Advanced Altitude Simulation P8 (AAS) – Current Status

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Abstract

The paper reports the current status of a DLR Lampoldshausen project towards the design, erection and operation of an advanced altitude simulation facility at the European R&T Facility P8. The system will allow for testing of sub-scale thrust chamber assemblies including supersonic surrounding flow around the nozzle. This facility will allow for investigation into the specifics of altitude simulation facilities but also on the interaction of nozzle and its exhaust plume and the surrounding co-flow for sub-sonic, transitional and low supersonic co-flow conditions. The design bases entirely on the broad experience on design and operation of various altitude simulation facilities such as the satellite engines bench P1.0, the cryogenic and storable upper stage engine facilities P4.1 and P4.2, sophisticated engineering design tools and continuous numerical effort. Knowledge about nozzle and thrust chamber design and operation bases on broad investigations carried out at the cold flow facility P6.2, and the hot fire bench M3 and P8.

1. Introduction

The investigation of rocket engine behavior under real flight conditions imposes the simulation of several complex physical problems. During the ascent of the launcher the ambient conditions vary rather drastically, while the temperature decrease has only a minor influence, the change of the surrounding flow from sub- to supersonic conditions and the vanishing atmospheric pressure cause severe variations of the boundary conditions for engine operation. Launchers which like the European ARIANE 5, the American Space Shuttle or the Japanese H2, are designed such that their core engines are ignited at ambient pressure on the launch pad and operate for a couple of hundred seconds with decreasing ambient pressure [1]. For the VULCAIN 2 of the ARIANE 5, at engine shutdown at an altitude of about 215 km, the pressure is lower than 10^{-6} mbar and surrounding flow velocities have reached values around 7000 m/s.

Obviously, these boundary and operating conditions variations have an impact on engine design and performance. Flow structures resulting from the launcher after-body may impact at the nozzle and the resulting asymmetric loads may deform the nozzle structure or couple with the flow inside the nozzle and cause a change in the internal nozzle flow which will finally result in flow separation and side loads [2-5]. In order to clarify the impact of these phenomena on engine operation in sufficient detail, facilities are available at each scale level and DLR operates a variety of such facilities. P1.0 is designed for satellite propulsion systems in the thrust range of 400-600 N, P6.2 is a facility designed for cold flow sub-scale studies with geometric scale of 1:25 taking VULCAIN 2 as a reference, while P4.1 (180 kN) and P4.2 (35 kN) are full scale systems designed for altitude simulation testing of upper stage engines such as VINCI and AESTUS [6-8]. Until now there is nofacility available in Europe which allows for an altitude simulation on engines of the VULCAIN 2 class. Only during the VULCAIN 2 recovery program, the P5 bench was modified in setting up a Load Simulation Device (LSD) in order to establish low pressure conditions (~ 200 mbar) around the engine [9].

The planned Advanced Altitude Simulation (AAS) at the P8 test bench, a facility which allows for 1:8 subscale testing (VULCAIN 2 Class), aims at filling the gap between the full scale upper stage facilities P4.1 and P4.2 and the cold flow facility P6.2 [10]. It is designed to allow for altitude simulation of sub-scale thrust chamber assemblies with co-flow around the engine. The current design limits the thrust level to roughly 30 kN and a supersonic surrounding flow to a Mach number of 2. In the end, the AAS P8 will be designed to allow for:

1. Investigations into the coupling of internal and external flow phenomena under hot gas conditions and sub-scale level to improve the identification and quantitative description of the domination physical phenomena; among these phenomena are nozzle deformation, occurrence of non-normal side loads, buffeting, post combustion in areas where hydrogen-rich exhaust gases mix with surrounding air;
2. Investigation into the design and operation of specificcomponents of such altitude simulation facilities to enable a more detailed understanding of their operation and/or to build a basis for future developments; of particular interest are diffusers, ejectors, pressure development, cooling methods and flow phenomena during transient operation of the engine;
3. Application and development of optical diagnostic methods to investigate the flow phenomenon in the region of interest, of particular interest are classical methods such as Schlieren, Schlieren, high speed imag-

ing in the visual and UV range or more sophisticated techniques like Backward-Oriented Schlieren (BOS) [11], infrared thermometry or non-intrusive velocity measurement tools.

4. Model development and validation for engineering analytical and numerical (CFD) tools applied for altitude simulation predictions of specific components and their interaction during steady state and transient operation phases and for prediction of the flow interactions
5. R&D into the coupling between specific features of thrust chamber assemblies and such facilities .

Obviously, the final design will be a compromise between the specific requirements of these different goals. However, they certainly have requirements in common, the need controlled boundary conditions and a controlled variation of operating conditions.

2. Design Methodology and Approach

The design for such a sophisticated facility requires verified tools for the different components and subsystems and their interactions. Design, erection and operation of the P4.1 facility provided a large experimental and numerical data base and finally yielded a set of verified engineering design tools which can be regarded as the state-of-the art in the field [12, 13]. However, the operating conditions at P8 and even more so the ones foreseen for AAS P8 are quite different. While the P8 facility allows for higher combustion chamber pressures which may exceed 25 MPa, the AAS P8 should allow for co-flow around chamber and nozzle with the pressure level of the co-flow adjustable to ascent conditions. On the other hand, the geometrical size of P8 is much smaller and requires a down-scaling of the major components for altitude simulation. Additionally to the experience gathered during the P4.1 project, the behavior of nozzles at varying external pressure and flow conditions have been studied in detail at the cold flow facility P6.2. This experimental effort has been accompanied by detailed numerical studies and obviously the results obtained there provide a broad data base for nozzle flows, coupling phenomena between nozzle and outer co-flow. Furthermore, during these research activities various optical diagnostic techniques have been applied and the combination of all these data, experiences and lessons learned will be taken into account for AAS P8 design [14-17].

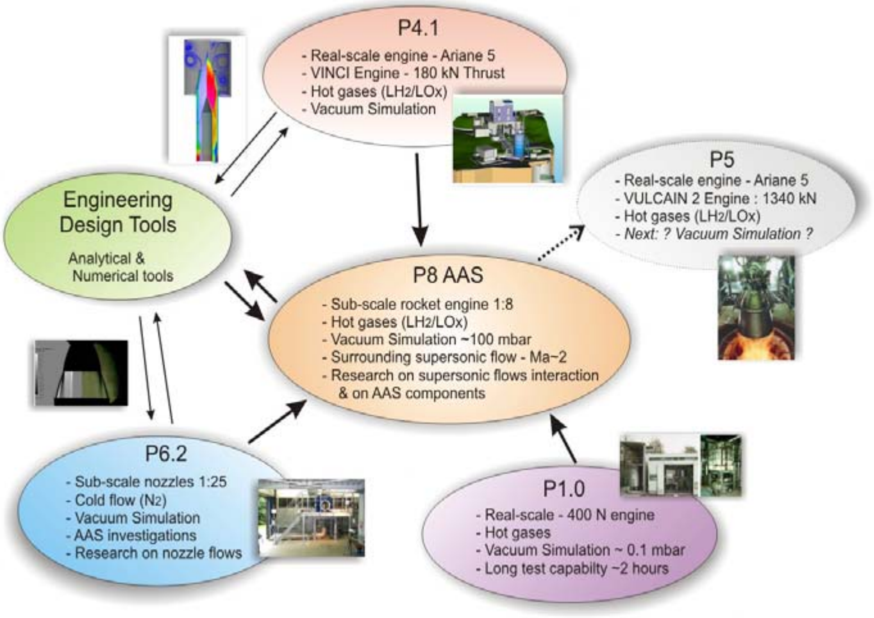

Fig. 1: Illustration of AAS P8 design methodology

The third element of the design process are the operational experience, the experimental data base and the knowledge about test facility and test specimen interaction gathered within the last decade at P8. The different users at P8 performed test campaigns in a broad range of operating conditions of combustion chamber pressure (30 to 250 bar), mass flow rates (0.5 kg/s to 17 kg/s) and propellants (GH2, LH2, GCH4, LOX) for main chamber, gas generator and staged combustion conditions [19-20]. Fig. 1 summarizes the design methodology. A combination of all the assets mentioned previously in a thoroughly followed design process will result in a successful AAS P8.

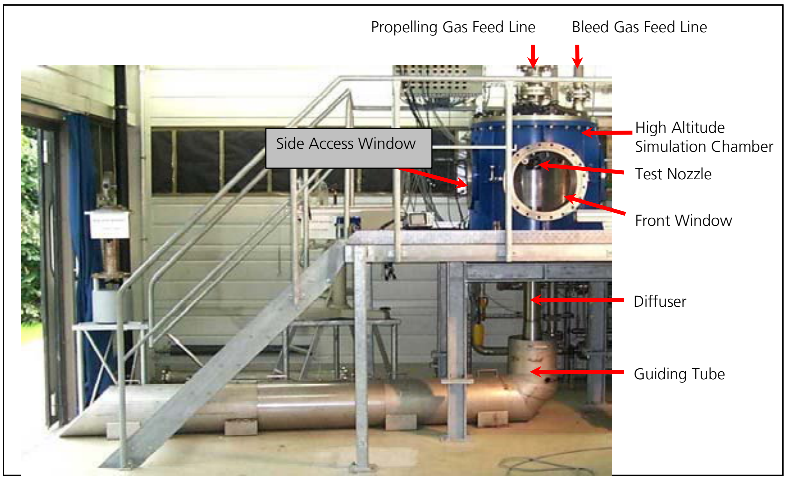

Fig. 2: Main features of P6.2 Altitude Simulation Test Facility

3. Cold Flow Activities

3.1 AAS Set-up at P6.2

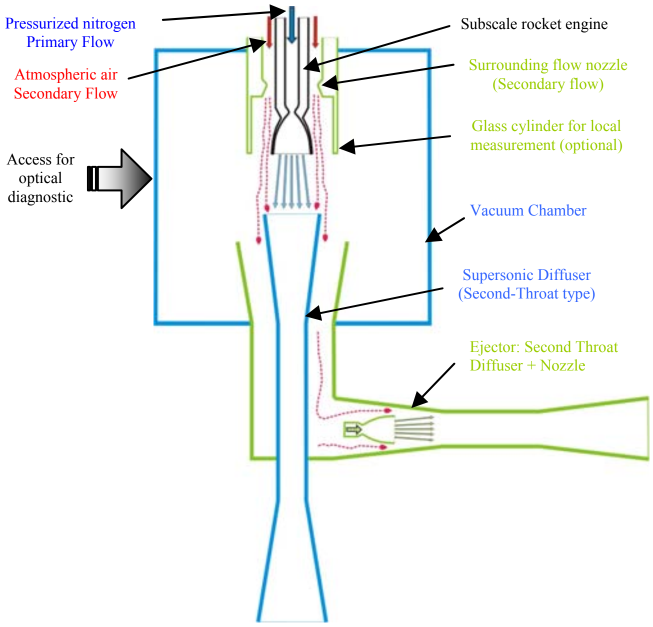

Fig. 3: Schematic of the AAS setup at P6.2

The P6.2 Facility is used for research into flow separation and side load phenomena of thrust nozzles having different contours in cold flow conditions. It allows for two experimental setups, one where the nozzle flow exists into ambient pressure and another one where the nozzle is operating in a vacuum chamber which can be operated in a mode with continuous adaptation of the ambient pressure to an actual flight phase. The test bench is equipped with gaseous nitrogen feeding system that allows working with a maximal pressure of 55 bar and with maximal mass flow of around 4 kg/s. Fig. 2 shows a picture of the P6.2 facility in altitude simulation mode, set up with diffuser and exhaust section connected without the upstream system of propelling and bleed gas supply. The test facility capabilities are summarized in the Table 1, for more detailed information see [7]. The AAS setup is composed of several sub components and a schematic of the specific setup is shown in Fig. 3. All features which are ASS specific such as the surrounding nozzle for secondary flow, the glass cylinder to allow for optical access and the ejector system with secondary throat diffuser and nozzle are marked in green color.

Sub Component	Description
Thrust Chamber Assembly (TCA) (Subscale chamber + nozzle)	Cold Nitrogen gas (ambient total temperature) Max. feeding pressure: 55 bar Max. Mass flow rate : ~4 kg/s
Altitude Simulation System (ASS) Vacuum Chamber + Supersonic diffuser	Vacuum pressure < 100 mbar; minimal VC pressure ~ 8 mbar Vacuum chamber dimensions: 800 mm diameter and 1000 mm high Three optical access windows: 2x400 mm and 1x500 mm diameters Interchangeability of diffuser types: Cylinder, secondary throat and center-body type diffuser
Surrounding Flow System (SFS) Surrounding flow nozzle + Ejector	Atmospheric air (ambient total temperature and pressure) Mass flow rate: 0.3kg/s up to ~ 1kg/s Feeding pressure ejector nozzle: max. 45 bar Mass flow rate ~3 kg/s Suction behavior of the ejector: 0,3 kg/s for 0.1 bar

Table 1: P6.2 Test Facility Capabilities

3.1.1 Subsystems and components description

TCA: Obviously, one of the main components of the setup is the thrust chamber with its dominating part for altitude purposes, the nozzle. Since P6.2 is a cold flow facility, the device mounted into P6.2 resembles only features such as chamber pressure, contraction and expansion nozzle contour. Fig. 3 reveals that the setup allows for optical access to the nozzle and the area of intersection of the plume with the surrounding high speed gas. Both, classical bell but also dual bell nozzles having different nozzle contours are objects of investigations using the AAS setup. Since the first object of interest will be a down-scaled VULCAIN 2 type chamber, all the experiments which were performed with a thrust-optimized bell type nozzle with similar expansion ratio.

ASS: The altitude simulation system consists of the vacuum chamber and the central supersonic diffuser which provides for the achievement of vacuum pressure inside the vacuum chamber (VC) and the recompression of the supersonic flow exhausting from the nozzle. However, in order to reach sufficient low pressures (some mbar) inside the VC and to ensure that full flowing nozzle conditions are achieved, the diffuser has to be in a chocked condition or that is to say to be “started”; meaning that at least in one section of the diffuser supersonic flow conditions have to be established. For the AAS test campaign a second throat diffuser is used which provides for a VC pressure smaller than 50 mbar.

SFS: The components of the system which provide for the surrounding flow and its mastering within the altitude simulation system are supply lines, guiding flow paths, the nozzle for the surrounding flow and the ejector.

Additionally, the system is equipped with a glass cylinder to allow for the optical access for flow visualization and diagnostic purposes. These components establish a supersonic flow around the nozzle and allow for the aspiration of the injected secondary mass flow introduced through the surrounding flow nozzle in order to keep low pressure levels inside the VC.

3.1.2 Optical diagnostics and measurement systems

In order to provide for the necessary data for comparison with numerical simulations, facility and components and sub-systems of interest are equipped with several pressure and temperature sensors at specific positions. The measurement system is composed of around 80 canals: ~ 64x Low Frequency canals (up to 1 kHz) and ~16xHigh Frequency canals (up to 50 kHz). Various optical techniques have been applied so far during different test campaigns at P6.2 [5, 7, 14]. For the validation campaigns reported here, the focus lays on a Z type Schlieren method. Additionally, a new technique, Background Oriented Schlieren (BOS), which catches the optical displacement of a pattern on a structure behind the flow caused by density gradients in the flow, will be tested during the validation phase [11]. Although this method yields results comparable to a conventional Schlieren setup with a somewhat poorer resolution, it has the advantage of an easier application.

3.2 Operation conditions and sample test results

As of today, the majority of the tests planned for P6.2, single component and sub-systems performance as well as their interaction and coupling have already been performed. Currently, these data are evaluated and compared with numerical simulations in order to modify the engineering design tools were necessary and appropriate. The tests are performed with a parabolic VULCAIN II like contour nozzle with similar expansion ratio. The chamber pressure is fixed to 48 bar while the vacuum pressure around the engine was kept around 30 mbar. Tests were performed with and without secondary surrounding flow. No ejector has been used; the vacuum is sustained by the subscale engine – supersonic diffuser combination. The tests are performed without glass cylinder and with a conical nozzle for the secondary flow. Table 2 summarizes the operating conditions of these tests.

Tests	Description
TCA characteristics	TOP Parabola nozzle - VULCAIN II like contour - Throat diameter = 11 mm Nozzle expansion ratio ε =53 (optional 100) - Nozzle end diameter 80 mm Pcc ~ 48 bar Mass flow = 1.1 kg/s
ASS	Vacuum pressure ~ 30 mbar Vacuum Pressure with secondary flow ~ 80 mbar Distance from nozzle end to diffuser inlet around 58mm
SFS	Atmospheric air (ambiant total temperature and pressure) Mass flow rate :170 g/s

Table 2:AAS P6.2 Test Conditions

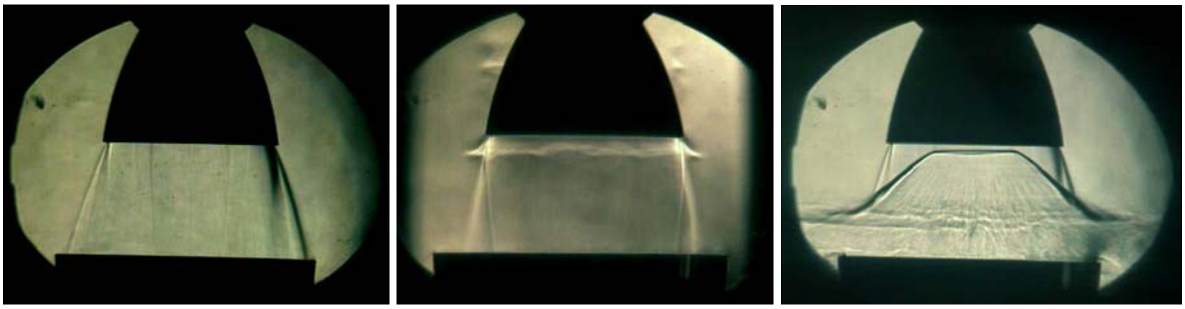

Fig. 4: Schlieren images with AAS installation at P6.2: Steady state without / with secondary flow (left, middle): Transient shutdown without secondary flow (right)

Figure 4 shows three Schlieren images taken with different setups (left, middle) and at different pressure ratios. While the left and the right image are taken with a vertical Schlieren setup and visualize a flow condition without surrounding co-flow, the middle image, taken with a horizontal Schlieren setup, shows the flow at a similar pressure ratio as the one on the left but with co-flow. The remaining test campaigns will focus on the application of optical access installations, the BOS technique and ejector behavior.

4. Comparison of numerical and experimental cold flow results

4.1 Description of the CFD model

ANSYS CFX 11.0 has been used to compute the different flow situations and to compare the solutions with experimental data. Mesh generations were performed applying ANSYS ICEM 11.0. Based on symmetry assumptions the computational effort can be reduced drastically. Furthermore, only the dominating features of the system such as nozzles and diffusers are modeled completely. The vacuum chamber is modeled only partially, ejector and feed lines are not taken into account. Two different geometries have been built with two dimensional axis symmetrical domains. The mesh is built with hexahedrons cells, because they give the better mesh quality. The first mesh for the simulation without co- flow is of around 76 000 cells, and the second is built with 123 000 cells. An additional mesh with around 300 000 nodes has been built to verify that results are not dependant of the mesh size (geometry with co-flow geometry). Example of the mesh built is given in the next image Fig. 5. The chosen turbulence model is the SST Menter turbulence model .

Nitrogen is used to model the primary flow and air for the secondary flow. The gases are modeled with applying a perfect gas approach because there is no significant temperature gradient influencing the heat capacity. The walls are modeled as adiabatic walls. The inlets are defined through total pressure and total temperature conditions with the corresponding measured values; like the outlet modeling.

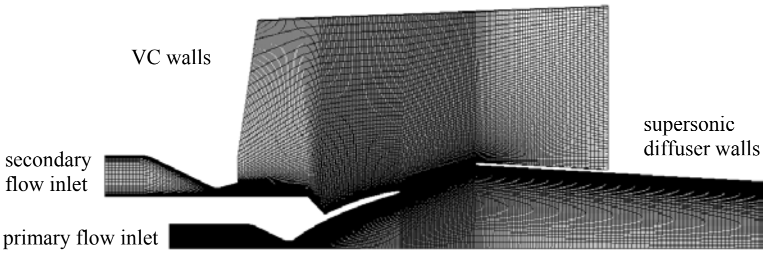

Fig. 5 : Mesh for the simulation with secondary flow

4.2 Comparison of experimental and numerical results

Figures 6 and 7 show a comparison of the experimental and numerical determined Schlieren images for the two different operating points defined in Table 2: a TCA pressure of 48 bar and a co-flow mass flow rate of 179 g/s. Each of the figures itself is subdivided in a numerical (left) and an experimental half (right).

Figure 6 shows a comparison of the flow situation between nozzle exit and diffuser inlet for the case without secondary flow. While free jet boundary and expansion fan are clearly visible in both images, the internal shock, a well known structure of thrust optimized contour nozzles, is much more pronounced in the numerical Schlieren image than in the experimental one which is due to the fact that the latter is a line-of sight image. Schlieren orientation and finite camera resolution play a role as well.

Fig. 6: Comparison of simulation and experiment without co-flowing gas

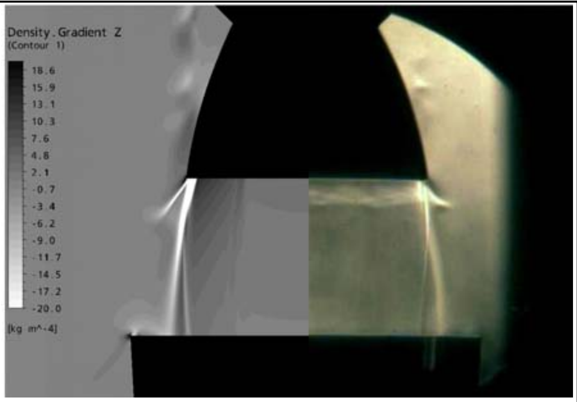

Fig. 7: Comparison of simulation and experiment with co-flowing gas

Figure 7 compares the same flow situation but now for the case with co-flowing gas and this secondary flow is injected with Mach number of around 2 through the annular nozzle.

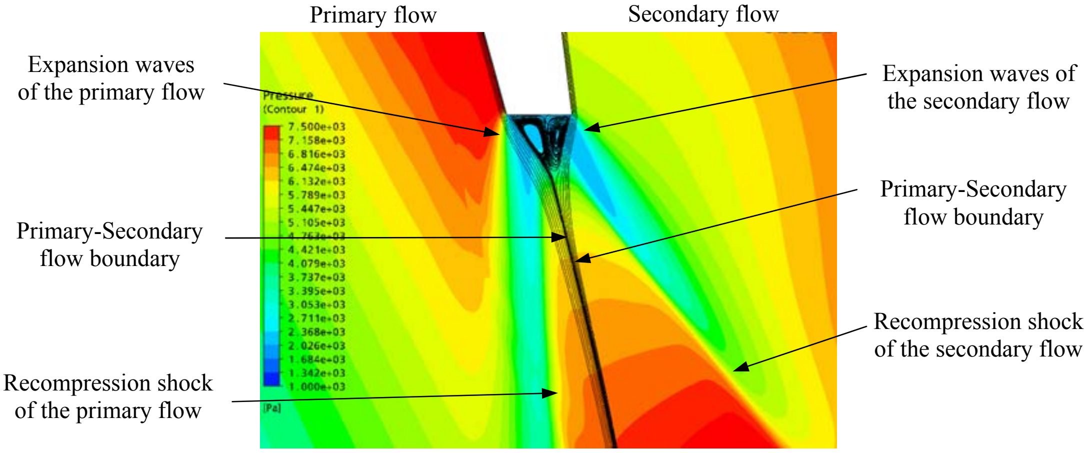

Fig. 8: Zoom on the flow configuration at the nozzle end – CFD simulation with secondary flow- Pressure contour + Streamlines

This secondary flow surrounding the nozzle is visible on the Schlieren images in the form of small spots near the external nozzle wall. A recompression shock, resulting from the interaction of the secondary flow with the primary flow is clearly visible on both the numerical and the experimental Schlieren pictures and forms an oblique shock (~ 45° to nozzle end plane) from the nozzle end wall lip. This shock structure is slightly smaller on experimental images than on CFD results and seems to be a more curved at its extremity. This shock structure is three dimensional but axis symmetrical and appears all around the nozzle end. Because of superposition effects, the "annular shock" yields marks onto the experimental Schlieren at the end of the nozzle which seems to be inside the subscale core flow, but is of course not. The boundary of the primary supersonic flow is also visible on both images: it is supposed to be the limit between both jets too. Finally a third characteristically structure is observed, it is the recompression shock going from the nozzle end into the diffuser inside the primary flow which exits from the nozzle.

Fig. 8 shows a zoom of the numerical results (pressure contours) obtained with the finer mesh (about two times finer in the nozzle end –diffuser inlet region) for the case with secondary flow. The results don't show significant differences to the ones obtained with the nominal mesh both in terms of shock structure observed on the Schlieren images or in terms of vacuum chamber pressure. However, interpretation of these data and consideration of theory allow for a better understanding of the flow phenomenon at the nozzle end [20]. On both sides of the nozzle lip, supersonic jets are flowing along the walls (internal wall=primary flow; external wall= secondary flow) up to the end. The abrupt change there results in expansion wave fans at the wall corners yielding local low pressure areas on both sides downstream of the corners. These expansion waves start to overlap further downstream and form two oblique shocks, which are oriented in other directions; that is to say towards primary core flow for the primary shock and towards VC walls for the secondary shock. After both shocks the pressure suddenly increases. Between both oblique shocks, the boundary between the primary and secondary flow can also be distinguished through the streamlines.

4. Foreseen Capability of the AAS system at P8

The foreseen capabilities of the next AAS installation at P8 Test Facility are summarized in the following Table 3. While the first application clearly aims at altitude simulation applications similar to the VULCAIN 2 during launch, the facility should as well be capable to provide for subscale testing of the majority of engines currently under discussion within the European FLPP program. Hence, AAS P8 will be able to entertain high thrust gas generator thrust chambers as well as staged combustion arrangements. Furthermore, it will be possible to use LOX/CH4 instead of LH2/LOX. The AAS will allow for various thrust nozzle types (TOP, TIC, dual bell,…) up to an expansion ratio of ε =100. Additional to conventional measurement techniques AAS will allow for extensive flow visualization techniques (high speed Schlieren and BOS).

Sub Component	AAS P8 Specifications	Vulcain II Spec.
TCA	Thrust optimized parabola (TOP) Nozzle area ratio ε =57 (optional 100) - Nozzle end diameter ~ 250 mm Throat diameter = 33 mm 75 bar <P_{cc}<115 bar (Nominal 85 bar) Mass flow ~3.1 kg/s (6kg/s maximum) 5,5<Rof<7,5 (Nominal 6.5)	TOP nozzle Area ratio: ε =57 P_{cc} = 115 bar Mass flow=320 kg/s Rof=7.2
AAS	Surrounding pressure adjustable between 1 bar and 100 mbar Windows for optical diagnostic: Schlieren, BOS Exchangeable primary and secondary nozzles and supersonic diffusers Supersonic diffuser to nozzle end distance can be varied	-
SFS	Air or Nitrogen (study post combustion of hydrogen rich exhaust gases; Surrounding flow up to Mach number 2 Mass flow rate up to 7kg/s	-

Table 3: AAS P8 Test Facility Capabilities

5. Hot Gases Activities

In order to provide for experimental data similar to those obtained at P6.2, nozzle experiments have to be performed at P8 already in an early phase of the project. These experiments have to be accompanied by appropriate numerical studies to finally have sufficient data available for the preliminary design review (PDR) scheduled for later this year.

5.1 Subscale Rocket Engine for the AAS at P8

In a first step, subscale hot gas tests were performed without any altitude simulation to obtain data about the behavior of the P8 and gain experience about nozzle specific measuring techniques which will be applied later. For these investigations a VULCAIN 2 – type subscale nozzle extension has been developed. Manufactured of

Figure 9: Subscale TCA for P8

Inconell® 600, the nozzle consists of two parts: The first one (from ε =5 up to ε =32) has cooling channels operating with ambient temperature hydrogen and the second one (from ε =32 up to ε =57) uses the hydrogen coming out of the cooling channels of the first part for film cooling. Fig. 9 shows the subscale thrust chamber assembly prior to testing at P8.

The design combines the classical milling technique for machining the cooling channel into the liner with electroplating of the outer shell (Nickel) and thus avoids welding of the closeout. This approach minimizes the buildup of strain during fabrication and testing. The nozzle skirt (second part) is exchangeable and allows for investigations into different nozzle concepts, i.e. dual bell contour nozzles.

Figure 10: Helical cooling channels of the first part of the nozzle

The cooling channels of the first part are helical, see Fig. 10. The coolant supply is split into four different parts which are equipped with closed loop control valves to allow for an individual adjustment of the cooling flow rates of the four quadrants. In a standard setup, the hydrogen coolant enters the nozzle to form a supersonic film and the variable slot geometry allows for the simulation of different injection velocities by constant mass flow ratios between main flow and coolant film. Fig. 11 shows the TCA with the nozzle sections mounted at P8.

The test campaign reported here has been performed for typical engine sea level start up conditions and included a variation of the combustion chamber pressure and mixture ratio later into the test between 50 bar up to 130 bar and oxygen to fuel ratio from 6 up to 7.3, respectively.

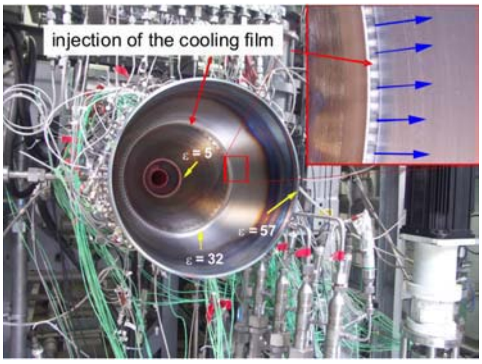

Figure 11: View of TCA mounted a P8

The instrumentation of the test specimen allows for rather detailed investigations of flow separation induced side loads through an arrangement of loads cells implemented into the interface between chamber and nozzle which are not reported here. Conventional pressure and temperature sensors have been combined with cameras detecting in the IR and UV spectrum, Fig. 12. Both the colored IR and the black and white OH images quite nicely reveal some key features of the flow.

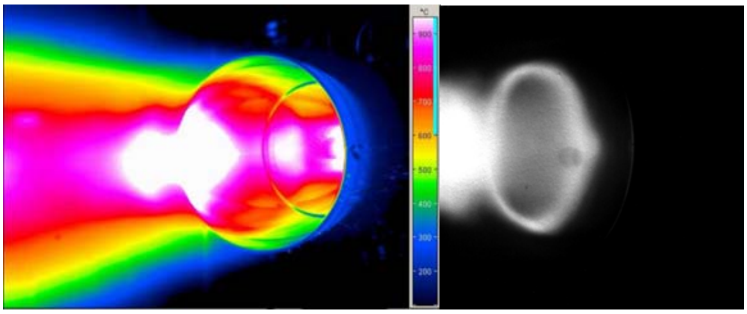

Fig. 12: Plume radiation images: IR (left) and UV (OH) (right)

5.2 Preliminary Design Studies of AAS P8

The design of the installation is done through the internal tools. These numerical and analytical tools have been validated and upgraded based on experimental results obtained at the different test facility in DLR Lampoldshausen: especially at the P6.2, P8 and at P4.1. For example, CFD simulations are performed in order to verify the feasibility of the concept and to optimize the design. For the very preliminary design of the installation 2D axis symmetrical simulations are performed.

The following Figure 13 illustrates on its left the mesh used for these preliminary design studies. The simulations accounts for the TCA, the surrounding and central supersonic diffuser and the annular secondary flow diffuser. Different geometries were computed such as different secondary flow nozzle geometries (conical or plug type nozzles), secondary flow annular diffuser sizes or with different gas model (with and without after burning). The Mach number contours for three different CFD simulations are shown on the right part of Fig. 13. From bottom to top, Mach number contours are presented for increasing outer diameter of the annular diffuser. Below a certain cross sectional area (bottom), the flow along the annular diffuser reaches supersonic velocities and in this case the “annular diffuser throat” is chocked and pressures upstream this region are higher than in non chocked condition. This phenomenon has to be avoided in order to keep low pressures in regions where supersonic flows interact, i.e. from the nozzle end to the diffuser inlet.

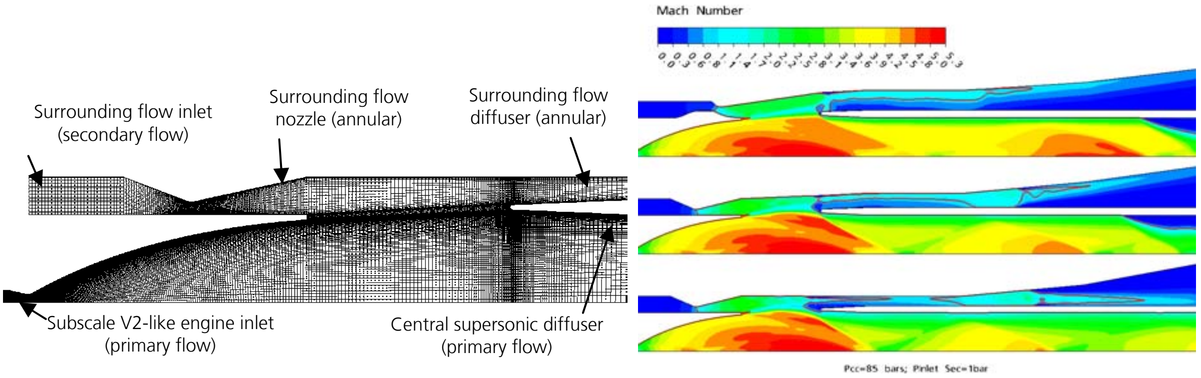

Fig. 13 : Illustration of the preliminary design study of the AAS installation at P8 - Left: Mesh for CFD simulations - Right: CFD results (Mach number contour)

The major goals of this preliminary design study are:

- Measurements of the mass flow rate which flows through the annular secondary diffuser, that is to say the mass flow which has to be aspired by the ejector system
- Determination of the gas temperature which flows into the annular secondary diffuser which is essential for dimensioning of a cooling system upstream of the ejector
- Determination of the thermal loads all surfaces of components exposed to hot gases in order to improve cooling system designs
- Evaluate optical access and flow structures in order to optimize the optical diagnostic access

6. Summary and Conclusion

Based on broad experimental and numerical experience with design, erection and operation of altitude simulation facilities and test benches for nozzles flow phenomena investigations, DLR is currently gathering experimental data in specially designed experiments at different test facilities accompanied by detailed numerical studies to fill the still existing knowledge gaps with the final aim to design and erect an altitude simulation test position at P8 facility. Up to date, cold flow studies of different altitude simulation setups at P6.2 have been performed accompanied by appropriate numerical analyses of these different flow situations applying ANSYS CFX. In parallel to these P6.2 related activities, hot gas subscale thrust chamber assembly which includes a TOP contoured nozzle with film cooling similar to VULCAIN 2 has been designed and tested at P8 test facility. Furthermore, a first set of preliminary numerical studies of an advanced altitude simulation setup at P8 have been performed as well. All these data will be used to prepare the preliminary design review scheduled for later this year.

The AAS P8 will allow for the operation of subscale thrust chamber assemblies with co-flowing gas up to Ma ~ 2 at vacuum pressure around 100 mbar. Finally, this facility will allow for studies into the coupling of the hot plume from different nozzle contours with the surrounding flow, into the nozzle flow separation, resulting in side loads during varying ambient pressure and flow conditions as well as into the investigation of the specific altitude simulation sub-systems, complexe optical diagnostics and the verification of numerical tools

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