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50 Years of Test Complex M11 in Lampoldshausen – Research on Space Propulsion Systems for Tomorrow

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Abstract

Basic research activities and thrust chamber oriented technology development activities for rocket and air-breathing (ram-/scramjet) propulsion systems are conducted at the M11 test complex at Lampoldshausen test site. The first part of M11 was erected in 1966. In the 50 years of its existence, important scientific results could be elaborated in the multifarious working areas and have been published in a very large number of publications in journals and on conferences. Today the R&D activities are focussed on the development of thrust chamber processes with advanced and above all green propellants. This publication gives a short overview of the history of the test complex and delivers a short inside into current R&D activities.

1. Introduction

The history of the M11 test complex at Lampoldshausen test site started in the 60s of the 20th century. A laboratory building with the name M11 with two test cells and a small office and laboratory wing was constructed in 1966. Figure 1 (left) shows a photography from the time of construction. Recessed on the left side of the image the two test cells can be seen in its first version and in between the entrance to the control room. On the right side is the office and laboratory wing in its first size.

In the course of time both building parts were several times enlarged and adapted to the new tasks. The office and laboratory wing was enlarged in 1979 and 1980 as well as the test cell area by a measurement and diagnostic room. While the existing laboratory rooms were used for work in the area of analytical and preparative chemistry, the new laboratories were dedicated to work with advanced physical measuring techniques and to work in the area of physical chemistry. In the following years several laser-based techniques, which have just been in ascendant in that time, like CARS, LIF, LDA, and PIV were prepared, tested, enhanced and used with regard to the applicability in rocket and ramjet model combustors and experimental setups.

The physico-chemistry laboratory and a large part of the offices were moved to the M3 building in 1992. This was necessary because the test runs at the new test bench P5 for the development tests of the Vulcain engine for Ariane 5 demand the evacuation of the M11 during the run times. The close collaboration of physico-chemistry laboratory and test complex is indispensable despite the spatial distance. On June 10th 2013 the student test field M11.5 was inaugurated. Since that date it is available for own research activities and for student groups of German universities for combustor and motor tests, especially in the scope of the STERN program. The right photography of Figure 1 shows the current view of the M11 test complex with the student test field M11.5 on the left side. The test cells and the laboratory in M3 building were again extensively refurbished in the last years. In chapter 3 a detailed overview about the current status and equipment will be given.

This publication will give a short overview about

- R&D topics, which have been carried out at M11 over the 50 years together with some important findings,
- the test positions including current experimental setups, and
- selected current research activities.

A small publication about the working areas in the history of M11 and also working areas at time of presentation was jet presented at the 3rd EUCASS conference at Brussels in 2009 [1]. The present publication, however, is significantly more detailed and up-to-date, but nevertheless not complete due to the limited number of pages. In each chapter references are given to exemplarily publications to offer detailed information for interested readers. The current publication is also partly based on a conference publication in German from 2016 [2]. It should furthermore be mentioned that the 1st Lampoldshausen Symposium on Advanced Rocket Propellants Research and Development was conducted in 2016. It gave a detailed overview about the state of the art of current research topics on advanced green propellants and was the opportunity to celebrate the 50th anniversary of the M11 test complex [3].

Figure 1: M11 test complex. Left: Snapshot from the construction in 1966. Right: Today's view.

2. The R&D phases at M11 test complex

The research and technology development (R&D) activities at the M11 during the last 50 years can be divided into four main phases, which are described in the following sub-chapters. The sketch in Figure 2 shows the chronology. All the work conducted in the past was and the current work is oriented and focussed on the global scientific trends as well as the German and European R&D demands.

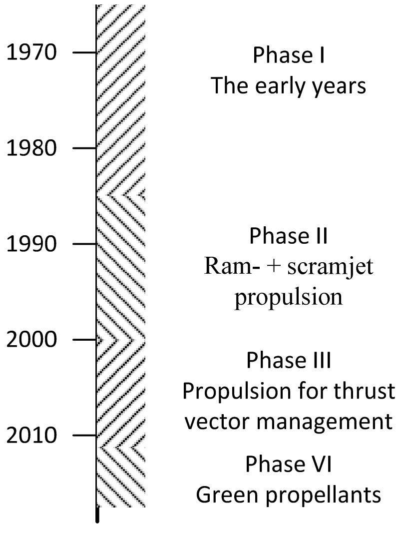

Figure 2: R&D phases

2.1. Phase I: The early years – Hybrids and solid fuel ramjets

In the years after the erection of the M11 test complex the main research activities were focused in the field of hybrid rockets. Both burning tests as well as theoretical investigations with various solid fuel / liquid oxidizer combinations were conducted. Many high energetic solid fuel / liquid oxidizer combinations were investigated. Most of the used propellant combinations and components were developed, produced or modified in the chemical laboratory of the M11. In model combustor tests liquid oxygen (LOX), liquid fluor (LF2), and FLOX (i.e. liquid oxygen mixed with liquid fluorine) were used. Figure 3 shows on the left side the sketch of a model combustor and a photography of a tests run. The high corrosivity of these fluor containing oxidizers demanded extensive security and physical precautions and led thus to a difficult handling. Detailed investigations were conducted amongst others also with metal particle additives. For example were investigated HTPB with embedded aluminium particles in combination with FLOX, but also solid lithium hydride additives in solid fuels with LOX and FLOX.

In mid 70s also work on solid fuel ramjet (SFRJ) propulsion started. "Metal" particle loadings of solid fuels for SFRJ got also scope of the research activities. Detailed investigations with aluminium, magnesia, silicon and boron as high energetic additives in particle shape were conducted. Within the scope of SFRJ research e.g. detailed measurements

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of temperature and concentration distributions inside combustors were performed. Figure 3 shows on the right side a photography of a test position for solid fuel ramjet investigations at the end of the 80s. For further information about the work in phase I, please see e.g. Refs. [5-14].

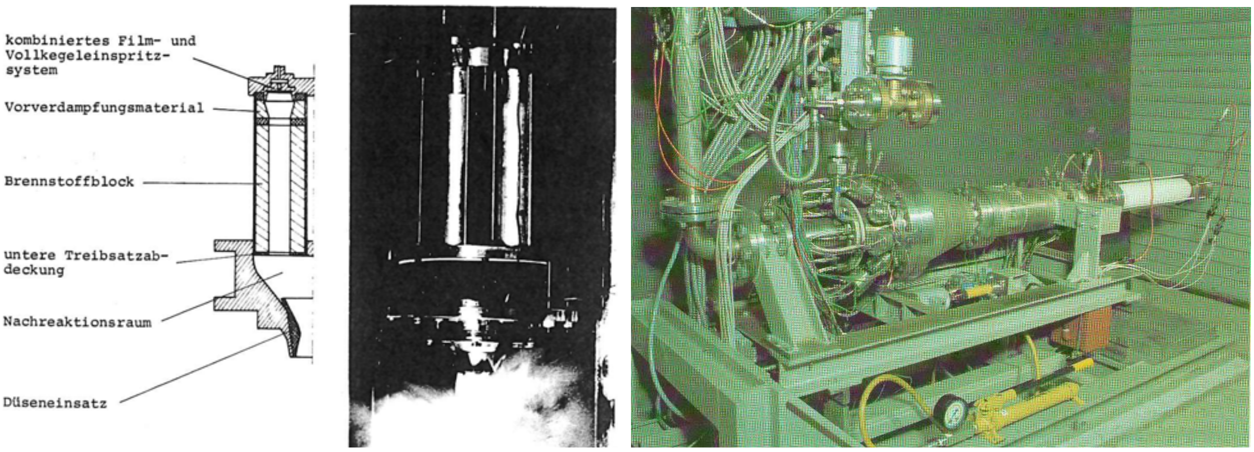

Figure 3: Left: Test run of a FLOX/polyethylene hybrid model thruster for an apogee engine and sketch of engine [4]
Right: Test position for solid fuel ramjet investigations at the end of the 80s.

2.2 Phase II: Research on ramjet and scramjet propulsion

In the second half of the 80s of the 20th century the focus of the research activities at M11 shifted to ramjet propulsion. Beside the yet existing SFRJ activities, also work with hydrogen as fuel for ramjet and scramjet (i.e. supersonic combustion ramjet) propulsion systems was started. For these activities further and advanced air heaters were built within the years for combustor investigations in connected pipe configuration. Mid of the 90s all test positions were equipped. These air heaters are necessary to simulate the hot air flow coming from the air intake into the combustor during the flight of a real flight vehicle at higher Mach numbers. They are still available today. H_2/O_2 burners with an additional (makeup) oxygen flow are used to produce “vitiated” hot air flows with the same oxygen content as in the surrounding air. Large storage capacities for air, oxygen and hydrogen are available to operate the test benches in the blow down mode offering test times from seconds up to partially minutes depending on the chosen test conditions concerning air temperature and pressure as well as fuel and air mass flow rates.

Some of these air heaters are able to produce hot air flows with up to 1500 K and are thus able to simulate flight conditions up to Mach numbers of ca. 5.8 at higher flight altitudes. Figure 3 shows the capabilities of the M11.3 test position to simulate typical ramjet flight conditions. Depending on the maximum available total pressure p_t of 12 bar and total temperature T_t of 800 K, the facility allows to conduct connected pipe experiments relevant for flight conditions up to Mach numbers $Ma_\infty \approx 3.6$, if an isentropic air intake is assumed. Figure 4 shows the capabilities of M11.1 and M11.4 test positions to simulate scramjet flight conditions for connected pipe experiments with hot vitiated air flows entering a model combustion chamber with $Ma_e = 2.0$ conditions via a Laval nozzle.

Separate diagnostic rooms on both sides of the test cell area were realized to protect the sensitive and expensive equipment of some laser-based diagnostic techniques against the harsh environment inside the test cells. Also for security reasons the test sequences of the experiments were conducted remote controlled via a Siemens SPS, except at M11.2 were the tests are manually operated via a control desk.

The left image of Fig. 5 shows test position M11.4 with air heater, thrust balance and a scramjet model combustor with optical access for laser-based diagnostics. The CARS technique was used for the non-intrusive determination of spatial temperature distributions inside the chamber in this experiment [15, 16]. Only the receiver optics was placed inside the test cell and the laser beams were guided from the laser source in the diagnostic room to the combustor via lenses and mirrors.

For the detailed investigation of the governing processes in the model combustion chambers of SFRJs and hydrogen fueled ramjets and scramjets, a large variety of intrusive and non-intrusive conventional and laser-based diagnostic techniques was used. Within the scope of these works some of the applied diagnostic tools had to be adapted to the harsh conditions in the test cells and the experimental setups, whereas even development and enhancement works had to be conducted for some of these tools. To these used techniques belong e.g. Particle Image Velocimetry (PIV), Laser-Induced Florescence (PLIF), video imaging of OH (spectroscopic) emission, sampling and pneumatic probe techniques, coherent anti-Stokes Raman scattering (CARS), black-and-white as well as Color Schlieren techniques together with conventional and high speed camera systems, shadowgraphy, Mie scattering techniques, pyrometry, flame spectroscopy, etc. For further information please see e.g. the overview publications [15, 17].

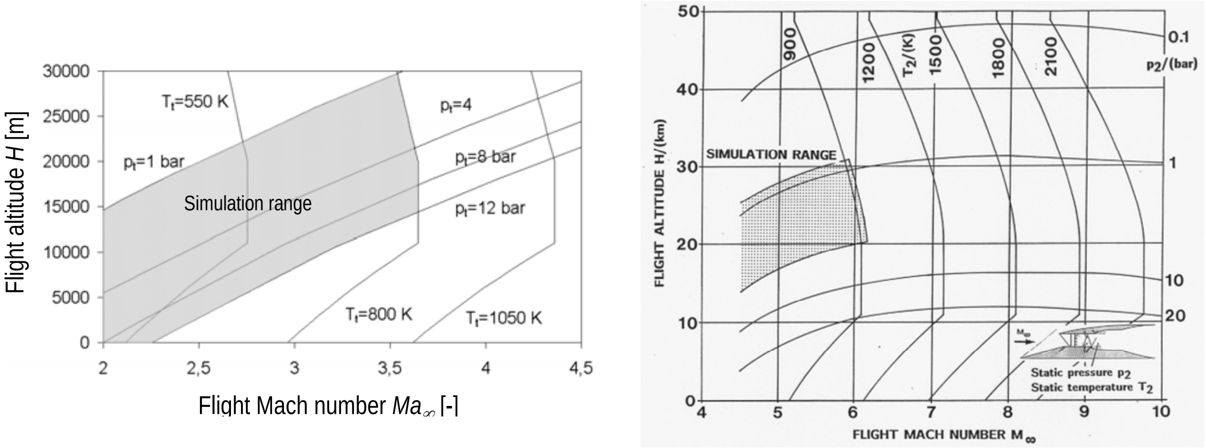

Figure 4: Left: Simulation range of M11.3 for (subsonic) ramjet combustor process research
Right: Simulation range of M11.4 and M11.1 for scramjet combustor process research with a combustor entrance Mach number $Ma_e = 2.0$.

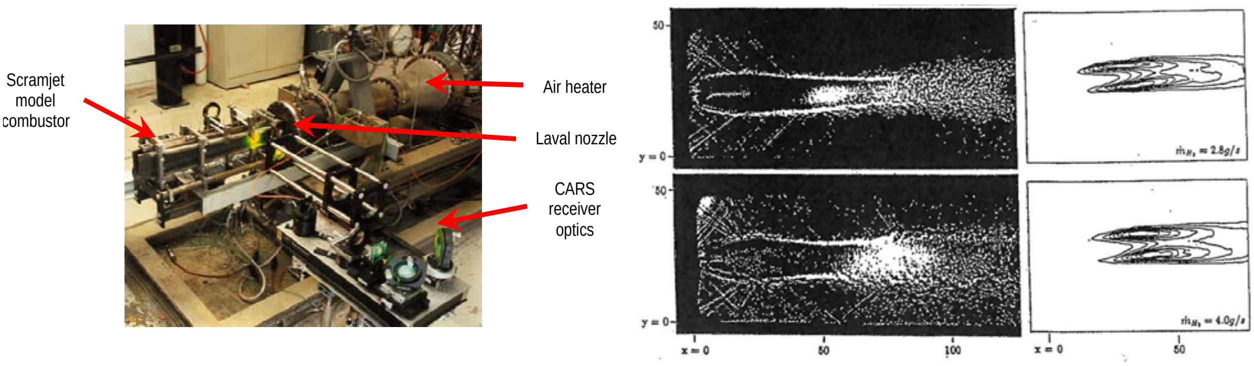

Figure 5: Left: Temperature measurements with CARS in a scramjet model combustor.
Right: Shadowgraph images and spontaneous OH emissions at different air mass flow rates [15].

In the 90s and to a minor degree still in the first years of the first decade of the 21st century detailed research activities on H_2 fueled ramjet and scramjet but also SFRJ combustor processes were conducted. The focus of the scramjet activities was on investigations on reaction processes in supersonic flows, see e.g. Refs. [15, 16, 18], compressible mixing layers (e.g. [19]), and the working behavior of different injector types. Several gaseous hydrogen fueled wall injector types but also strut injector types were investigated in the first half of the 90s accompanying the German hypersonic technology program and the Sänger concept project.

In the second half of this first decade the scramjet activities were focused on the German/French DLR-ONERA-project JAPHAR [20] and later on in the LAPCAT project, which was funded by the European Community. The R&D work in both projects aimed on the development of generic supersonic planes with scramjet engines. The conducted studies have shown that wedge-shaped strut injectors with plane contours have insufficient mixing and combustion behavior with the supersonic air flow within the limited length of a typical combustor. Strategies to enhance the mixing behavior like the production of axial vortices were investigated. The influence of the outer shape of the strut injectors on the mixing behavior and the pressure increase along the combustor length was investigated amongst others. Figure 6 shows the sketch of one of the used model combustors with optical access for diagnostics on the sides and Figure 7 presents two of the investigated injectors. Detailed information on this and other investigations as for example flow pattern, combustion behavior, distributions of temperature, pressure and intermediate stable reaction products have been presented in various papers, e.g. [15, 18-26].

Within the scope of research on SFRJ detailed investigations were conducted concerning the use of distinct metal particle additives. These metals have a higher volumetric heat of combustion as hydrocarbon based solid fuels in which they are embedded and offering thus theoretically better performance characteristics. Boron was of special interest because it has the highest value after the extremely toxic beryllium. A planar step combustor, which can be seen in Fig. 8, was used for obtaining a better understanding of the occurring multi-phase combustion processes

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above the surface of the solid fuels. This basic experimental setup allows the access of optical diagnostic tools to the combustion process above the plane solid fuel slab. The slab is positioned behind a rearward facing step which acts as flame holder. Temperatures and air velocities upstream the step were relevant for SFRJ applications.

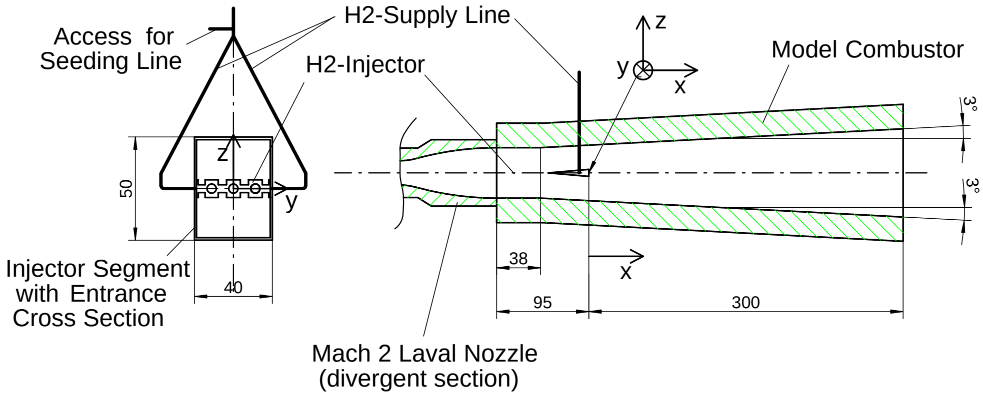

Figure 6: Modular scramjet model combustor with exchangeable strut injectors [18].

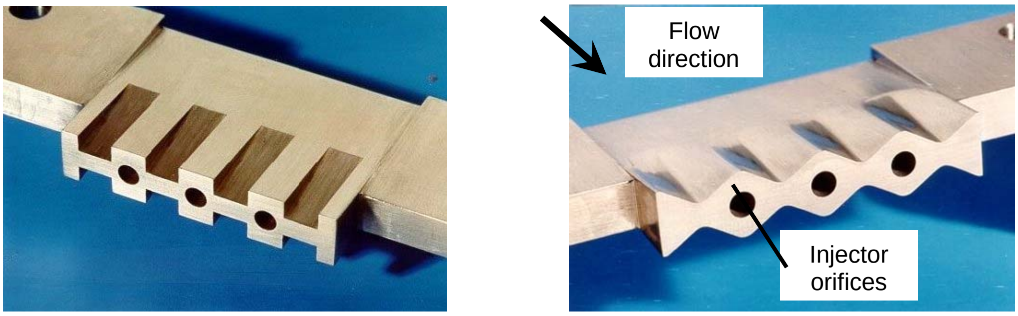

Figure 7: Investigated swept strut injectors. Left: USCER injector. Right: WAVE injector. [18].

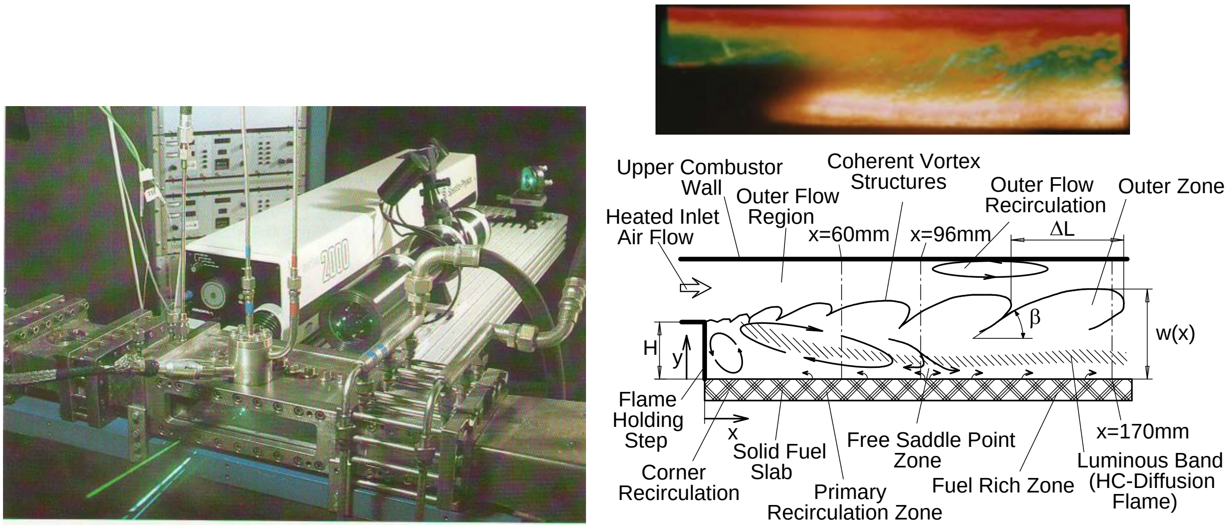

Figure 8: Planar step combustor. Left: Determination of velocity distributions with LDV [27]. Right: Color Schlieren image (top) and sketch with main features of the flow and combustion process above the solid fuel slab [17].

This experimental setup has jet been used in the second half of the 80s, where the solid fuel slabs were replaced by a sinter metal plate through which gaseous fuel was introduced into the planar step combustor [27]. The left image of Fig. 8 shows the experimental setup at that time, where a LDV was used for the determination of velocity profiles inside the combustor.

The use of various intrusive and non-intrusive diagnostic methods led to a significantly better understanding of the highly turbulent multi-phase flow and combustion process above solid fuel slabs with and without metal particle additives. Distributions of velocities, gas temperatures and concentrations of stable intermediate reaction products could be obtained. They were used to describe the movement of the gas phase and of the reacting particle phase in the recirculation zone behind the step and the downstream following boundary layer with the embedded reaction zone. Especially for boron particles detailed investigation were conducted. Large scale coherent structures could be observed as can be seen on the color Schlieren image on the right side of Fig. 8. These structures exist especially in the region above the diffusion flame, which is embedded in the reacting boundary layer, and show the intensive mixing process. This could also be confirmed by the bimodal gas phase temperature distributions obtained from CARS measurements. For detailed information on this working area, see Refs. [17, 28-30].

2.3 Phase III: Propulsion for thrust vector management

Beside the classical demands for the development of future propulsion systems like increase of velocity, thrust, specific impulse, flight distances or efficiency in combination with the reduction of the engine size and the costs, new demands are coming more and more into focus, which have been rated as secondary up to now. To these secondary demands belong safety, environmental friendliness and thrust on demand capability up to a complete thrust management.

Gel propellants or rather gel fuels and gel oxidizers offer the possibility to combine a thrust magnitude variation capability on demand with simple handling and storage characteristics but also reduced hazard potential for environment and persons. A detailed description about advantages as well as safety and environmental aspects is given in Refs. [31, 32].

Investigations on thrust vector (direction) variation by injection of reactive and non-reactive gases in a planar thrust nozzle with plane side windows at M11.3 were yet started prior to phase III [33]. During phase III the focus of R&D work related to thrust vector direction shifted to investigations on the applicability of ceramic materials and structures for jet vanes and thrust nozzles.

Since 1999 R&D work on gel rockets and gel ramjets is conducted at the M11 test complex. Since 2001 the gel activities are also part of the German Gel Propulsion Technology (GGPT) working group, see e.g. [34]. The close collaboration of industry, research organizations and governmental offices (Bayern-Chemie, DLR Institute of Space Propulsion, Fraunhofer Institute of Chemical Technology (ICT), WTD91, and the Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support (BAAINBw, formerly BWB)) led to a successful development of gel propulsion technology. This close collaboration continues also in phase IV.

The work on gel propulsion in phase III was conducted at three test positions. At M11.2 investigations on the spray behavior were conducted under ambient pressure conditions. The left two images of Fig. 9 show typical shadowgraph images from two sides of the spray behavior with a like on like impinging jet injector. These short exposure images were obtained at mean jet exit velocities and mean generalized Reynolds numbers.

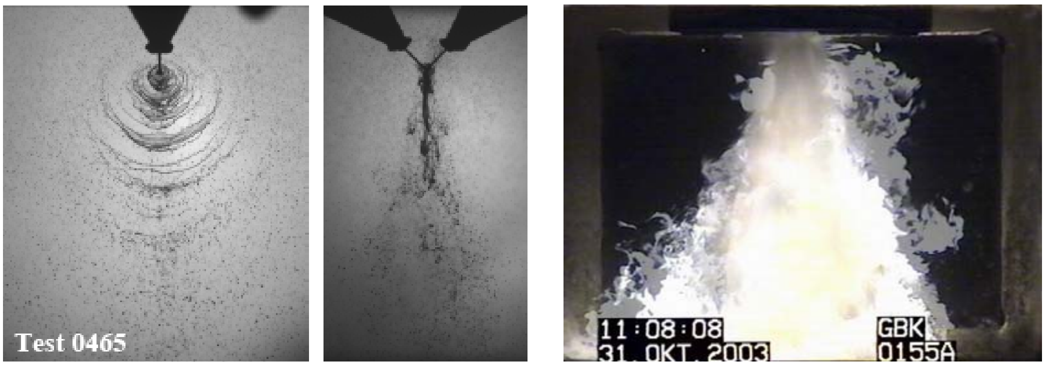

Figure 9: Left: shadowgraph images obtained from 2 sides of the spray behavior of a kerosene/Thixatrol gel with an impinging jet injector. $\bar{u}$= 12 m/s, $Re_{\mathrm{gen,HBE}}$ = 1335 [35].
Right: Burning gel spray in pressurized chamber under ramjet relevant boundary conditions [36].

Spray, ignition and combustion tests up to ramjet relevant boundary conditions concerning air inlet temperatures and combustor pressures were conducted at M11.3. The right image of Fig. 9 presents a view through one of the windows and shows the combustion of gelled JetA-1 sprayed with an impinging jet injector. The work on rocket combustor process development was conducted with the model combustor of the technology demonstrator TD-B at M11.4. The left image of Fig. 10 was obtained during a test run. The thrust magnitude variation capability of a gel propulsion

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system could be demonstrated the first time in Germany in 2005 at this facility. Furthermore detailed rheological investigations were conducted at the physico-chemistry laboratory, which served as base for analytical and numerical investigations on the flow behavior of gel propellants. For further information about the work in phase III, see Refs. [31, 34-46].

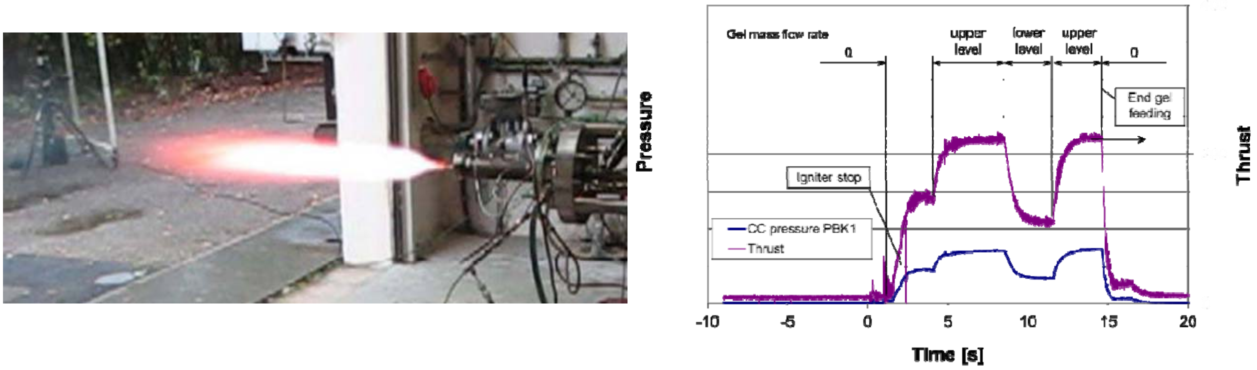

Figure 10: German gel propulsion technology demonstrator TD-B. Left: Test run. Right: combustor pressure and thrust histories [36].

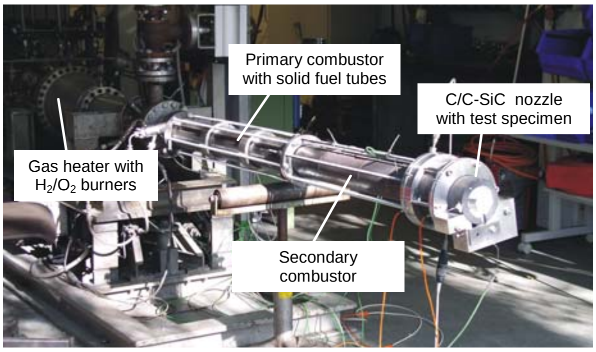

Figure 11: HotGaF facility at M11.1 with C/C-SiC nozzle and holder for C/C-SiC material probes [47].

The combustor process of solid propellants with high metal particle loadings leads to significant erosion effects on thrust chamber nozzles and jet vanes of rocket and ramjet propulsion systems. An experimental setup was realized at M11.1, which produces a highly particle and droplet laden multiphase jet wash with temperature and area specific impulse densities similar to distinct small solid rocket motors with high solid particle loadings. Aim of these investigations was on the one hand to show the influence of the condensed phase (Al_2O_3, Al, etc.) within the jet wash on the abrasion of jet vanes and material probes and on the other hand to offer an experimental setup of the development of advanced materials and structures with reduced abrasion for thrust chambers.

The hot abrasive jet wash was produced by the combustion of Al particle containing solid fuels within an oxygen enriched hot gas flow which was produced with a modified air heater at M11.1. The experimental setup allowed the free variation of the test time in which the abrasive jet wash attacked the probes. A quick by-pass valve upstream the combustor allows a very quick combustor pressure decrease at previously selected times and thus a quick stop of a test run. This allows the determination of histories of the abrasive process.

Figure 11 shows the abrasive hot gas facility (HotGaF) with a material probe positioned within the thrust chamber. The material probes and the jet vanes were made of C/C-SiC ceramics and were developed and manufactured at the DLR Institute of structures and Design. Chlorine containing additives for the simulation of HCl were not used in these experiments. For further information, see Ref. [47].

2.4 Phase IV: Propulsion systems with advanced green propellants

For the reduction of health and environmental risks the REACH regulation was implemented in Europe by the European Community. This affects also more and more the space and the defense sectors. Hydrazine, which is the most important propellant for satellite reaction control systems, is listed on the REACH list of substances of very high concern (SVHC) since 2011 because of its significant toxicity and carcinogenicity. Thus it must be expected that its use may significantly be reduced in future. Other propellants and for them relevant ingredients get meanwhile also more and more into the focus of REACH as for example the hydrazine derivate MMH, dinitrogen tetroxide N_2O_4 and ammonium perchlorate (AP). This increased safety and environmental awareness and the extension of mission ranges and boundary conditions demand the intense search for alternative green propellants, which should additionally have better performance characteristics. This task is very extensive and complex. It contains detailed investigations of various properties and at least the qualification of suitable propellant candidates with regard to their applicability in future propulsion systems. Especially against the background of the current and the expected future ratings with respect to REACH, actions have urgently to be taken.

Research and technology development work on advanced green propellants based on energetic ionic liquids (EILs) started in 2009 mainly within the scope of the EC-funded project GRASP [48]. The Institute of Space Propulsion was involved in the screening process of species, which could possibly be used as green propellants. Furthermore model thruster and durability tests were conducted with the ammonium dinitramide (ADN) based EIL FLP-106. Within the years various other interesting propellant candidates were tested. To these belong e.g. other EILs and nitrous oxide based monopropellant mixtures with hydrocarbons. The work on gel and hybrid rockets is also focused on the use of green propellants [31, 32]. Detailed information to the current working areas at M11 test complex and the physico-chemistry laboratory will be given in chapter 4.

3. Overview M11 test complex

The M11 test complex consist of 4 test positions M11.1 - M11.4 in two test cells and the research and student test field M11.5. Each test position is equipped with up-to-date remote control and measuring systems to enable complex investigations on flow, ignition and combustion processes. The 200 bar gas supply system for H_2, O_2, N_2 and air offers a high flexibility for the test campaigns. Each test position offers a specific combination of test conditions together with high flexibility.

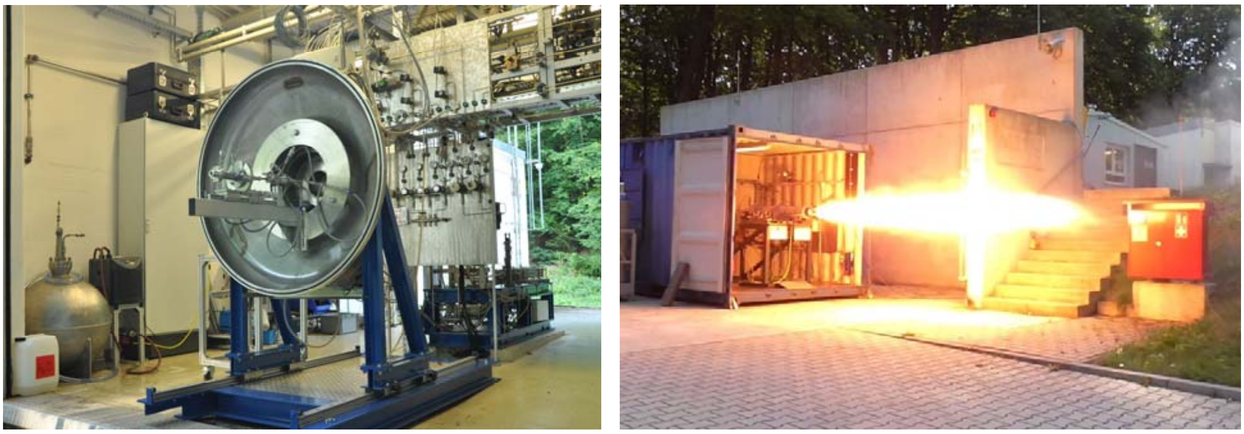

Figure 12: Left: Front cover of vacuum chamber with model thruster at M11.2. Right: Test run of HyEnD hybrid rocket engine at M11.5.

Test position M11.1 is equipped with an air heater for the simulation of ram-/scramjet combustor entrance conditions. The air heater in its current version is able to deliver up to 5 kg/s hot (vitiated) air at up to 1500 K total temperature and 25 bar total pressure. Scramjet combustor processes with a transpiration cooled wall structure are currently investigated.

A vacuum chamber is available at test position M11.2 for investigation of injection processes of advanced propellants for satellite propulsion systems and hazard-free simulation fluids. Very intense and quick vaporization processes (flash vaporization) occur under vacuum-near chamber conditions leading to a spray behavior different to them at ambient and higher pressures. Furthermore a large vacuum chamber is available for ignition and run tests of model thrusters with advanced propellants on thrust levels relevant for satellite applications. An ejector system will come soon into service for long duration testing of thrusters under vacuum-near conditions. The left image of Fig. 12 shows the front cover of the large vacuum chamber with the thrust balance and a model combustor.

The combustion behavior of fuel/oxidizer combinations for hybrid rockets is under investigation at M11.3. Various solid propellants are burned with gaseous oxygen. In 2010 work on hybrid rockets was restarted at Lampoldshausen at this test position. For the investigations the previously described planer step combustor is used here in a modified version [49]. The optical access via large windows at both sides of the chamber offers the use of high-speed cameras for the observation of the combustion and ignition processes. A further small model combustor for cylindrical fuel grains allows investigations of combustor processes under boundary conditions closer to reality.

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Combustor process investigations with gel propellants are conducted at M11.4. Two propellant feeding devices allow mono- as well as bipropellant combustor tests. At this test position investigations on reduction of combustor sizes, influence of additives, and ignition and combustion properties are conducted.

The research and student test field M11.5 was erected in 2013 and hosts two test containers for small and medium size rocket engines and model combustors. This test field is available for student groups especially for them which are funded by the DLR Space Management within the STERN program, see e.g. [51]. The HyEnD student group of the University of Stuttgart developed a hybrid rocket and tested their 10 kN engine at this test field [51] prior to their world record flight (> 32 km altitude) at ESRANGE near Kiruna in the north of Sweden, see e.g. [52-54]. The right image of Fig. 12 shows a typical test run of their rocket engine. Furthermore a test container of the Institute of Space Propulsion is positioned. In this container new green propellants for satellite applications are tested in model combustors.

At the physico chemistry laboratory advanced propellants are developed and pre-qualified. The laboratory offers furthermore support in research and chemical analysis for other departments of the institute and external customers. The laboratory complex consists of four laboratory rooms in the M3 building and a remote controlled research-scale propellant production facility in G49, which is located next to M11. Beside state-of-the-art analytical apparatuses and a wide-ranging know-how in handling of energetic materials, the available infrastructure allows the handling of propellants which are subject to the German explosive law.

The diagnostic possibilities cover wet chemistry and instrumental analytics for the investigation of gaseous, liquid, gelled and solid probes by spectroscopic and chromatographic diagnostic tools up to the determination of physical and chemical parameters of low and high viscous fluids. The spectroscopic methods allow structure determination, proof of identity, and quantitative determination of gaseous, liquid and solid substances as well as trace analysis of a large number of elements and molecules.

The infrastructure of the two fuel and oxidizer laboratory rooms allows the safe handling of storable propellants like hydrazine, NTO, hydrogen peroxide, etc. The infrastructure is also suitable for investigations on material compatibilities [56], ignition behavior of hypergolic propellant combinations and determination of material properties.

4. Current working areas

4.1 Gel propulsion

Gel propulsion systems combine (as jet mentioned in chapter 2.3) essential advantages of liquid propulsion systems like throttleability, engine shut-down and re-ignition with the simple handling and storage characteristics of solid propellants. Because of this advantage combination gel propulsion systems are attractive for many application fields like sounding rockets and stages with thrust variation and termination capabilities, highly agile missiles, lander propulsion systems, ramjets and reaction control systems. The in Germany developed gel propellant family has additionally distinct advantages concerning safety features and environmental aspects [31, 32, 56].

Gels are shear-thinning non-Newtonian fluids. During the gelation process the gelling agent forms a three-dimensional network in which the propellant, or a fuel or an oxidizer, is embedded. At rest a gel behaves like an elastic solid. Under a sufficiently high applied shear stress the gel structure starts to get destroyed and the sheared gel gets flowable. Because of this this flowability the flow rate of gels to a combustor and thus the thrust of a gel engine can be varied.

At test position M11.4 the combustor processes with environmentally friendly propellant gels with good combustion and performance properties are investigated [57]. Current aim of this work is to get a better understanding of combustor, injector and feeding processes, which shall serve as base for a reliable design and development of future gel propulsion systems with high performance characteristics and stable combustion processes. This work is embedded in the activities within the German Gel Propulsion Technology (GGPT) working group [58-60].

For the development of gel propulsion systems a detailed knowledge on the non-Newtonian physical and rheological gel properties and their flow behavior is mandatory. The occurring effects are manifold and demand extensive investigations. The flow behavior of gels for example shows distinct differences to Newtonian fluids. An experimental setup for the investigation of the flow behavior and pressure losses in dependence upon rheological thixotropic and thus time-dependent, shear-thinning and geometrical properties will get into service soon.

Investigations on the spray behavior have shown that with increasing jet velocities sufficiently small droplets can be produced; see e.g. the leftmost shadowgraph image of Fig 13. The atomization of gel propellants to sufficiently small droplets with a large total surface is necessary for the realization of compact combustors. Unfortunately not all propellant gels can be atomized to small droplets. Thread-like structures are formed instead as can be seen on the second shadowgraph image in Fig. 13. Detailed investigations have shown that this behavior can be related to visco-elastic effects in the gel structure [61].

For the determination of the influence of the combustor size on the combustion behavior, detailed investigations with modular combustion chambers of different lengths and diameters are conducted. Aim is to provide a basis for the determination of optimized combustor geometries with good combustion efficiencies and stable combustion [62, 63]. A model combustor with optical access for detailed investigation on the combustor processes was realized [64]. The right image of Fig. 13 was obtained during a test run.

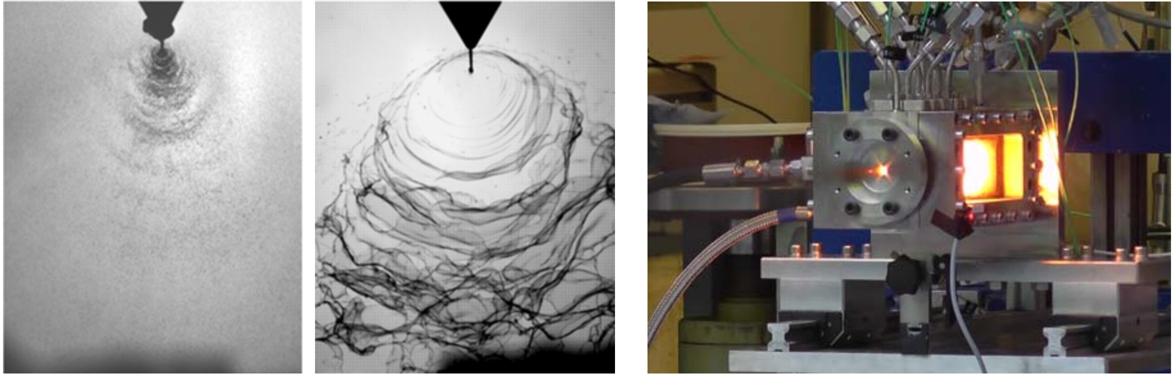

Figure 13: Left: Two shadowgraph images of the spray behavior of different gels with production of droplets (left) and threads (right). Right: Test run of a model combustor with optical access at M11.4.

4.2 Propulsion systems for orbital applications

Detailed investigations are ongoing at the M11 test complex to identify and test suitable advanced green propellant candidates, which might be able to replace the highly toxic hydrazine and in future also its derivates in reaction control systems of satellites and upper stages. To this task belongs the development of stable combustion and ignition processes. As promising candidates are currently investigated at M11 energetic ionic liquids (EILs) based on ADN and ethane / nitrous oxide mixtures (HyNOx: hydrocarbons mixed with nitrous oxide). ADN-based EILs have higher densities and higher specific impulses in comparison to hydrazine. HyNOx is attractive because of its very high specific impulse.

Figure 14: Left: Shadowgraph image of flash vaporization. Right: HyNOx model combustor at M11.5.

The novel ADN-based green propellants demand for the characterization with regard to their possible applicability extensive and detailed investigations of various aspects [65]. To this belongs amongst others the investigation of the spontaneous vaporization if fluids (flash vaporization), which are introduced very quickly into vacuum near conditions during the injection process. In the focus of this work are flash vaporization behavior of solutions of ADN in water and their possible crystallization behavior, see e.g. the left image of Fig. 14. Current investigations are conducted with urea / water solutions as non-energetic and simple handling substituent. Transparent injectors of PMMA with different geometries are used. They allow the visualization of the processes inside the bore hole like cavitation, etc. This offers the possibility to investigate the influence of processes inside the injector bore on the external spray characteristics.

The work on ignition and combustion of ADN-based propellants is conducted in the frame of the EC Horizon2020 funded project Rheform. These propellants are typically ignited by a heated catalyst bed. Aim of the current work is to find suitable alternative ignition methods, which are advantageous especially for larger engines. Currently are tested a torch igniter and a laser-based igniter. Droplets of ADN-based gels are introduced to an acoustic levitator

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and ignited by a Nd:YAG pulse laser. The laser pulse atomized the droplet but a sufficiently strong ignition could not be observed. The ignition tests with the torch igniter have partly been successful. An optimization of the heat transfer from the igniter to the propellant, especially at higher propellant mass flow rates, is necessary. For futher information see e.g. [66].

The research activities on ethane / nitrous oxide mixtures are conducted within the frame of the DLR strategy project FutureFuels. Various injector modules were tested with regard to the safe introduction of the propellant into the combustor. Focus of this work is to prevent flame flashback by porous materials, which can be combined with injector elements. Furthermore a detailed investigation was conducted for the determination of the characteristic velocity c^* within the model combustor [67].

Parallel to the hot gas tests detailed investigations were conducted with porous materials in a separate experimental setup. Two different materials with different pore sizes and different lengths were tested. Five different gases and various pre-pressures were used for the through-flow testing. Furthermore work for the determination of heat transfers was conducted, also numerical calculations of combustor processes making use of a kinetic model developed within the FutureFuels project by another institute. For further information, see e.g. [68].

4.3 Hybrid rocket propulsion

Hybrid rockets are advantageous because of their simple handling and safety characteristics in comparison to other propulsion system types. The inherent safety caused by the separation of fuel and oxidizer and their different aggregate state offers the possibility to use this propulsion system for educational purposes with students but also for space tourism as for example SpaceShipOne and Two. The focus of the basic research activities at M11 is the increase of combustion efficiency and of regression rates but also on the analysis of combustion instabilities. The experimental setup for these investigations is the modified planar step combustor (left image of Fig. 15), which was used previously for other investigations. The right image was obtained from a high speed video of a test run and shows the combustion process of a paraffin-based fuel with gaseous oxygen. Typical for this advanced fuel type is the liquefaction of the fuel surface so that droplets are sheared off, which leads to the increased regression rates [49, 50, 69]. Beside different fuels also different oxidizers like oxygen and nitrous oxide are in the focus of investigations. Important international collaborations on distinct research themes exist.

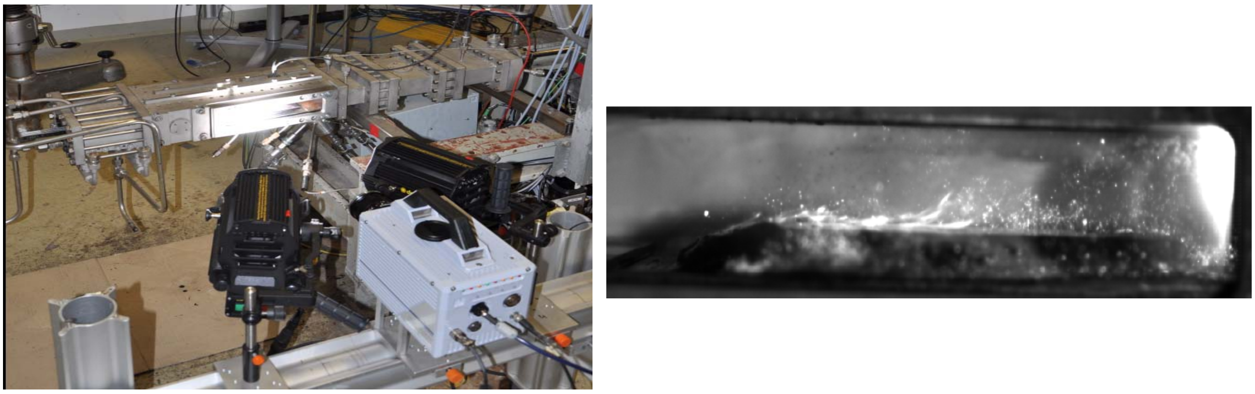

Figure 15: Left: Experimental setup with optical access at M11.3. Right: Combustion process above a solid fuel slab.

4.4 Scramjet propulsion

The applicability of transpiration cooling systems to scramjet propulsion systems is investigated at test position M11.1. The high thermal loads on combustor walls (up to 5 MW/m² and wall temperatures in the range of 3000 K for Mach 8, see e.g. [70]) are one of the major challenges for the realization of scramjet engines. A promising and interesting method for the reduction of thermal loads of wall structures could be transpiration cooling. A cooling fluid (in our case gaseous hydrogen which is as fuel onboard) is pushed through porous wall segments and reduces thus the heat flux to the wall by the production of a cooler protection flow immediately above the wall. Up to now the understanding of the occurring phenomena from the interaction of the reacting H_2 wall protection flow with shocks within the main flow, produced e.g. by flame holders or injector struts, is rudimentary up to now.

An experimental setup with a rectangular cross section and windows on the side walls for optical access was realized and can be seen on the left image of Fig. 15. A wedge shaped shock generator is positioned in the center region of the chamber and is movable in vertical and horizontal directions. This allows the movement of the shock system and thus a variation of the interaction line with the boundary layer. For further information, see e.g. [71, 72].

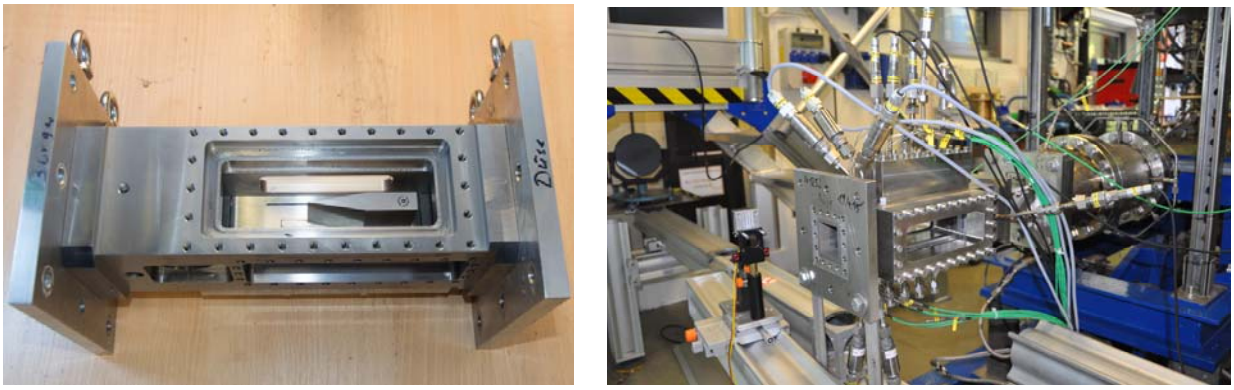

Figure 16: Scramjet model combustor for the investigation of transpiration cooling processes. Left: combustor without windows. Right: Experimental setup with combustor at M11.1.

5. Conclusions and outlook

Within the 50 years of the existence of the M11 test complex extensive research and technology development activities were conducted. Detailed findings in the fields of flow, spray, ignition and combustion processes in model combustors and experimental setups could be obtained. Rheological, physical and chemical properties of a large variety of propellants, especially of gel propellants and hybrid fuels could be determined. Different intrusive and non-intrusive diagnostic tools could be adapted to the harsh environment in the test cells and could be used in various test campaigns. The obtained results are presented in a large number publications and reports.

The main working areas at the M11 changed in the course of time. At the beginning in the 60s of the last century hybrid rockets were investigated, followed by ramjets/scramjets, propulsion systems with thrust variation capability, and currently propulsion systems with advanced green propellants. The development of suitable advanced green propellants and propulsion systems with better performance characteristics as currently used systems gets more and more important. The M11 test complex is excellently suitable for this task so that also in future interesting results and contributions for the development of future green rocket and ramjet propulsion systems can be expected.

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Nomenclature

H	flight attitude, m
Ma	Mach number, -
Ma_e	combustor entrance Mach number, -
Ma_∞	flight Mach number of air flow, -
Re	Reynolds number, -
p_t	air total pressure, bar
T_t	air total temperature, K
$\bar{u}$	average jet exit velocity, m/s
We	Weber number, -

Subscripts and abbreviations

ADN	Ammonium dinitramide
AP	ammonium perchlorate
EIL	energetic ionic liquid
R&D	research and technology development
FLOX	mixture of liquid oxygen + liquid fluorine
gen	generalized
HBE	Herschel-Bulkley Extended
HTPB	hydroxyl terminated polybutadiene
LOX	liquid oxygen
SFRJ	solid fuel ramjet
SVHC	substance(s) of very high concern
2	static condition at combustor entrance

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