CHALLENGES OF TEST FACILITIES FOR SPACE PROPULSION

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1. ABSTRACT

The objective to test space propulsion systems on ground conditions defines the challenges for the test facilities. The requests are triggered by the research, development, qualification and acceptance of rocket engines. Notable is the testing of rocket engines in space environmental conditions. There is an ongoing need to adapted test positions or to improve the test potentials to the actual research and developments in space propulsion, basically in thrust chamber technologies.

The paper deals with the main challenges concerning test facility engineering and operational conditions at the European test centre in Lampoldshausen and present the actual activities to prepare the facilities for future test objectives.

2. INTRODUCTION

From the beginning of the 1960s, DLR Lampoldshausen (Figure 1) has been involved in all European launcher programs. One of the tasks has been the testing of rocket engines.

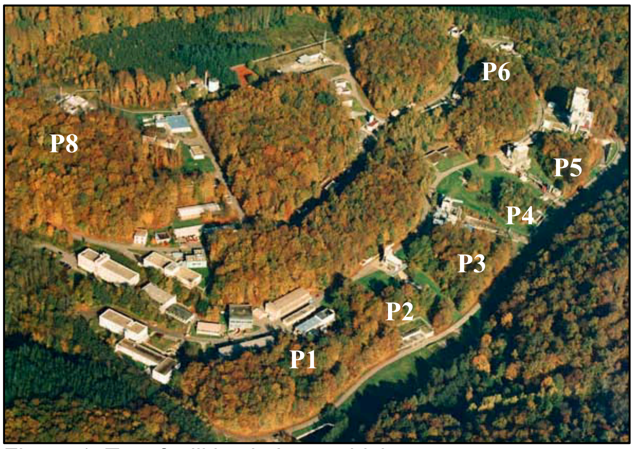

Figure 1: Test facilities in Lampoldshausen

The test facilities P1 and P2 were erected and are in operation since 1962 with adaptation to the particular test objectives. The mid-sixties were characterised by development and acceptance testing of the third stage of the ELDO launcher. The facilities P3 and P4 for high altitude testing and sea level conditions were erected.

In 1973 the ARIANE launcher programme starts. The test bench P4 was equipped for the development test of the VIKING engine under sea level condition and altitude simulation with 800 KN vacuum thrust. Following further adjustments the second stage of ARIANE 1-4 and the AR4 booster (PAL) were tested.

With the development of the ARIANE 5 the test bench P3 (1988) and P5 (1990) including storage areas were erected for the development of the VULCAIN engine. Ongoing on P5 the VULCAIN engine is tested. P4.2 was adapted to the altitude simulation of the AESTUS upper stage engine in 1992.

The research facility P8 for high pressure combustor technology was erected in 1992 and the P6.2 test bench for cold gas nozzle research under vacuum and sea level conditions started operation in 1998.

Actual the test facility P4.1 is adapted to the altitude simulation of the VINCI engine.

To meet all the challenges special experiences and competences were developed for the engineering and operation of test facilities. Notable is the altitude simulation technique for rocket engines, the exhaust gas guiding systems and the propellant feeding systems. Additional know how were required concerning measurement and diagnostics.

Unique for Lampoldshausen is the dual-use of the competences for research testing and the tests of rocket engines. Visualisation techniques and equipment for research are now shared with the facilities P4.1 VINCI tests and P5 VULCAIN II tests.

The Engineering of the space propulsion institute in Lampoldshausen has started to develop the necessary technologies for future testing. Notable are the further development of the altitude simulation and investigations for methane testing. Future activities are intended concerning exhaust gas guiding systems and noise reduction.

3. TEST BENCH SPECIFICATIONS

The test bench specification and test objectives by the customer or the scientist define the technical systems and lay out of the test facility. Specifications are concerning

- General Specifications like general test operation, design rules, etc.
- Test hardware (Engine, passenger tests, flight hardware, etc.)
- Interface specifications for test specimen (Functional, mechanical, electrical, environmental, etc.)
- Operational specifications (schedule, safety, quality and cleanliness, access, tools, etc.)
- Engine operations (conditioning, checks, integration, handling, etc.)
- Measurement and Cabling (Acquisition, measurements, diagnostics, special measurements systems like thrust measurement, accuracy, etc.)
- Control and command (sequences. parameters, redlines, regulation, monitoring, etc.)
- Test results restitution (analysis, data handling, etc.)

Triggered by the development of rocket propulsion systems and research activities the test bench specifications have been increased in volume and complexity.

Today there much more test objectives required for the test. There are a high amount of measurements, regulations and special control and command systems needed to test different operational points or mission requirements including re ignition.

4. CHALLENGES OF TEST BENCHES

The challenges of the test facilities in Lampoldshausen are closely connected to the development of the ARIANE launcher and the research activities in combustor technologies. Of particular importance for the Engineering in Lampoldshausen are the challenges concerning:

- Feeding systems for rocket engines
- Altitude Simulation for Space Propulsion

A brief overview of the technologies already used at the test bench demonstrates the challenges to the systems.

4.1. Feeding systems

4.1.1. Storable Propellants

In 1973 the ARIANE launcher program starts. The testing of the Viking engine, the second stage and the AR4 booster (PAL) was characterized by the handling of big quantities of storable propellants (Figure 2).

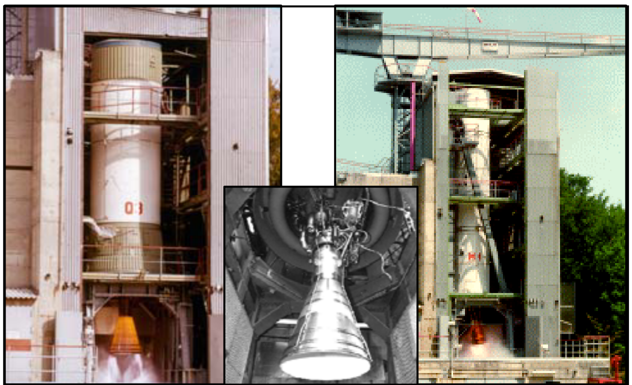

Figure 2: ARIANE 4 Testing

The environmental hazard of N2O4 and UDMH needs waste water treatment and personal protective equipment.

The waste water treatment was done by chemical neutralisation of the containing propellants. Actual the waste water treatment is done by H2O2 and UV reactors to reduce the production of salt in the water. There is a project to replace in mid term the UV reactors by solar installations.

The treatment of contaminated gases is done with a cold trap followed by a water trap. Cleaning of lines and valves are done by heating and evacuation. Special safety areas, weather conditions and emergency systems are requested for testing.

The handling of storable propellants is still required for the altitude simulation of the AESTUS engine at P4.2 and the Satellite propulsion at P1.0.

Today the federal immission protection law requires strongly reduced immission. The statutory order on hazardous incidents requires special evaluation of the dispersion in case of emergency. Wind corridors are requested to limit the dispersion of hazard gases.

4.1.2. Cryogenic Propellants

The development of the ARIANE 5 (Figure 3) were characterised by the handling of big quantities of liquid hydrogen (LH2) and liquid Oxygen (LOX). The P5 were erected (Figure 4) for VULCAIN.

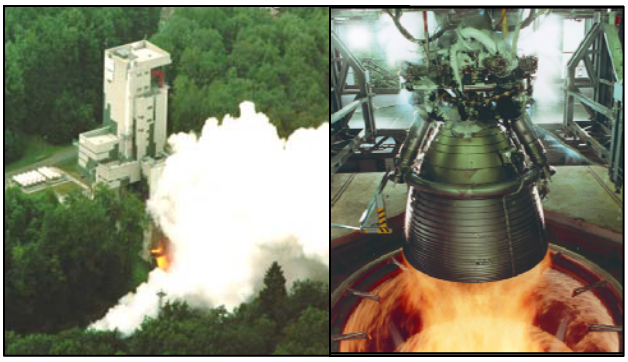

Figure 3: VULCAIN II at P5

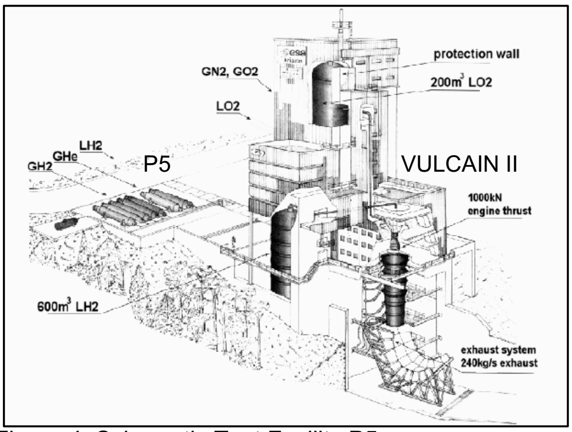

Figure 4: Schematic Test Facility P5

High pressure conditions for the cryogenic propellants were requested for the development tests of the thrust chamber at P3.1 and at the research facility P8 (Figure 5).

Figure 5: Test Facility P8

Challenges are the handling of cryogenic propellants in low and high pressures (> 300 bars) and the control of interface conditions to the engine. Especially the pressure and temperatures have to be respected.

Special Engineering competences are linked to the cryogenic feed systems considering design, safety, functional criteria and operational conditions.

- The design has to respect cryogenic temperature by vacuum insulation or super insulation. All the equipments like the run tanks, cryo fittings, flair and vent stack, etc. needs special designs in function and material.
- Safety conditions linked to blocking of cryogenic liquids, cleanliness requirements concerning particles, explosives, etc. has to be considered.
- Special functional conditions like collapse factor for pressurisation, two phase flows, sub-, trans- and super critical conditions, sub cooled propellants and spontaneous evaporation, evaporation losses, etc. occurs.
- The test bench operation has to respect conditioning, chill down, hot run and reconditioning phases. Special operations like “bubble blow out” are necessary to reach liquid conditions.

4.1.3. Stage like Feeding conditions

The principle task of the engine supply systems is always to simulate the feeding conditions of a launcher. The request of stage like and flight like interface conditions especially the pump inlet pressure requires special technologies.

For the VULCAIN engine technologies like the shut down of the booster has to be simulated by a pressure profile at the pump inlets, especially for the LOX supply. This is realized by throttle valve at the engine inlet and a powerful pressurization and depressurization system of the run tank. Additionally a POGO oscillation system is integrated to test the damping devices for the flight lines.

For the VINCI test facility P4.1 the feeding system is equipped with buffers to simulate the stage feeding conditions during Start Up and Shut Down (Figure 6).

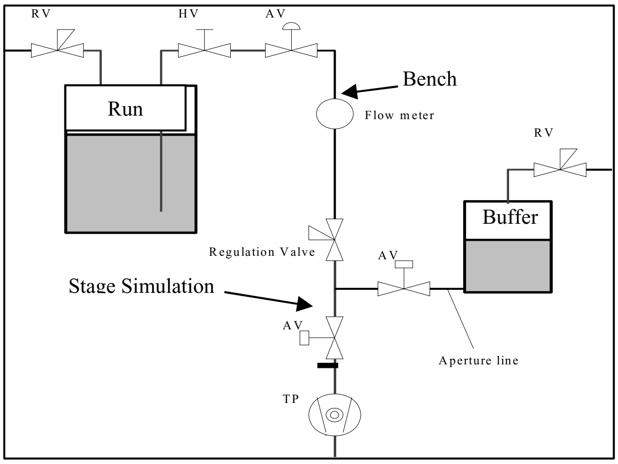

Figure 6: P4.1 – VINCI Stage Like Feeding Conditions

The “stage simulation line” represents stage like function for the pressure drop of the flight lines.

The final chill down of the engine, the ignition and start up is performed by the buffer. After reaching steady state conditions there is a switching from the buffer to the run tank. During shut down of the engine the buffer can be connected again to prevent the water hammer. Additional parameters do be respected are given by the resistance of the bench line, characteristics of the valves, volume of the buffer, pressurization characteristics of the buffer, etc. The dynamical simulation of the feeding lines is done by a “Lumped Parameter Model” calculation. The test results show the expected and calculated conditions.

4.2. Altitude Simulation of Space Propulsion

Altitude simulation of space propulsion is still requested to develop and qualifies rocket propulsion in space environmental conditions.

The task of altitude simulation consists of creating the test condition within a vacuum cell. This is primarily low ambient pressure of just few mbar. Special operational conditions are linked to the transients during Start-Up and Shut-Down of the engine with respect to the nozzle loads. Maintenance of the vacuum with running engine is achieved by using the energy of the exhaust jet. The supersonic gas flow is decelerated and compressed by a diffuser. Additional extraction of the exhaust gas by steam jet ejectors and condensation maintains the necessary pressure conditions.

To provide the large quantities of steam, rocket steam generators with liquid Oxygen and Alcohol are used. The principle of rocket steam generators is to inject water into the hot gases of a rocket combustion chamber and to evaporate the water in a mixture chamber.

The challenges for the P4.1 altitude simulation (Figure 7) of the Vinci engine require new technologies. Notable are the use of adapters to test different test configurations on the same test position, the use of a centre body diffuser and the cooling systems for the high heat loads of H2/O2 combustion. Special attention is given to the dynamical behaviour of the altitude simulation during start up and shut down of the engine. The big nozzle structures are very sensitive to loads of flow separation during transient phases. Powerful steam ejectors adapt the pressure in time to the chamber pressure conditions during start up and shut down of the engine. 240 kg/s of steam is needed for P4.1.

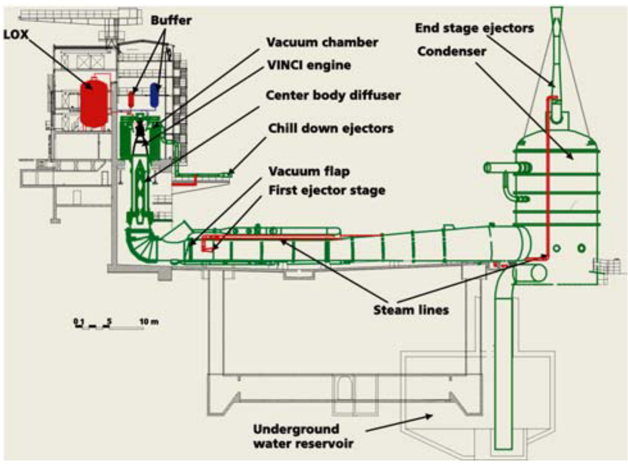

Figure 7: P4.1 – VINCI Altitude Simulation

5. ACTUAL ENGINEERING PROJECTS

Actual there are two major projects to meet the challenges for the future. These are:

- **G**reen **P**ro**p**ellant Test facility P6.1; **GPP - P6.1**
- **A**dvanced **A**ltitude **S**imulation **P8**; **AAS - P8**

5.1. Green Propellant Test facility P6.1

There are increasing activities in methane / oxygen combustion driven by research and technology. The motivations are basic understanding, to prepare design methodologies and tools for engineering and technology, to identify critical fields for application and to extend the combustor technology competence. For the investigation in the combustion process of LOX/CH4 there are already tests performed at the test facility P8 with a single injector combustor and at M3 with the micro combustor. Actual the test facility P6.1 for special research in green propellants is under construction and the first tests are scheduled for end of this year.

The P6 test facility consist of two test positions the P6.2 for cold gas testing in sea level and high altitude conditions and the P6.1 used in former times for the development of an H2/O2 steam generator. Now the test position P6.1 will be modified for green propellants. The project has started in 2005 and will be finished mid of this year for the first stage of extension, means operational with gaseous methane G-CH4 and oxygen LOX.

The interface conditions (Table 1) should allow subscale combustor testing up to 60 bar chamber pressure and up to 1 kg/s mass flow.

	mass flow [kg/s]	temperature [K]	pressure [bar]
Methane	0,04 – 0,2	110 – 185, ambient	20 – 120
Oxygen	0,15 – 1	100	20 – 90
H2O	1 – 5	ambient	20 – 90
Hydrogen (growth potential)	0,025 – 0,250	100 – 150 K	20 - 120

Table 1: Interface Conditions P6.1

Due to the cryogenic interface conditions of liquid oxygen, liquid natural gas and deep cooled hydrogen or methane gas the supply is designed for pre cooling and jacket cooling. There are two cooling media available:

- Gaseous nitrogen of 77 K < T < 183 K ± 2 K supplied by an evaporator
- Liquid nitrogen (growth potential) 1 bar / 77 K < p / T < 6 bar / 96 K two phase conditions

The propellant feed system P6.1 (Figure 8) is design for high pressure supply:

- **Run tank LOX :**

  0,1 m³ / 200 bar / 77 K, pressurized with GOX
- **Run tank CH4 (first stage of extension):**

  0,3 m³ / 200 bar / 77 K, pressurized with CH4
- **Run tank cooling water:**

  1 m³/ 200 bar/ ambient temperature, GN2 pressurized
- **Gaseous pressurization system:**

  GOX: 4 m³ / 300 bar / ambient temperature

  CH4: 3 m³ / 300 bar / ambient temperature
- **Feed lines:**

  ∅ = 25 mm / 200 bar, LN2 / GN2 jacket cooled.
- Mass flow regulated by electrically activated valves and measurement by Coriolis devices.
- Interface of injector head to combustion chamber valves optimised

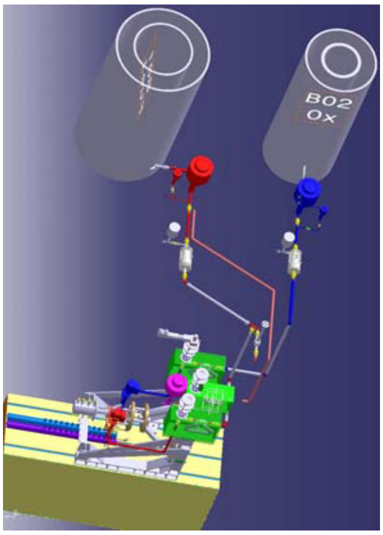

Figure 8: Propellant Feed system P6.1

5.2. Altitude Simulation P8 (AAS-P8)

The objective of the AAS-P8 is to modify one of the test positions at the test facility P8 for flight like ambient test conditions. Basic requirements are the generation of thermal loads by hot gas, variable and adjustable ambient pressure and surrounding flow conditions. With the application of visualization techniques and optical diagnostics the flow conditions and thermal loads will be investigated on subscale level.

New developments and the improvement of operational conditions demand the further development of the altitude simulation techniques.

Challenges are:

- Improvement of altitude simulation concerning cooling behaviour, the dynamical behaviour of the diffuser or requests by visualization techniques and diagnostics.
- Nozzle for space environment with high expansion ratio nozzles and new materials.
- Nozzles for main stage and booster engines requests testing close to environmental flight conditions with flight loads. Additionally investigations in advanced nozzle designs like dual bell or extendable nozzles are required.

To meet these challenges the project “Advanced Altitude Simulation P8; **AAS – P8**” was started. The objective is to modify a test position at the research test facility P8 for testing subscale combustor in flight conditions and investigate altitude simulation technique.

5.2.1. Motivation for AAS-P8

Research in high altitude simulation

Due to high heat loads of the diffuser there are investigations for the cooling behaviour. Objective is to improve the live time and to increase the load cycles. Possibilities are the protection or film cooling.

Special interest are given to the dynamical behaviour of the altitude simulation during start up and shut down of the engine as well as pulse mode operations. Databases to verify the semi empirical models and to improve the forecast of operational conditions are necessary.

Testing of nozzles in vacuum conditions

Nozzles with high expansion ratios like the VINCI nozzle (Figure 9) are very sensitive to the flow separation during start up and shut down. The dynamical conditions of the altitude simulation have to be respected.

Maintenance of the vacuum is achieved by using the energy of the exhaust jet. The supersonic gas flow is decelerated and compressed by a diffuser.

High suction capacities of the ejectors or special techniques like the use of an auxiliary nozzle for priming of the diffuser are require. The supersonic flow of the diffuser is started by the auxiliary nozzle flow (Priming) similar to the blind stability of an ejector system. The engine itself has to start the super sonic flow of the diffuser inlet. Therefore the start up and shut down of the engine has very smooth pressure evolutions.

Figure 9: VINCI engine

Testing of nozzles for main stage engines

The transition from sea level conditions to high altitude conditions during flight requires special nozzle design for maximum thrust. With advanced nozzles like dual bell nozzle or extendable nozzle the performance can be increased (Figure 10).

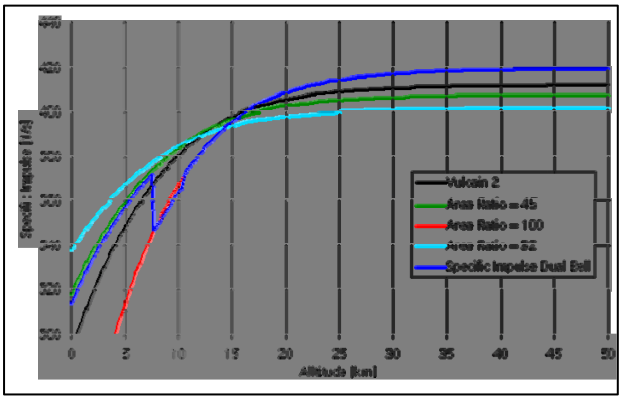

Figure 10: Specific Impulse to Expansion Ratio

The pressure profile during flight from 1 bar at sea level down to some mbar in high altitude is requested for testing

Unexpected events during flight drive the necessity to test engine closer to flight conditions and flight loads. A Load Simulation Device for the VULCAIN II nozzle (Figure 11) controlled the pressure around the nozzle and applied buffeting loads.

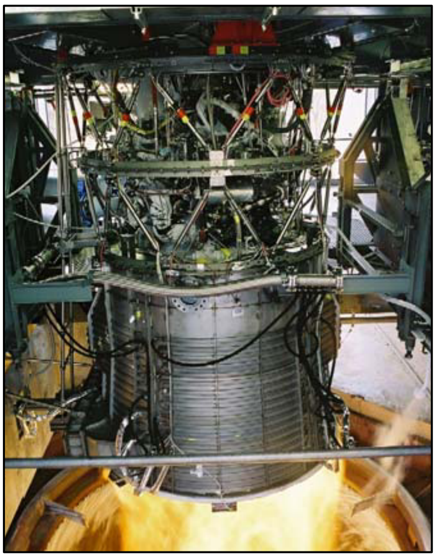

Figure 11: Load Simulation Device VULCAIN II Nozzle

Visualisation techniques

The investigation in flow separation phenomena requires the use of visualization techniques. Methods previously used for basic research are now being implemented at the big test plants P5 and P4.1.

5.2.2. Specification and Design AAS-P8

The project is focuses on 3 topics, the altitude simulation, the subscale combustor and the visualization techniques. The basic conditions are:

- Subscale combustor and hot gas conditions – VULCAIN II class
- Variable and adjustable pressure 1 bar – 100 mbar
- Surrounding flow conditions up to M = 2
- Modular design for investigation in altitude simulation, visualization technique and diagnostics

Subscale Combustor

The subscale combustor (Figure 12) is scaled to VULCAIN engine 1 to 8.

This means mixture ratios ROF = 5 – 7,5, chamber pressures Pc = 40 - 150 bar, mass flows m = 3 - 6 kg/s, thermodynamic and flow characteristics VULCAIN II like and operational with Hydrogen as well as Methane.

The nozzle extension is exchangeable with expansion ratios ε of nominal ε = 60 and maximum ε = 100. The nozzle exit diameter is maximum D = 330 mm.

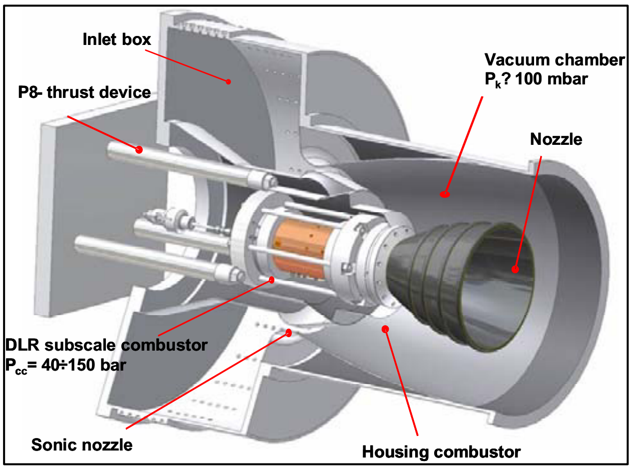

Figure 12: Subscale Combustor

First run-in tests with the chamber are performed (Figure 13) and the "VULCAIN II – scaling" is verified.

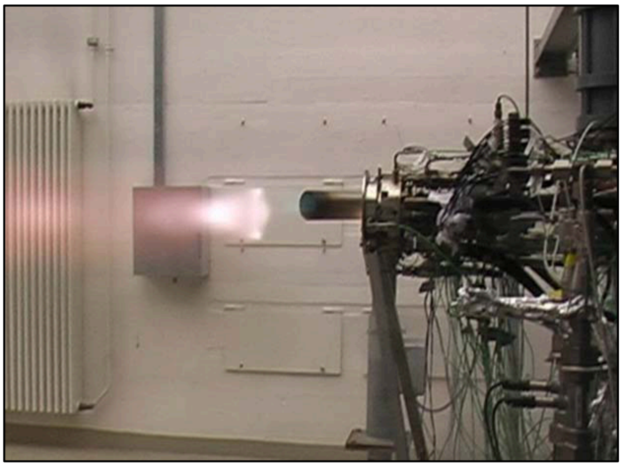
Figure 13: Run In Tests Subscale Combustor

Altitude Simulation P8

The design of the altitude simulation (Figure 14) focuses on different objectives:

- The priming and operation of the diffuser will be investigated by using an auxiliary nozzle. Priorities are to generate basic understanding in the behaviour and transient conditions. The focus is on different nozzle designs such as cantered nozzles or annular nozzles as well as cooling methods.
- The cooling of the diffuser will be investigated. The focus is in further development of the water cooling by new materials or optimizing of the cooling channels. Additional investigations are focused in basic studies for a cooling film.
- The technique for variable and adjustable pressure conditions will be investigated.
- The generation of the surrounding flow conditions will be investigated.

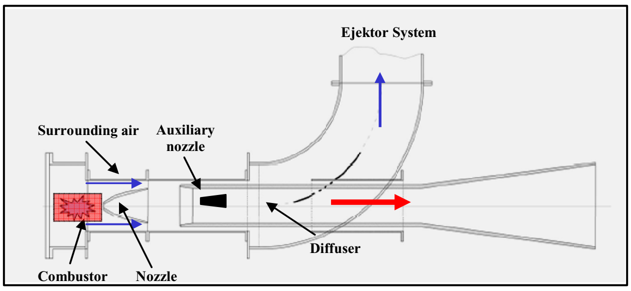

Figure 14: Altitude Simulation P8

A cold gas model (Figure 15) for the verification of basic parameters will be tested at cold test facility P6.2.

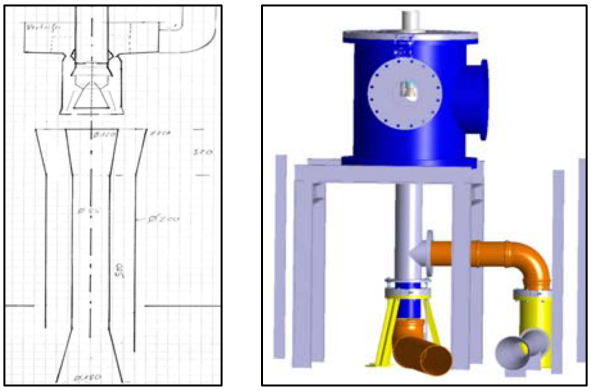
Figure 15: Cold Gas Model P6.2

Visualization

For characterization of the flow there will be two independent methods applied in parallel (Figure 16).

- Background oriented Schlieren (BOS) – for getting information on the density distribution and shock systems in the outside flow
- Particle Image Velocimetry (PIV) to get information on the velocity distribution.

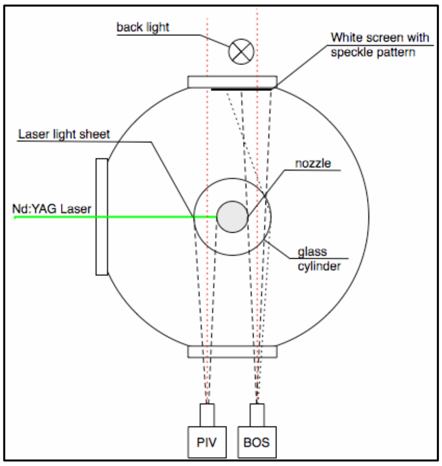

Figure 16: Visualization techniques

6. CONCLUSION

With the actual Engineering projects DLR Lampoldshausen will meet the challenges for future testing.

Additional activities are in preparation concerning exhaust gas guiding systems and noise reduction.

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