The M11 Test Complex at DLR in Lampoldshausen

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Abstract
The M11 test complex of the DLR Institute of Space Propulsion is used since 43 years for basic research and combustor process relevant technology development activities for various propulsion systems and components. Hybrid rockets, solid fuel ramjets and hydrogen fueled ramjets and scramjets were the main working areas in the past. Today the work is mainly focused on research for gel propulsion systems. The present publication gives a brief overview about these and other activities.

1. Introduction

The history of the M11 test complex began in the 60s of the 20th century. A laboratory building named M11 was erected in 1966 at the Lampoldshausen test site of the DVL, which is today part of the German Aerospace Center DLR, with offices, laboratory rooms, two test cells and a control room. Within the years the building was several times enlarged to serve for the different research tasks, which changed and grew with the years. In the year 1992 the chemical and physical laboratories and the major part of the offices were shifted to the M3 building due to the increasing activities within the scope of the Vulcain engine test activities at the P5 test facility nearby. Today are available at the M11 four test positions, which are described later with more detail, control rooms, diagnostic rooms, some offices, a small machine shop, and a gel fuel production facility. The close collaboration with the chemical laboratories at the M3 building is today still given due to common research tasks.

Figure 1: Left: Photography from the erection of the M11 test complex in October 1966.
Right: Actual view of the test cell area of the M11 test complex.

The present paper gives a short overview about the research activities, which were both conducted in the past and which are ongoing today in the test cells at the M11 test complex. The presentation includes information about the facility and some experimental setups. Due to limited space this overview can show only some activities briefly as examples. References, if available and citable, are given additionally for readers, which are interested in more detailed information.

2. 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 combinations like solid polyethylene and FLOX (i.e. liquid oxygen mixed with liquid fluorine), FLOX with HTPB with and without embedded aluminium particles, FLOX and LOX with polyethylene but also solid lithium hydride and liquid fluorine were investigated. Most of the used propellant combinations and components were developed, produced or modified in the chemical laboratory of the M11. In the mid 70s also work on solid fuel ramjet (SFRJ) propulsion started. The use of "metal" particle loadings of solid fuels both for hybrids and for SFRJ was also scope of the research activities. Detailed investigations with aluminium, magnesia, silicium and boron as high energetic additives were conducted. Within the scope of SFRJ research e.g. detailed measurements of temperature and concentration distributions inside combustors were conducted. For further information please see e.g. Refs. [1-10].

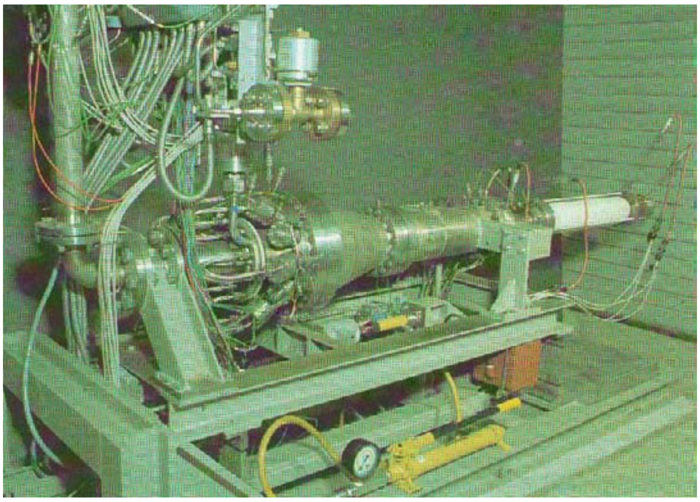


Figure 2: Test facility for solid fuel ramjet investigations at the end of the 80ies [6].

3. The mid term - Research on ramjet propulsion

3.1 Technical equipment

In the second half of the 80s in 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 ramjet) propulsion systems was started. For these activities further and advanced air heaters were build within the years so that 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 and 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 simulating flight conditions up to Mach numbers of ca. 5.8 at higher 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 the 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.

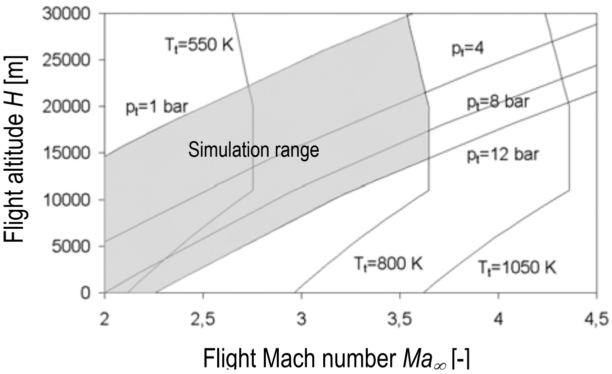


Figure 3: Simulation range of M11.3 for (subsonic) ramjet combustor process research.

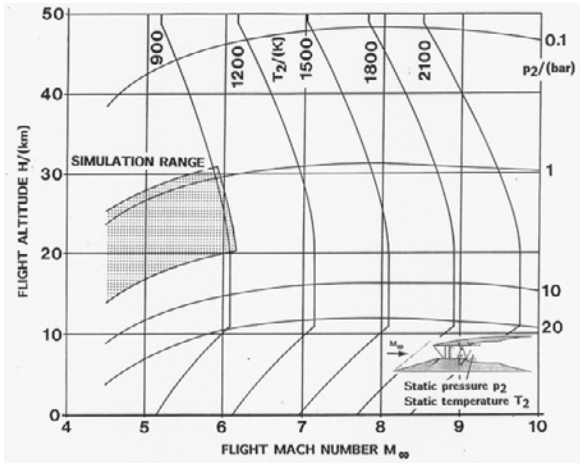


Figure 4: Simulation range of M11.4 and M11.1 for scramjet combustor process research with a combustor entrance Mach number $Ma_e = 2.0$.

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. Figure 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 temperatures inside the chamber in this experiment. 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 SFRJ and hydrogen fueled ramjet and scramjet model combustion chambers 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. Some of the used techniques were e.g. Particle Image Velocimetry (PIV), Laser-Induced Florescence (PLIF), video imaging of OH-(spectroscopic)emission, sampling and pneumatic probe techniques, coherent anti-Stokes scattering (CARS), black-and-white as well as Color Schlieren together with conventional and high speed camera systems, shadowgraphy, Mie scattering techniques, pyrometry, flame spectroscopy, etc. For further information please see e.g. Refs. [11, 12].

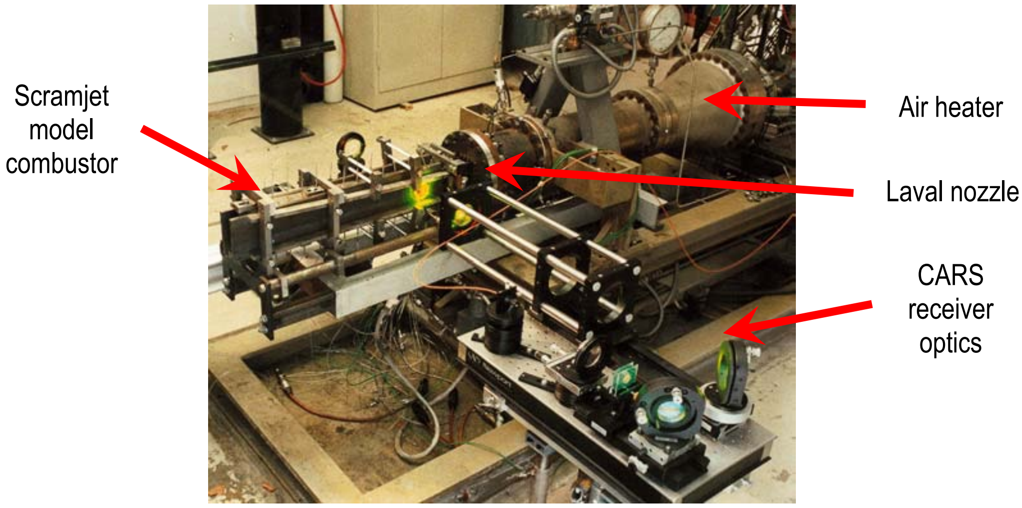


Figure 5: Non-intrusive temperature measurements with CARS inside a scramjet model combustor at M11.4 test position.

3.2 Research activities

In the 90s of the last and in the first decade of the actual century extensive research activities were conducted concerning the use of hydrogen as fuel for ramjet and scramjet propulsion systems. The focus of the M11 scramjet related research activities was on detailed studies on supersonic flame characteristics, compressible mixing layers, mixing enhancement, and injector performances. Several hydrogen injector concepts (strut injection and wall injection) were investigated in detail in relation to the German hypersonic technology program in the first part of the 90s. In the second half of the 90s the activities were mainly focused in the joint DLR-ONERA program JAPHAR [13] and later on in the actual century in the LAPCAT program, which was funded by the European Community. In both programs research activities are conducted in relation to the development of future generic scramjet flight vehicles.

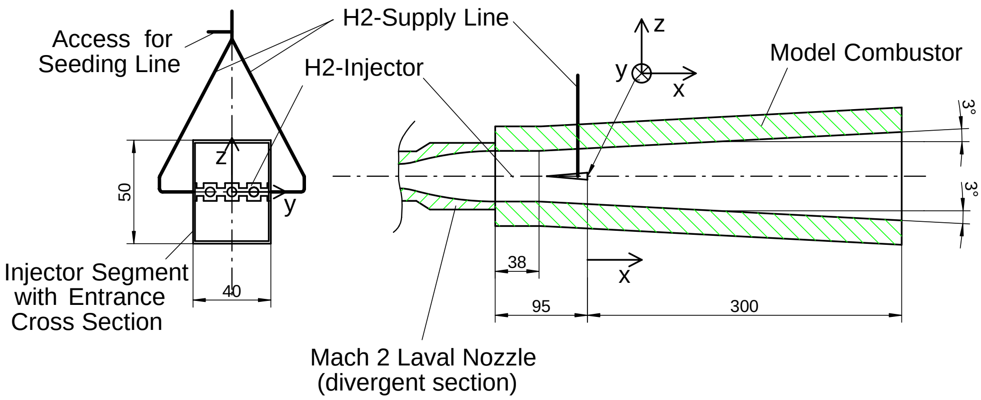


Figure 6: Scramjet model combustion chamber with installed injector. [14]

Detailed studies on supersonic flame characteristics, compressible mixing layers and injector performances were conducted. Due to the fact that the compressible mixing layers of plane strut injectors didn't show the sufficient mixing behavior of the injected fuel with the hot supersonic air flow within the limited length of a scramjet combustor, new strategies for mixing enhancement, e.g. by the introduction of axial vortices, were investigated. One of the tasks was to show the influence of the outer shape of two different injectors on the combustion chamber flow with respect to mixing enhancement and pressure increase by combustion heat release [14]. Figures 6 and 7 show the sketch a modular scramjet model combustor and photographs of two investigated injectors. Further detailed information about this and other at M11 conducted investigations together with obtained results concerning e.g. flow field and partly also temperatures and concentration of various stable reaction (intermediate) products, etc. is given in various publications, see e.g. Refs. [11, 14-21].

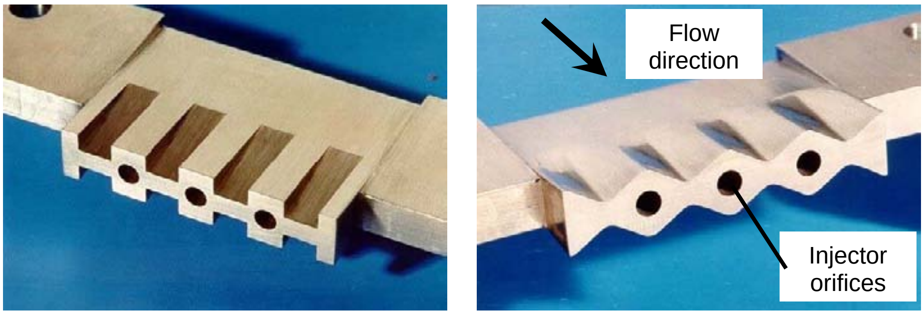


Figure 7: Studied hydrogen injectors; left: USCER injector; right: WAVE injector [14].

In the scope of solid fuel ramjet propulsion the use of metal particle additives, which have significantly higher volumetric energy contents like commonly used hydrocarbon based fuels, was investigated with the aim of increasing flight performances. For getting a better understanding of the multiphase combustion process above the solid fuel surface, a planar rearward-facing step combustor was used as the basic experimental set-up, with which investigations could be conducted under conditions of air inlet velocity and temperature relevant to ramjet applications. This facility was already used in the second half of the 80s, whereas the burning solid fuel was simulated by a flow of gaseous fuel through a sinter metal plate; see e.g. Ref. [22]. Figure 8 shows an image of the step combustor and a Laser Doppler Velocimetry (LDV) setup for the determination of velocity profiles.

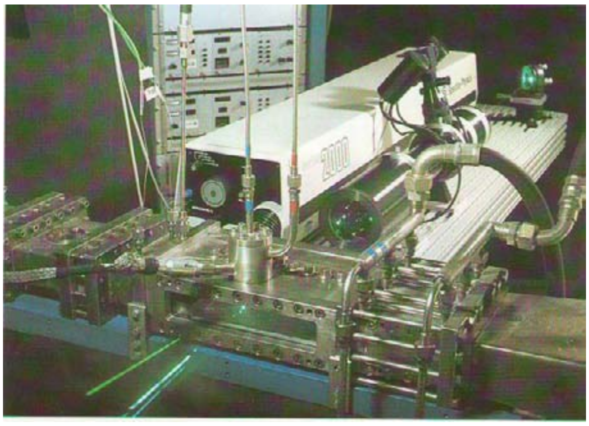


Fig. 8: Planar step combustor with Laser Doppler Velocimetry setup for the determination of velocity profiles [22].

In the 90s the use of various diagnostic tools gave a new insight in the combustion processes of solid fuel slabs with and without boron particle addition inside the planar step combustor. The highly turbulent, multi-phase combustion process was analyzed with various intrusive and non-intrusive diagnostic techniques. Gas phase temperature distributions and particle velocities as well as concentrations of various stable reaction products were determined in order to show the movement and the combustion of the reacting particle phase in the recirculation zone and the downstream boundary layer with the embedded reaction zone. Large scale, coherent vortex structures have been observed as can be seen on the Color Schlieren image of Fig. 9. These structures exist predominantly in the region above the hydrocarbon diffusion flame located inside the developing boundary layer and show an intense and highly turbulent mixing process. For more detailed information please see e.g. Refs. [12, 23-25].

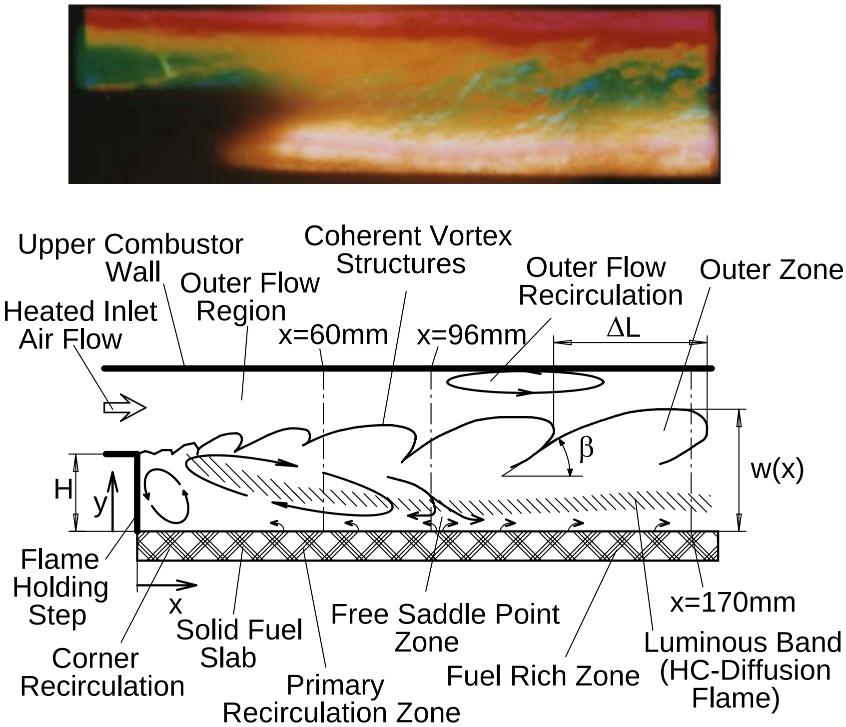
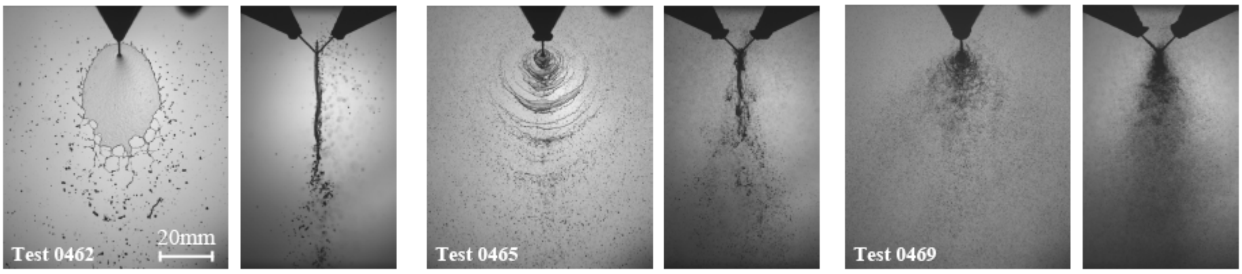


Fig. 9: Sketch and Color Schlieren image of flow field and combustion characteristics of the solid fuel combustion process inside a step combustor [12].

4. The 21st century – Thrust vector controlled propulsion

Beside the classical demands on propulsion systems like increase of velocity, thrust level, specific impulse, flight ranges and efficiency together with combustor size minimization, new aspects like safety, environmental friendly propellants and throttleability up to thrust vector control got more and more into the focus of research and development efforts in the last years. Gel fuels and propellants offer the possibility of thrust level variation as the conducted research and technology development activities show, which were started in the year 2000 at the M11 test complex. Thrust direction variation can be realized by jet vanes, which are positioned in the jet wash in or behind the expansion part of a thrust generating nozzle. Material testing for jet vane development is a further small part of the research activities at M11. It has to be mentioned in this context that in the second half of 80s and in the first half of the 90s already experimental and numerical investigations on thrust vector direction variation by secondary gas injection into the expanding part of a planar nozzle were conducted; see e.g. Ref. [26].
Gelled fuels and propellants are interesting for ramjet and rocket propulsion systems, because of their safety and performance benefits. Due to their non-Newtonian flow behavior, which can for example be seen as the shear-rate dependency of the shear viscosity, they offer the possibility to build engines, which both can be throttled similar to engines with liquid fuels and which have similar simple handling and storage characteristics like engines with solid fuels. Because gelled propellants do not behave like common liquid fuels, which are in most cases Newtonian liquids with a constant viscosity, detailed research work was

conducted and is still ongoing concerning rheology, flow and spray behavior and combustion characteristics at M11 test complex and the chemical laboratory.
Figure 10 presents as examples some relevant shadowgraph images of the spray behavior of gel fuels, whereas an impinging jet injector was used. The break-up process of gel fuels, which shows similarities to Newtonian fluids in a large range, is possible for distinct injection conditions and set-ups as detailed experiments have shown. For the characterization of the spray behavior dimensionless numbers like Reynolds and Weber numbers are necessary. Due to the fact that the viscosity is a function of the applied shear-rate the conventional Reynolds number with its constant viscosity of Newtonian fluids cannot be used. Thus detailed investigations concerning the rheological and the flow behavior had to be conducted. In the scope of the work an equation, which describes the shear-viscosity/shear-rate dependence (i.e. the Herschel-Bulkley Extended HBE equation), and a formula for a generalized Reynolds number were derived. Furthermore the transition range from laminar to turbulent flows in tubes for HBE fluids could be determined [37].



$\bar{u}$ = 5 m/s, $Re_{gen\ HBE}$ = 470 (rimless pattern) | $\bar{u}$ = 12 m/s, $Re_{gen\ HBE}$ = 1335 (Ligament structures) | $\bar{u}$ = 31 m/s, $Re_{gen\ HBE}$ = 3805 (Fully developed pattern)

Figure 10: View from two sides on the break-up process with droplet formation of a kerosene/Thixatrol gel in dependence of the generalized HBE Reynolds number $Re_{gen\ HBE}$ [37] making use of a doublet impinging jet injector.

The addition of metal particles like aluminium, magnesia or boron to gel fuels is interesting, because they offer the possibility to enhance the volumetric energy content of gel fuels without taking sedimentation effects, especially under storage conditions, into account. Detailed basic research activities concerning the investigation of spray and combustion behavior of metallized gels in relation to ramjet propulsion were conducted and are still ongoing. Furthermore investigations concerning the development of rocket combustor processes are conducted as can be seen e.g. on the image in Fig. 11. More detailed information concerning the research activities on gel propulsion and the obtained results are given in various publications, see e.g. Refs. [27-36].

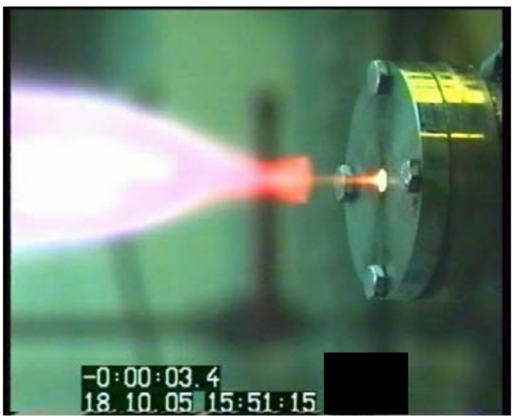


Figure 11: Test run with a rocket model combustor making use of gelled propellants

For the test of erosion and high temperature stability of different materials to withstand the highly abrasive hot jet-wash in or behind the expansion part of the thrust generating nozzle of propulsion systems, a test facility was developed and built at the M11 test complex. This facility is able to produce strongly particle and droplet laden hot gas flows with temperatures and area specific impulse densities of the condensed phase, which are similar to distinct smaller solid rocket motors with high metal particle loading of the propellant grain. The hot abrasive jet-wash is produced by the combustion of aluminium particle containing, solid fuel tubes with a preheated, oxygen enriched air in the primary and the subsequent secondary combustion chamber.
Figure 12 shows a photography of the abrasive hot gas facility (HotGaF) at M11, for which the air heater at one test position was modified. Chloric additives were not used in the experiments, because the primary goal of the conducted investigations was to show the influence of the condensed phase (Al_2O_3, Al, etc.) in the jet-wash on the abrasion of jet vane samples. These samples consist of carbon fiber reinforced C/C-SiC ceramics and are produced by the DLR Institute of Structures and Design. The heating of the oxygen enriched air is conducted by hydrogen/oxygen burners. Due to the design of the test facility similar to a connected pipe ramjet combustor test facility, the time period, in which the abrasive jet-wash attacks the sample, can be varied by the quick shut-down of the “air” heater at pre-selected times. Thus abrasion histories can be obtained with this facility. For further information please see e.g. Ref. [37].

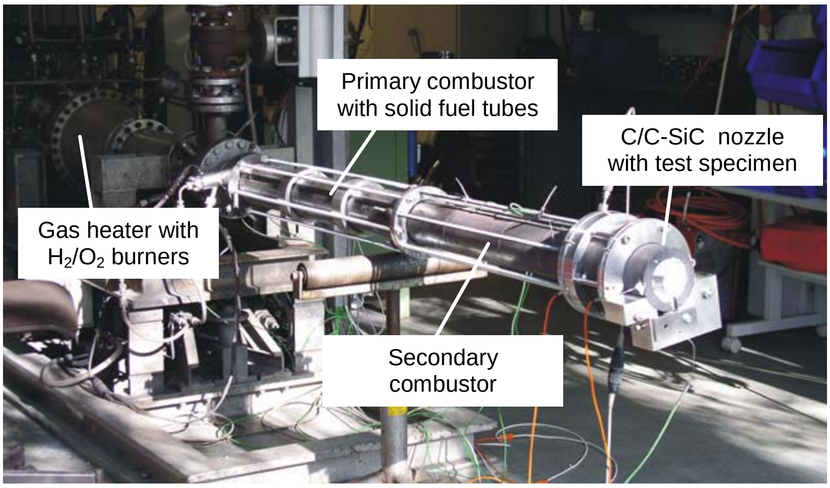


Figure 12: HotGaF facility with C/C-SiC nozzle, metallic sample fixture and C/C-SiC test specimen [37].

4. Conclusions

Within 43 years basic research and combustor process technology development activities on various propulsion systems and components were conducted at the M11 test complex at Lampoldshausen. Detailed knowledge could be obtained on governing processes in (model) combustors of the investigated systems and the use of various diagnostic tools and their adaptation to the harsh environment in test cells and model combustors. Results were presented in a large number of publications. The main working areas in the past covered hybrid rockets, solid fuel ramjets as well as hydrogen fueled ramjets and scramjets. In the scope of the research activities on ramjet and scramjet propulsion, also test benches with air heaters were developed, which are able to deliver hot air flows with partly up to 1500 K and which are still used today. At present the work at M11 is mainly focused on gel propulsion systems and a small activity on material testing for jet vanes.

Acknowledgements

The author would like to thank all colleagues and co-workers, whose work, support and help was essential for the success of the conducted research activities at the M11 test complex. This can clearly be seen by the large number of publications and internal reports, whereas in the present paper only a small number could be cited due to limited space.

Nomenclature

H	flight altitude, 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

crit	critical
FLOX	mixture of liquid oxygen + liquid fluorine
gen	generalized
HBE	Herschel-Bulkley Extended
HTPB	hydroxyl terminated polybutadiene
LOX	liquid oxygen
SFRJ	solid fuel ramjet
2	static condition at combustor entrance

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