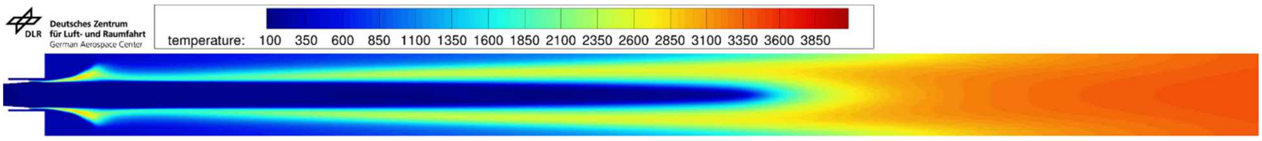

Figure 3: REST-HF10 test case, temperature at steady state conditions.

Additionally, first investigations of the influence of different impurities within the fuel and / or oxidizer mass flow on the combustion were conducted [16]. These investigations where performed by determining the influence of those impurities on the flamelet tables, which later were used in the simulation of a 2D generic test chamber to show the potential influence on the combustion process within the camber.

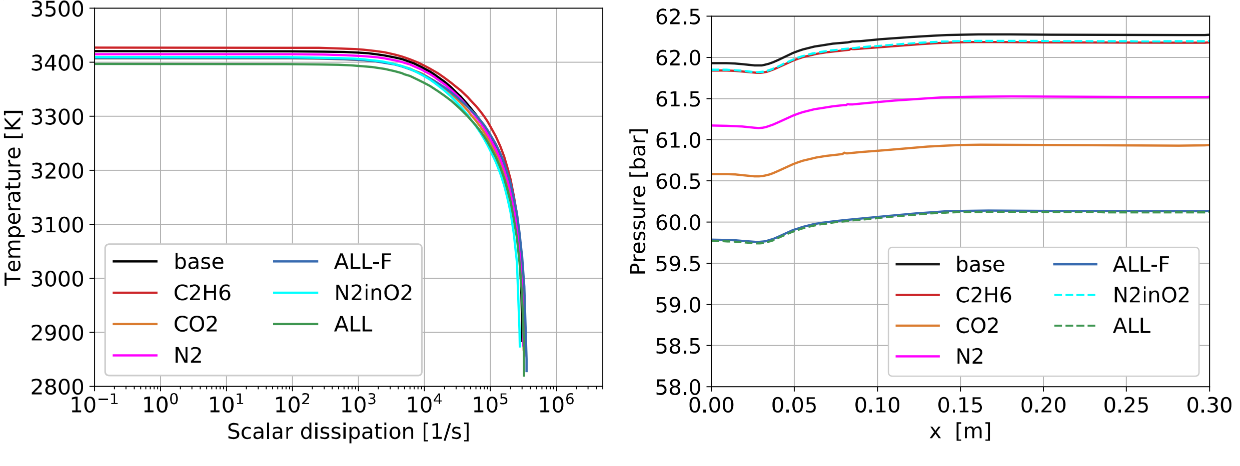

Figure 4: Left: Temperature over scalar dissipation at the respective stoichiometric point for different pollutants of the fuel and/or oxidizer at 20 bar. Right: Combustion chamber wall pressure for different pollutants of the fuel and/or oxidizer (target pressure 60 bar) [16].

Finally, multiple numerical simulations of the processes in the experimental combustion chamber BKN in 2D and 3D have been performed. The focus of investigation thereby was manifold, including quantifying the influence of different

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window cooling geometries and mass flow rates, or showing the influence of different chamber lengths. As a final result a full-3D, steady-state simulation of the test case presented in the next chapter was performed.

4.5. Experimental combustion chamber "BKN" at test bench P8

The use of CFD simulations in engine development can accelerate the optimization of new injector geometries. However, numerical modelling must be capable of handling a highly turbulent reactive flow including large thermal gradients, from cryogenic fluid conditions up to temperatures of more than 3500 K, and real gas effects [25]. Such modelling needs high-quality validation data from suitable experimental test cases [26,27]. In addition to global parameters such as combustion chamber pressure and mass flow rates, highly detailed information concerning flow parameters and boundary conditions are needed to validate that the aforementioned processes are sufficiently captured in simulations [28].

The combustion chamber model 'N' (BKN) has been developed at the Institute of Space Propulsion to provide an optimized set of validation data. During the development of this experiment, the focus was placed on its suitability for validation purposes. Therefore, the experiment is extensively equipped with conventional diagnostics, such as thermocouples and pressure sensors, positioned for effective comparison with CFD results. The most innovative feature is the large optical access window with a length of 255 mm, which allows the world's first full-length flame visualization from a main-stage engine-scaled injector with representative mass flow rates [29]. The window's inner surface matches the contour of the combustion chamber wall to minimize disturbance to the symmetry of the flow field in the combustion chamber.

Within the framework of the Future Fuels project, tests have been performed with BKN using the propellant combination of liquid oxygen and compressed natural gas (LOX/CNG). An exemplary instantaneous snapshot and time-average image at 66.8 bar chamber pressure and ratio of oxidizer to fuel (ROF) of 2.8 are visualized in Fig. 5 and Fig. 6.

Detailed information is given in Ref. [30], presented at the EUCASS 2022 in the session "DLR Future Fuels Project".

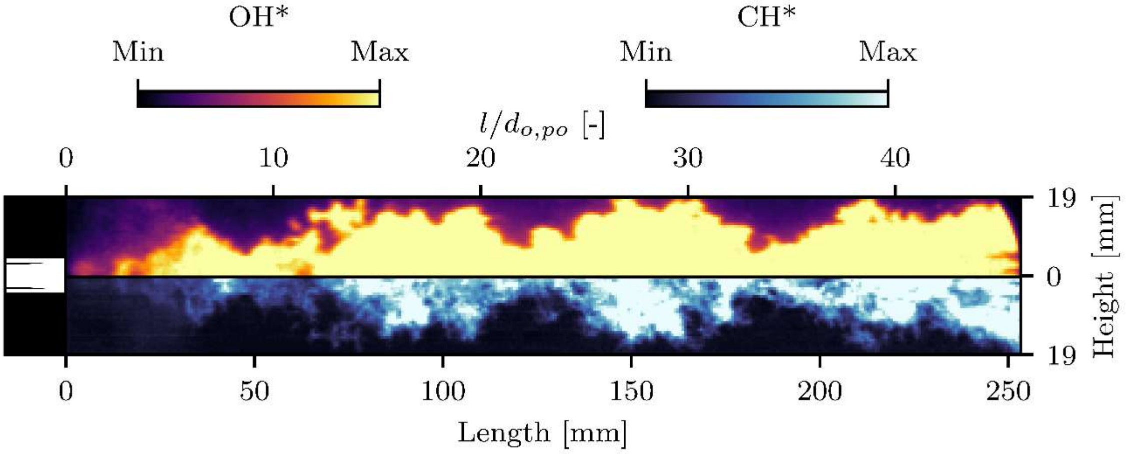

Figure 5: Instantaneous flame radiation imaging (OH*/CH*) for a 66.8 bar and ROF 2.8 load point [17].

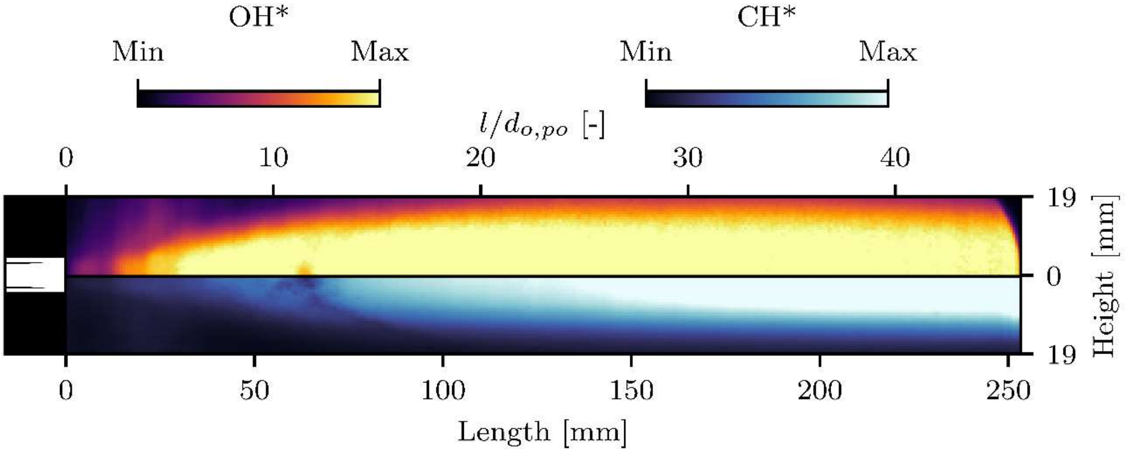

Figure 6: Time-averaged flame radiation imaging (OH*/CH*) for a 66.8 bar and ROF 2.8 load point [17].

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5. HyNOx (Hydrocarbons / Nitrous Oxide)

The main work package HAP 5.2. of the project focused on propellants consisting of nitrous oxide (N_2O) and light hydrocarbons (C_2H_4 and C_2H_6). Here, the propellant combination was investigated as premixed monopropellant as well as conventional bipropellant. Nitrous oxide / fuel combinations are prospective green propellants, as their specific impulse is in the order of 300 s and thus comparable to storable bipropellant combinations like MMH/MON. Furthermore, the propellant combinations are non-toxic and promise system advantages like self-pressurized systems, easy ignitability and low-cost propulsion systems [15,31-34].
The aim of the activities regarding HyNOx propellants was to develop and test a re-ignitable, throttleable model thruster with an TRL of 4. The final engine should deliver a vacuum thrust of 22 N and above.
To support the thruster development several milestones were defined and could all be achieved in the course of the project:

a) Develop, validate and improve reaction mechanisms for N_2O/C_2H_4 or N_2O/C_2H_6 combustion in rocket engine applications [35-39]
b) Conduct CFD simulations of the combustion processes to gain deeper insight in the ongoing processes [40]
c) Evaluate different flame arresters regarding their reliability in the model combustor [32,41,42]
d) Develop and test a regenerative cooled combustor for long term operation

The above-mentioned tasks a) and b) as well as c) and d) were strongly interconnected. As e.g. the reaction mechanisms were the base for the later CFD simulations and the reliable operation of the flame arresters, these simulations are the prerequisite for a safe thruster operation. This section will give a short spot on the highlights of the numerical simulations.

5.1. Reaction mechanism development and CFD simulations

Measurements of laminar flame speeds and ignition delay times of several nitrous oxide /ethane and nitrous oxide/ethene mixtures were performed at DLR's Institute of Combustion Technology in Stuttgart and were used as validation targets for development of detailed reaction mechanism for N_2O/C_2H_4 and N_2O/C_2H_6, which show very good agreement with experimental results [35-39]. Additionally, a reaction model with a reduced size was developed [39] for use in CFD simulations.
The reaction mechanisms were used to simulate two different combustion processes with Ansys Fluent: First, the transient flame propagation process in a dedicated flame arrester test setup was simulated. Here, combustion of the N_2O/C_2H_4 flame was simulated with the corresponding mechanism. Figure 7 shows a high-speed image of the propagating flame in the test setup, Fig. 8 gives the corresponding numerical simulation for an identical time step after ignition. The upper half of Fig. 8 shows the temperature inside the closed test chamber, the lower half shows the heat of reaction and indicates the flame front. The combination of experiments and numerical simulations helped to understand the ongoing combustion processes, flame propagation and quenching processes and allowed an appropriate design of flame arresters.

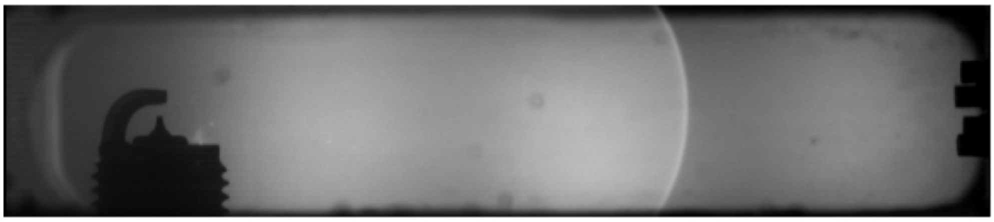

Figure 7: Flame propagation in flame arrester test setup as reference for numerical simulation.

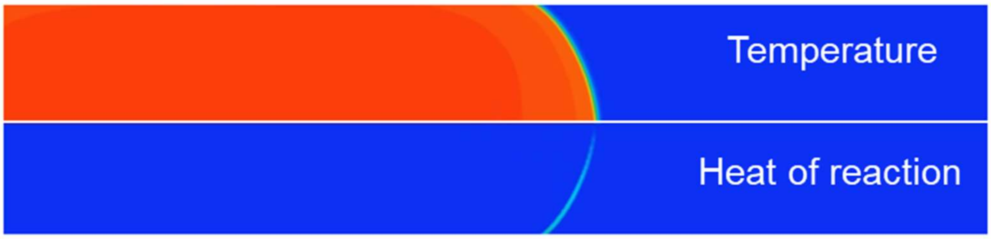

Figure 8: Temperature profile (upper half) and heat of reaction (lower half) of corresponding CFD simulation.

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Second, the stationary combustion process during operation of the research thruster was simulated. Here the aim was to compare the results of the numerical simulations to the experimental results (chamber pressure, heat flux and thrust) and thus to assess the quality of the numerical models. The simulations were then used to investigate the axial heat flux profile at the chamber wall and to locate the flame position. By using the validated reaction mechanisms, future thrusters can be designed efficiently. Figure 9 shows a picture of the thruster during hot firing at the test bench M11 in Lampoldshausen [43,44]. Figure 10 shows the calculated temperature profile of the premixed N_2O/C_2H_4 flame inside the research thruster during steady state operation.

Figure 9: Hot run of the research combustor.

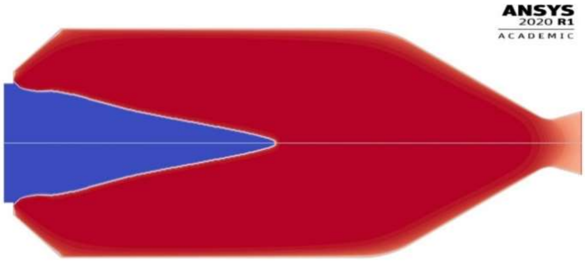

Figure 10: CFD simulation of the combustion process inside the research thruster, temperature profile indicated.

After several improvements and iterations, the simulations showed a fair agreement with the experimental data: The chamber pressure was approximated with deviations of less than 0.1 bar, while the heat flux deviation was lower than 20%.

6. Green gelled propellants.

An approach to comply with ever-increasing safety requirements for rocket propellants is to alter the rheology from a purely liquid form to a paste-like or a gelled form. The goal of this altering of the flowing properties of rocket fuels, oxidizers, and monopropellants is to prevent them from leaking out of broken lines or tanks or to prevent spills to cover large areas. As pointed out by Ciezki and Naumann [45] by this means fires or explosions during fueling and storage may be prevented. This is especially beneficial if a hypergolic oxidizer/fuel pair is used. If at all only a minor quantity can react if a contact occurs during a simultaneous leak in both feeding lines [46-48]. The change in the flow behavior is produced in such a way that the propellant components stay semi-solid during storage, i.e. if no force is applied. As soon the propellant is forced into a line or pumped, i.e. when shear is applied, the viscosity rapidly drops. Ciezki and Madlener [49] investigated the flow behavior in propellant lines in great detail. Stiefel [50] later showed that if certain gelling agents are used, the pumping of gelled substances may even result in lower pressure losses than in pumping ordinary (Newtonian) liquids. Another important implication of the altered rheology is the ability to hold particles in place without sedimentation effects during prolonged storage. This enables the addition of aluminum and other metal particles [51,52], energetic substances and pyrotechnical substances [53,54], and hypergolic ignition catalysts [55,56]. The main aim of the Green Gelled Propellants working package was to explore and focus on these possibilities.

6.1. Hypergolic catalysts

One aspect studied in great detail was the hypergolization of amine fuels with copper and manganese salts and with silver, manganese, and platinum nanoparticles. In [55] Kurilov et al. depicted their screening methodology for finding fuels and ignition catalysts that enable hypergolic reaction with 98% hydrogen peroxide. For the categorization, they used a system of health hazard tiers based on GHS hazard sentences. The multistep screening was carried out with regard to the requirements described in Table 2.

The screening resulted in the identification of TMMDA, TMEDA, N,N-dimethylethylenediamine (uDMEDA), and N,N-dimethyl-1,3-propanediamine (uDMPDA) as the most promising propellant candidates. As hypergolic ignition additive copper chloride ($CuCL_2$) and manganese acetate tetrahydrate was chosen (MAT). To assess the hypergolic properties, drop tests were carried out. Some of the tested hypergolic gels and an ignition sequence achieved in one of the tests are depicted in Fig. 11. The final result of the screening process is depicted in Table 3.

Table 2: Propellant requirements, from [55].

Requirement	Acceptance Level	Preferred Level
Health hazards	No H310, H330, H340, H350, H360 hazard statements – no fatal toxicity, no carcinogens, no mutagens, no fertility damage	No H311, H331, H341, H351, H361 – no toxicity, no suspected carcinogens, mutagens of teratogens
Storability	Boiling point: above 60°C	Freezing point: below -20°C Boiling point: above 60°C
Hypergolic ignition delay (glass vial drop test)	< 50 ms	< 10 ms
Specific Impulse (CEA, 70 bar, 70:1) with 98% H_2O_2	> 280 s	> 300 s
Density Impulse (CEA, 70 bar, 70:1) with 98% H_2O_2	> 350 s·g/cm^3	> 380 s·g/cm^3
Price per kg	< 1500 €	< 330 €

To sum up, four amine-based fuel compositions were identified as promising hypergolic candidates. They all satisfied energetic and health hazard requirements defined at the beginning of the screening. However, only the TMEDA-based gel was capable to deliver the desired ignition characteristics. Therefore, future research activities will be focused on this formulation.

Figure 11: Left: Hypergolic gels; Right: Hypergolic ignition sequence. From [55].

Table 3: Fuel screening results, from [55].

Base Fluid	Gellator	Catalyst	Number of tests	Ignition Delay [ms]		Specific Impulse (70 bar, 70:1) w/ 98% H_2O_2 [s]	Density Impulse (70 bar, 70:1) w/ 98% H_2O_2 [s·g/cm^3]
				Mean value	Standard deviation		
TMMDA	AEROSIL® 200	$CuCl_2$	3	112	9.5	302	402
TMMDA	AEROSIL® 200	MAT	3	112.5	44.7	302	402
TMEDA	AEROSIL® 200	$CuCl_2$	7	14.3	1.5	301	499
uDMEDA	AEROSIL® 200	$CuCl_2$	6	56.3	15.3	301	401

Ricker et al. [56] further optimized the system gelled TMEDA / 98% H_2O_2. In their work they used silver, platinum, and manganese dioxide nanoparticles. In an initial step, the silver nanoparticles were identified as the most promising means of hypergolic ignition. In further steps the particle size dispersion method and the influence of the stabilizer (see Fig. 12) were optimized. First results indicate that an ignition delay of about 9 ms could perhaps be realized with a silver nanoparticle loading of 5 wt.%.

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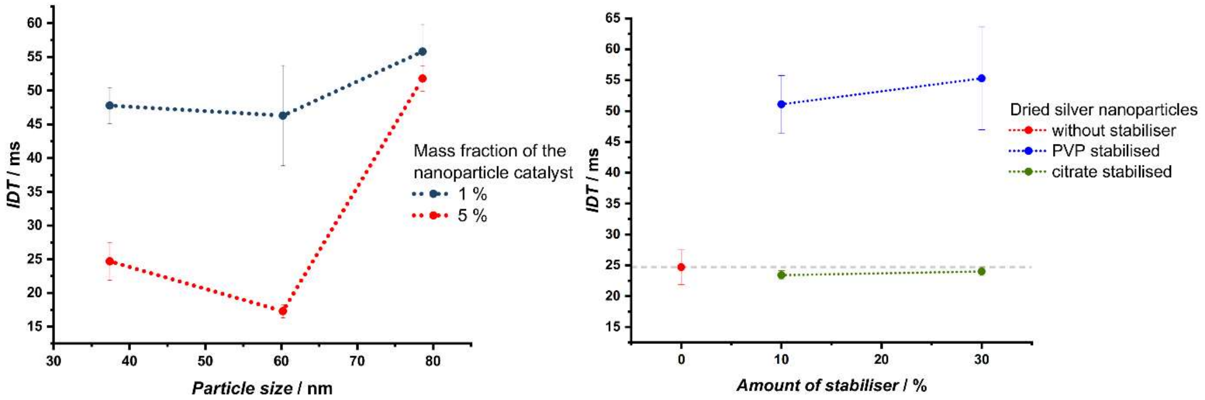

Figure 12: Left: Influence of silver nanoparticle properties on hypergolic ignition delay time (IDT). Right: Influence of stabilizer on the ignition delay time. From [56].

6.2. Metallic additives

As part of another working package the incorporation of metal particles into liquid monopropellant formulations was investigated. For this type of propellant, the term “homogenous slurry propellant” (HSP) was chosen by the Lampoldshausen working group. Possible applications for HSPs lie within the same niche as for solid propellants, i.e. HSPs would be used as kick- or deorbiting stage or in tactical missiles. However, by using HSP some challenges arising from the use of solid propellants may be solved. For instance, no cracks may form as in solid propellants since HSPs are semi-liquid and are stored in tanks rather than in the combustion chamber. Additionally, unlike a solid rocket propellant, HSPs may be throttled by simply varying the propellant mass flow. Furthermore, with a suitable ignition device, the restart capability may be achieved in HSPs. Further details on HSPs can be found in Kurilov et al. [57]. Here only the most important findings will be presented.

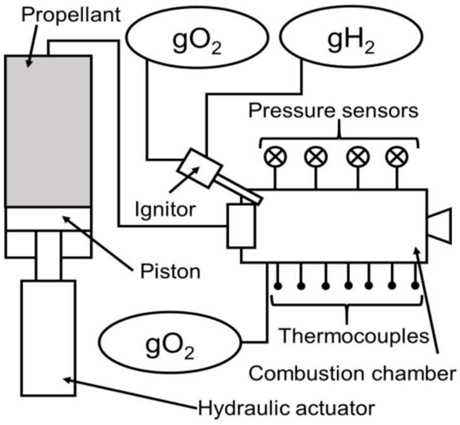

Figure 13: Combustion chamber test setup, from [57].

During an experimental campaign, two different HSP formulations were investigated. The aim of the investigation was to assess if an energetic base liquid also containing a phlegmatizing additive or a non-energetic base liquid shall be used. In Table 4 the investigated propellant compositions are depicted.

Table 4: Propellant compositions, from [57].

Designation	Base fluid	Metal fuel	Gelling agent	Additives
HSP 201	Low energetic	Aluminum	Polymer-based	-
HSP 312	High energetic	Aluminum	Polymer-based and SiO_2-based	Phlegmatizing agent

The propellants were burned in a 200 mm long combustion chamber with an inner diameter of 40 mm. An overview sketch of the test setup is shown in Fig. 13. An impinging jet injector was used to inject and atomize the propellant. As a source of ignition, a two-stage torch igniter was used. As a first step during the ignition sequence, a hydrogen-rich H_2/O_2 mixture was ignited. As stable combustion was reached in the pilot chamber and as soon as the injection of this mixture produced pressure and temperature rise inside the main chamber, additional gaseous oxygen was injected into the main combustion chamber. The amount of this additionally injected oxygen was chosen to exactly reach a stoichiometric H_2/O_2 ratio in order to maximize heat generation inside the combustor. After achieving stable H_2/O_2 combustion, the HSP was introduced into the chamber via the injector bores. During the first approx. 1000 ms the pilot chamber was running in parallel to support the HSP combustion. In some tests, the additional or boost oxygen, i.e. the second igniter stage, was left running for the whole duration of the test. This was done for safety reasons, especially to avoid hard restarts in the case that the HSP combustion should cease prematurely.

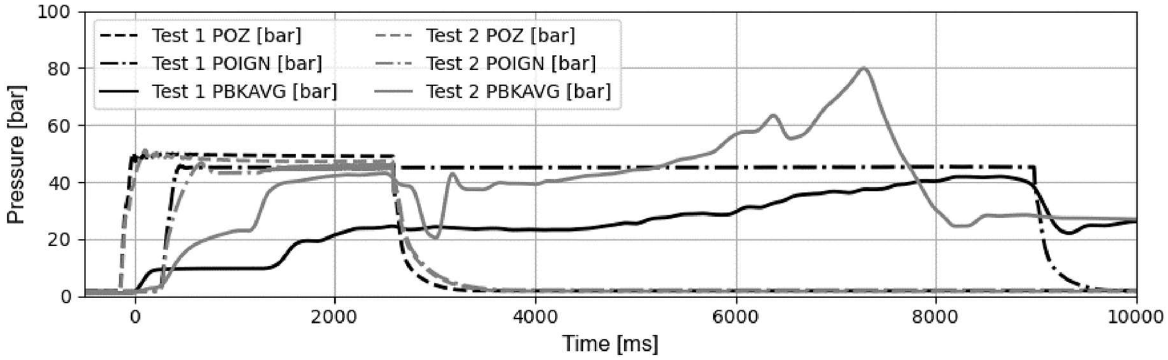

Figure 14: Pressure readings in HSP 201 tests (test runs 1 & 2), from [57].

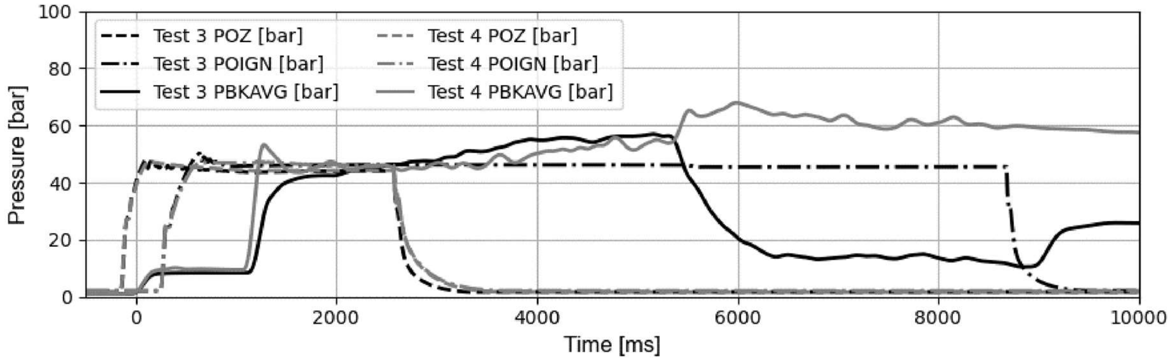

Figure 15: Pressure readings in HSP 312 tests (test runs 3 & 4), from [57].

In Figure 14 the pressure readings of two tests with the HSP 201 and in Fig. 15 two tests with the HSP 312 propellants are shown. POZ is the feed pressure of the pilot chamber gases (H_2 and O_2), POIGN is the pressure at which the oxygen for the second ignition stage is supplied, and PBKAVG is the combustion chamber pressure.

Figure 16: Residues inside the nozzle region. Left: after test 2. Right: after test 3. From [57].

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In test 1 only a lower than the expected theoretical combustion chamber pressure was reached (≈ 25 bar). The combustion however did not cease since the second ignition stage was left running by injecting the oxygen at 45 bar. Only a small amount of additional oxygen (approx. 2-3% of propellant mass flow) was sufficient to keep a continuous combustion. The C^* combustion efficiency was evaluated to be 55% within the analysis window (at 3500 ms – 4000 ms). In test 2 a higher pressure level (approx. 40 bar) was reached during the ignition phase. This can be contributed to a 20% higher propellant mass flow in test 2. In this case, stable combustion could be reached even though the second igniter stage was not left running. Combustion efficiency was measured to be 76 %. However, as also in test 1, the chamber pressure increased during the duration of the test run. This can be attributed to the accumulation of unburnt propellant within the nozzle throat region. This clearly can be seen on the left image of Fig. 16. The residues found in the nozzle region were analyzed with a Netsch STA 449F3 TGA apparatus in an open crucible under O_2 flow and 10K/min heating. Within the TGA temperature interval of 120 – 1000 °C, a quite high mass loss occurred which proves that combustible material remained in these accumulations was quite high. thus, for test run 2 the combustion process within the combustion chamber was far from being complete.

In test 3, in which HSP 312 containing an energetic base liquid was used, the desired combustion chamber pressure level was reached already during the ignition and start-up phase. In this test, the ignitor second stage oxygen was left running again. However, since the combustion pressure quickly rose above the oxygen injection pressure, no additional oxygen was supplied during the combustion experiment. The C^* combustion efficiency within the 3500 – 4000 ms time interval was almost 100%. During test 4, which was conducted without the long-running second ignition stage, similar results could be achieved. In both test 3 and test 4, no debris around the nozzle did accumulate. The white melt layer on the right side of Fig. 16 could be traced back to the used SiO_2 based gellant. The TGA analysis did not show any significant mass loss within the 120 – 1000 °C temperature interval.

As a result of this test series, it became evident that only if a highly energetic base fluid was used, an extensive aluminum combustion with very high efficiencies can be achieved. Therefore, future research efforts will be concentrated on this type of formulation.

7. Conclusions and Outlook

Three promising propellant combinations were investigated within the scope of the four years term between 2018-2021 of the cross-sectional and interdisciplinary project “Future Fuels”. They were the bipropellant combination liquid methane / liquid oxygen (LCH4/LOX), the mono- and bipropellant system of nitrous oxide / light hydrocarbons (i.e. N_2O/C_2H_6 and N_2O/C_2H_4), and the gelled bipropellant combination gelled ionic liquid / hydrogen peroxide (EIL/H_2O_2). The obtained results were very promising and show the advantages of all the investigated propellant combinations. Due to the fact that this is an overview paper, detailed information of the conducted work and its results is given in the other papers presented in the prearranged Special Session: “DLR Future Fuels Project” at EUCASS 2022 at Lille, France.

Finalizing it can be said that the obtained results and developed technologies are encouraging and thus interesting for future applications. Nevertheless, there are still tasks to solve on the way to future applications. A successor project NeoFuels with four years duration has been started at the beginning of 2021 with new aims and but with the same strategic orientation within an interdisciplinary cross-sectional project structure. We hope that the results and developed technologies within “Future Fuels” can contribute a little bit to get nearer to a green and sustainable space propulsion in the future.

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