Cold Gas Subscale Test Facility P6.2 at DLR Lampoldshausen

H. Kronmüller*, K. Schäfer§, H. Zimmermann&, R. Stark+
DLR, Deutsches Zentrum für Luft- und Raumfahrt
Institute of Space Propulsion, D-74239 Lampoldshausen a. K., Germany,
Tel. +49-6298-28-671, Fax: +49-6298-2298

* Head of the Cold Gas Subscale Test Facility P6.2, Department of Engineering, harald.kronmueller@dlr.de
§ Head of Engineering Department, klaus.schaefer@dlr.de
& Development of High Altitude Simulation, Department of Engineering, herbert.zimmermann@dlr.de
+ Head of Nozzle Group, Department of Technology, ralf.stark@dlr.de

ABSTRACT

The cold gas Subscale Test Facility (SSTF) P6.2, located at the German Aerospace Center DLR in Lampoldshausen is used to test nozzles, diffusers and ejectors in an easy, quick, reliable and effective way with gaseous nitrogen. Some experimental set-ups with nozzles, diffusers and ejectors will be showed. Additional, visualisation technique with an infrared camera and colour Schlieren of the SSTF will be illustrated. Comparison to CFD programs and mathematical models are indicated.

NOMENCLATURE

Symbols

A	area
D	hydraulic diameter
L	length of centerbody diffuser
m	mass flow
r	radius
x	length

Subscripts

a	ambient
alt	altitude chamber
c	"combustion" chamber
e	exit
ejc	ejector
t	throat
w	wall

Abbreviations

CFD	Computer Fluid Dynamics
GB	Giga Byte
HASC	High Altitude Simulation Chamber
IR	Infrared
MCC	Measurement, Control and Command System
opt.	optional
RSS	Restricted Shock Separation
SSTF	Subscale Test Facility
TIC	Truncated Ideal Contour
TOP	Thrust Optimised Parabola

INTRODUCTION

SSTF was established in late 1998 after a construction time of about half a year. The first test was done in December 1998. A further extension of the facility was done in August 1999. The objective was to have a relative cheap possibility and an easy to handle configuration to perform tests and to study gas dynamic behaviour in the field of altitude simulation and flow separation of nozzles. The relation between model and original is the Reynolds Number (Reynolds Number Analogy) and Mach Number. Is the Reynolds Number similar to the model, one can transform the results from the SSTF directly to the original.

Figure 1: Cold Gas Subscale Test Facility P6.2

Rocket motors, designed for operation in high altitude, need a nozzle with large expansion (A_e / A_t) for effective utilisation of the engine pressure p_c. When they are tested under sea-level conditions, the flow separates in the nozzle wall. To evaluate the performance of such engines, sufficient low pressure environment has to be simulated in testing installations. Therefore models of future nozzle concepts, diffusers and ejector systems can be tested for preliminary investigations at the cold gas Subscale Test Facility P6.2 in Lampoldshausen.

SET-UP OF P6.2

Fundamental of SSTF

The Cold Gas Subscale Test Facility consists of a closed High Altitude Simulation Chamber (HASC) combined with a super- or subsonic diffuser, see Figure 1 and optional since a short while ago with an ejector system, see Figure 4. The propelling gas line is fed with gaseous nitrogen at pressures up to p_c = 4 MPa (opt. 6 MPa). Nitrogen is used rather than air in order to prevent condensation. Inside the HASC different kind of nozzles could be mounted in vertical position. Mainly bell shaped nozzles were tested. The ejector system is also fed with gaseous nitrogen with pressures up to p_{ejc} = 4 MPa. The supersonic diffusers use the self sustaining principle in the means that it utilises the momentum of the rocket exhaust to decrease the nozzle back pressure inside the HASC. As the diffuser flow becomes supersonic over its full area, the inside of the altitude chamber becomes decoupled from the ambience, and pressures down to 40 mbar can be reached. If the ejector system is used, it is possible to start the nozzle in low pressure conditions inside the HASC. A huge range of pressure ratios p_c / p_a, usually between 1 and 1200, can be realised. In order to be able to influence the altitude chamber pressure p_{alt} without varying the feeding pressure p_c an additional nitrogen line has been installed, which leads into the altitude chamber by means of a ring-shaped manifold at the top of the HASC, see Figure 3 and 4. The additional bleed gas allows to decrease p_{alt} from 0.1 MPa to a value equal to an altitude of 25 km[1] for research of transition phenomena like lift off of a rocket. In this case the ejector system in Figure 4 is not in use. The test facility is supplied by eight high pressure bottles of gaseous nitrogen with nearly 989 Norm m³, that allows a maximum test duration of about 7 minutes, depending on the set-up and the test pressure profile of p_c and p_{ejc}. A minimum of two tests can be performed

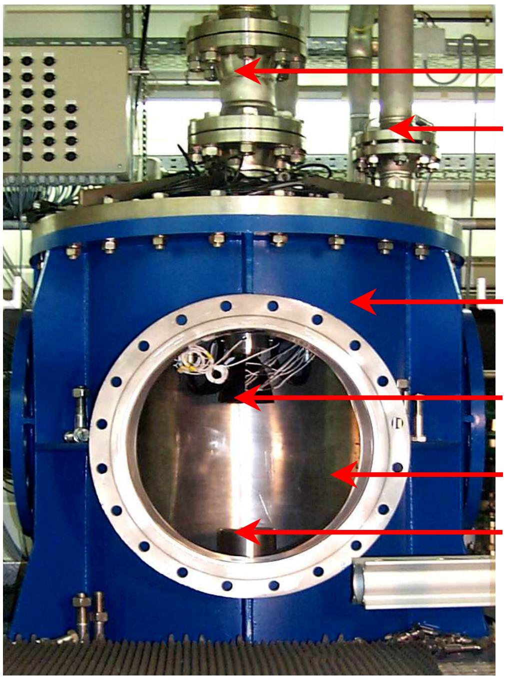

Figure 2: Front view of HASC of P6.2 with equipped nozzle and tube diffuser

P6.2 Simulation Tasks:
<u>Investigations in diffusers for altitude simulation:</u> ✓ verification of modeling and design, ✓ transient studies, ✓ parameter studies.
<u>Investigations of ejectors for altitude simulation:</u> ✓ verification of modeling and design, ✓ transient studies, ✓ stability.
<u>Investigations of nozzles:</u> ✓ flow separation phenomenology, ✓ side loads, ✓ advanced nozzles, e.g. Dual Bell.

Table 1: P6.2 Simulation Tasks

- <u>gas supply:</u>	
max. feeding pressure p_c	4 MPa (opt. 6 MPa)
max. ejector system pressure p_{ejc}	4 MPa (opt. 6 MPa)
min. altitude chamber pressure p_{alt} without ejector system	< 4000 Pa
min. altitude chamber pressure p_{alt} with ejector system	< 2500 Pa
N_2 feeding gas mass flow rate	2.8 kg/s (opt. 4.2 kg/s)
N_2 ejector gas flow rate	2.8 kg/s (opt. 4.2 kg/s)
N_2 bleed gas flow rate	2.8 kg/s
- <u>measurement system:</u>	
high frequency system (HF)	16x 50 or 8x 100 kHz
low frequency system (LF)	64x 1 kHz
Anti-aliasing filter for LF/HF	50x
Data capacity per test	4 GB
- <u>altitude chamber</u>	
axial length	1000 mm
diameter	800 mm
window access	1x Ø500 mm (acrylic glass) 2x Ø400 mm (with 210 mm Quartz glass)

Table 2: Features of SSTF

[1] according to US Standard Atmosphere

per test day. The HASC provides optical access through three windows, two windows with a diameter of 400 mm and one with a diameter of 500 mm. The inner diameter of the chamber is 800 mm and the height is 1000 mm. Due to the windows or the large space inside of the open HASC, it is possible to use laser measurement technique, infrared cameras or colour Schlieren optics. The tests run with a MCC system which consists of a control, a command and a measurement system connected with a computer. The measurement system consists of a high and a low frequency recording system. With the high frequency system it is possible to sample data up to 100 kHz. The low frequency system is able to record data up to 1 kHz. Adjustable anti-aliasing filters can be used. Also 32 event channels are available. The data capacity per test is about 4 GB. During each test run a video equipment is used to record optically. The most important properties of the test facility are summed up in Table 2.

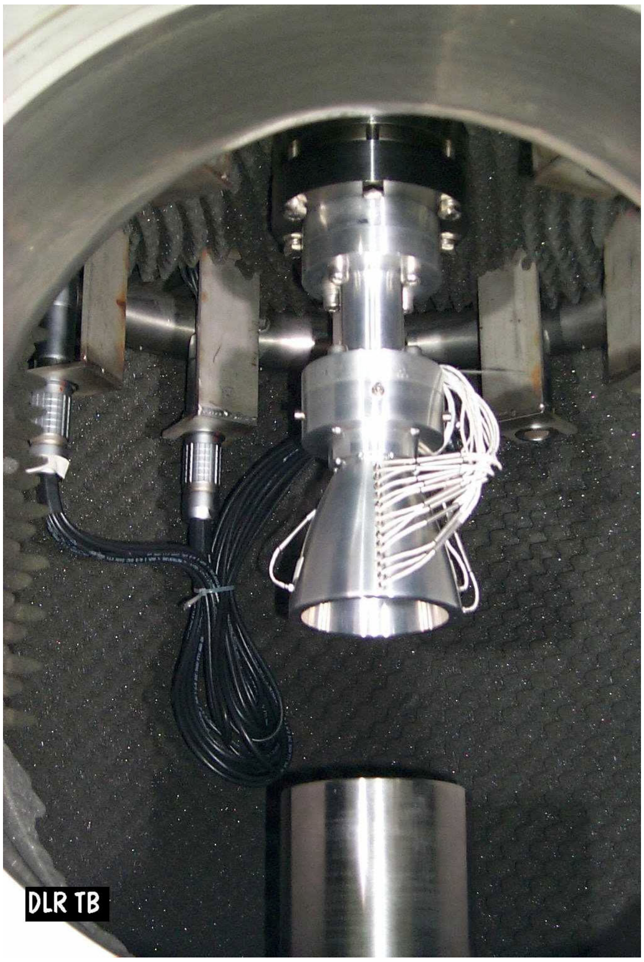

Figure 3: TOP nozzle mounted inside the HASC including pressure transducers

Ejector System

The new installed ejector system, see Figure 4, evacuates the system and the HASC before starting the nozzle. The objective is to simulate a starting of the nozzle in low pressure environment. A cone nozzle or a Thrust Optimised Parabola (TOP) nozzle contour will be used for the ejector system. With the information we get from the tests, it is possible to check our mathematical models e.g. characteristic lines. Of course it is also possible to operate the ejector system out of design, e.g. to see chugging.

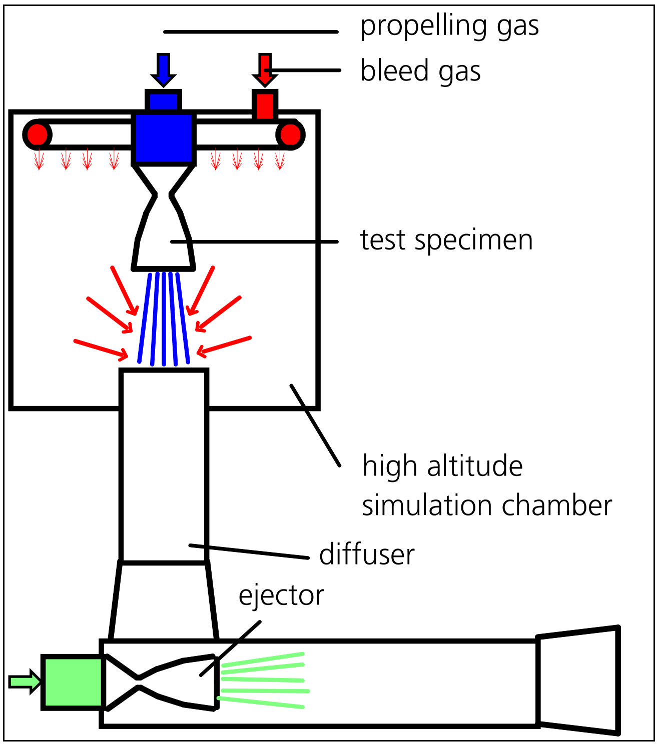

Figure 4: P6.2 SSTF with new installed ejector

Horizontal Test Possibility

In order to prevent some unforeseen influences of the HASC or of the diffusers during sea level tests of the nozzles, it is also possible to set up a horizontal test position as seen in Figure 5. The maximal feeding pressure is also 4 MPa with an option of 6 MPa.

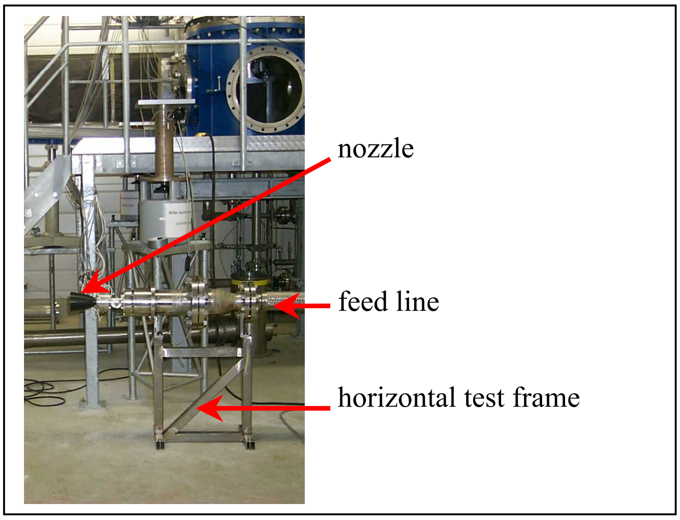

Figure 5: horizontal test set-up of SSTF P6.2

Measurement and Data recording

Pressure and Temperature Transducer:

The pressure transducers which are mainly used on the SSTF are fabricated from Kulite Semiconductor Products Inc[2]. Of course different measurement ranges of pressure levels were covered e.g. combustion chamber and nozzle wall pressure. The principle of the measurement is an active full Wheatstone bridge which is diffused in a membrane of silicon. With these pressure transducers it is also possible to measure the temperature of the gas at the same time while measuring the pressure. Also conventional Pt100 transducers were used to measure the temperature e.g. in the HASC or in the feed lines.

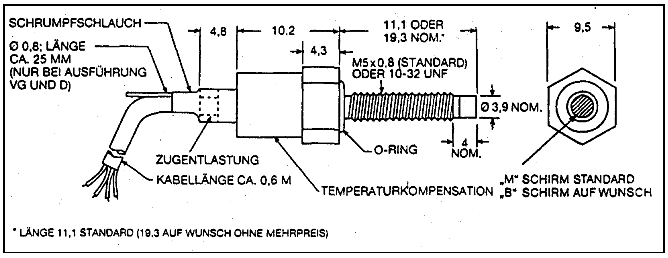

Figure 6: Sketch of Kulite Pressure Transducer

Data recording:

The computer system is a conventional workstation. The received data is stored on hard discs on the test facility. This data is analysed and diagrammed with a tool from Dynaworks, see Figure 7.

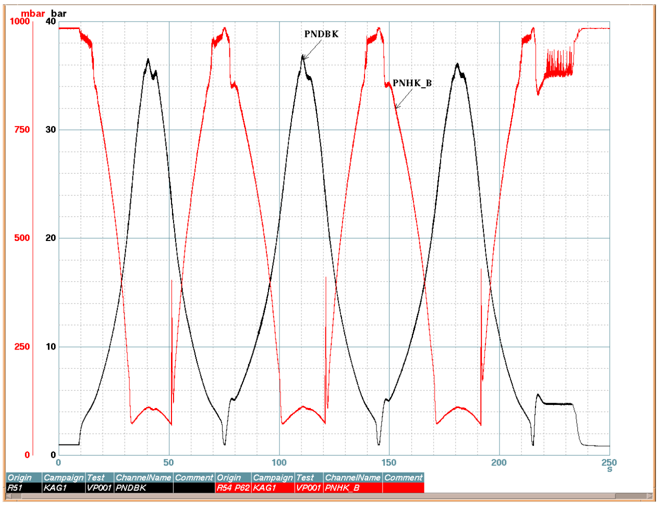

Figure 7: Example plot of a combustion chamber and altitude chamber pressure in Dynaworks

PERFORMED TESTS

Figure 8 shows a short statistic of some tests which were performed in the last 2 years on P6.2.

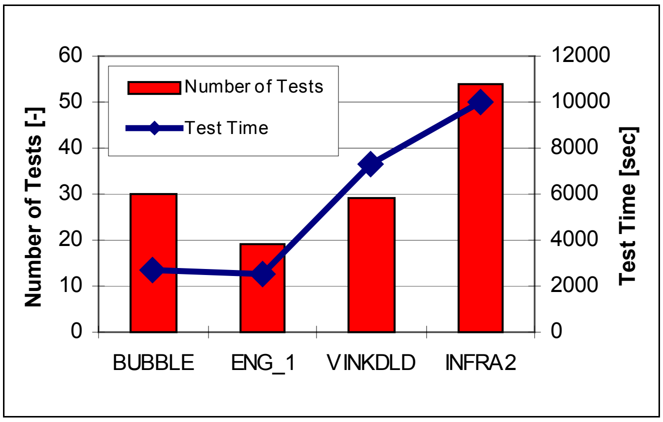

Figure 8: statistic over a few campaigns

Nozzles

Different types of nozzle contours were tested for flow examination at the SSTF, namely a TOP, a truncated ideal contour nozzle (TIC), a dual bell nozzle and a simple cone nozzle with a half angle of 15 degree. For the subscale tests aluminium nozzles with a throat diameter r_t = 10 mm were used, yielding maximum mass flows in the range of $m \approx 4.2$ kg/s. Numerous dynamic wall pressure sensors are placed both upstream and downstream of the throat. The absolute pressure value is measured at scanning frequencies of 1 or 25 kHz, static pressure values can be reached by averaging the signals over an integration time of 0.25s. In overexpanded rocket nozzles the flow separates from the nozzle wall as long as the ratio of wall pressure to ambient pressure p_w / p_a is lower than about one third [1]. However, flow separation in rocket nozzles is undesired because it can lead to dangerous lateral forces, so-called side-loads which might damage the nozzle. This is why in rocket engines, contours are used which - in the case of nominal conditions - yield an exit wall pressure high enough to prevent flow separation.

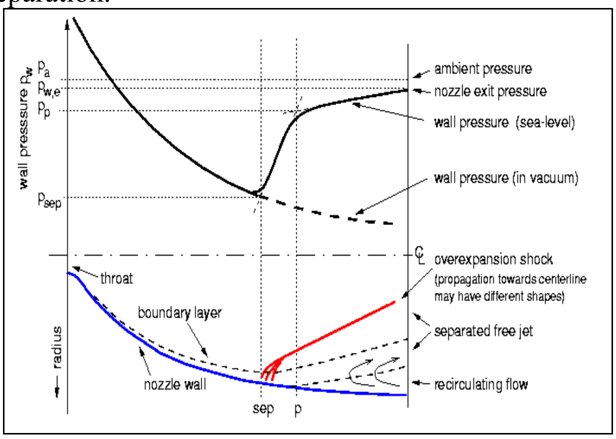

Figure 9: Free Shock Separation

In highly overexpanding flow condition, the plume of the TOP nozzle types show the cap-shock pattern, which results from an interaction of the recompression shock adapting the overexpanding exhaust flow to ambient pressure, and an inverse Mach reflection of the internal shock at the nozzle centreline. In recent years, the cap-shock pattern has been identified as the

[2] http://www.kulite.com

key driver for the transition in separation pattern from free- to restricted shock separation and vice versa [6]. The typical flow phenomenology for free and restricted shock separation is given in Figure 9 and 10.

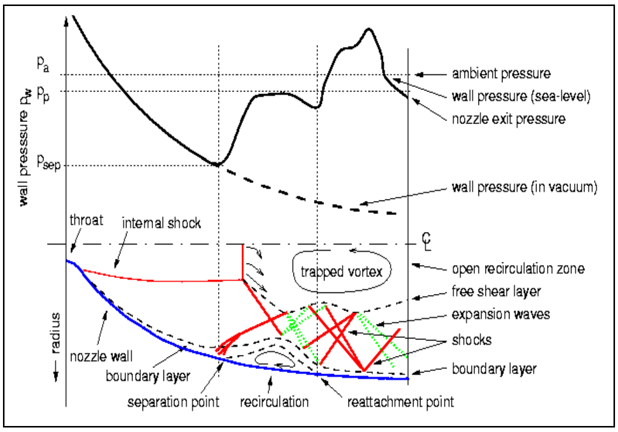

Figure 10: Restricted Shock Separation

Also a model of the new VINCI upperstage nozzle in ε = 22 configuration was tested including a “gimballing” device, see Figure 11. This gimballing device is not movable. Only fixed deflection can be adjusted.

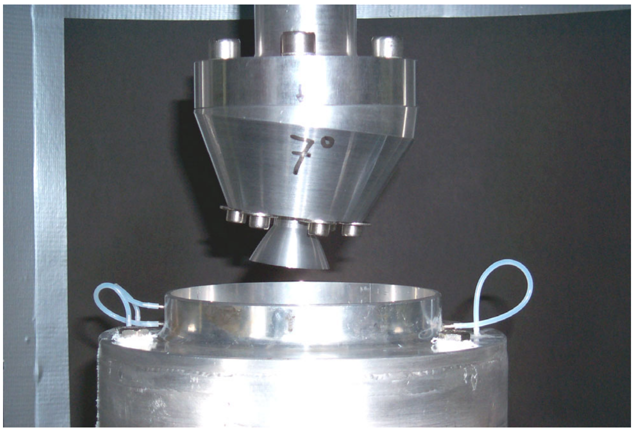

Figure 11: Fixed gimballing device for a nozzle adjusted with 7 degree exhausting in a centerbody diffuser

Diffusers

Three different types of supersonic diffusers were tested at the SSTF, namely a tube diffuser, a second throat diffuser and a centre-body diffuser. First, investigations of the start-up and shut-down (hysteresis) behaviour of different types of diffusers have been done. Also the influence of the distance between the nozzle exit area and the diffuser inlet area was an objective of an investigation. Additionally for the centerbody diffuser the influence of geometric conditions, e.g. the ratio of length to diameter L / D were tested. With this information it is possible to check our mathematical models e.g. characteristic lines. It is also possible to check the influence of the load conditions e.g. from the gimballing of the nozzle, see Figure 11.
One subsonic diffuser is also available to guide the exhaust gases out of the test cell.

Tube Diffuser:

A tube diffuser is the easiest variety of diffusers. It consists of a simple tube with a short divergent outlet.

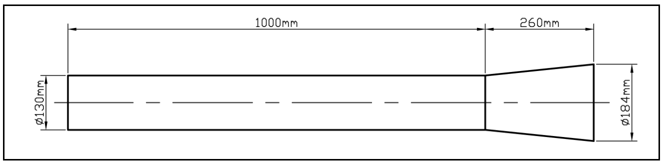

Figure 12: Sketch of a Tube Diffuser

Second Throat Diffuser:

A second throat diffuser is similar to the tube diffuser but with an additional stricture, called second throat after the throat of the nozzle.

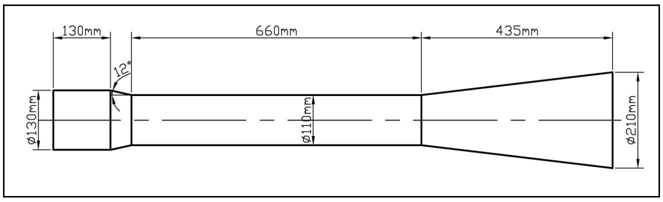

Figure 13: Sketch of a Second Throat Diffuser

Centerbody Diffuser:

A centerbody diffuser is a mixture of the two above mentioned diffusers. It consists of a simple tube and inside of an axis-symmetrical centerbody with a rounded cone. The centerbody creates the principle of a second throat. All diffuser constructions were made by DLR Lampoldshausen.

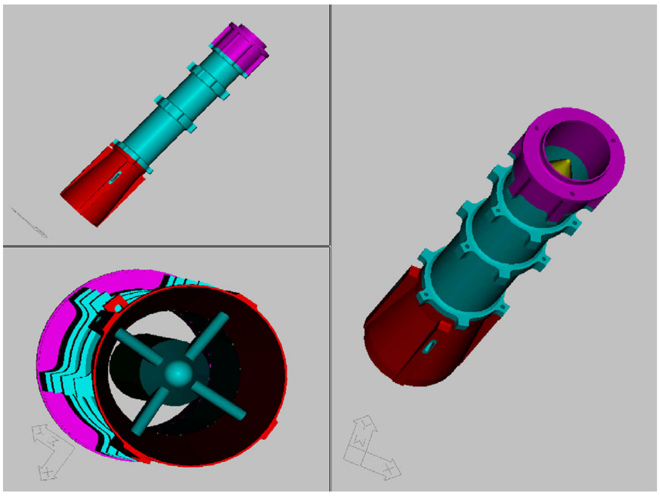

Figure 14: Centerbody Diffuser under construction

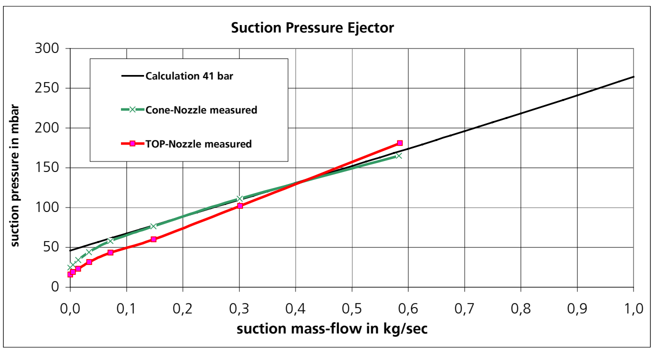

Figure 15: Comparison of calculated and test data

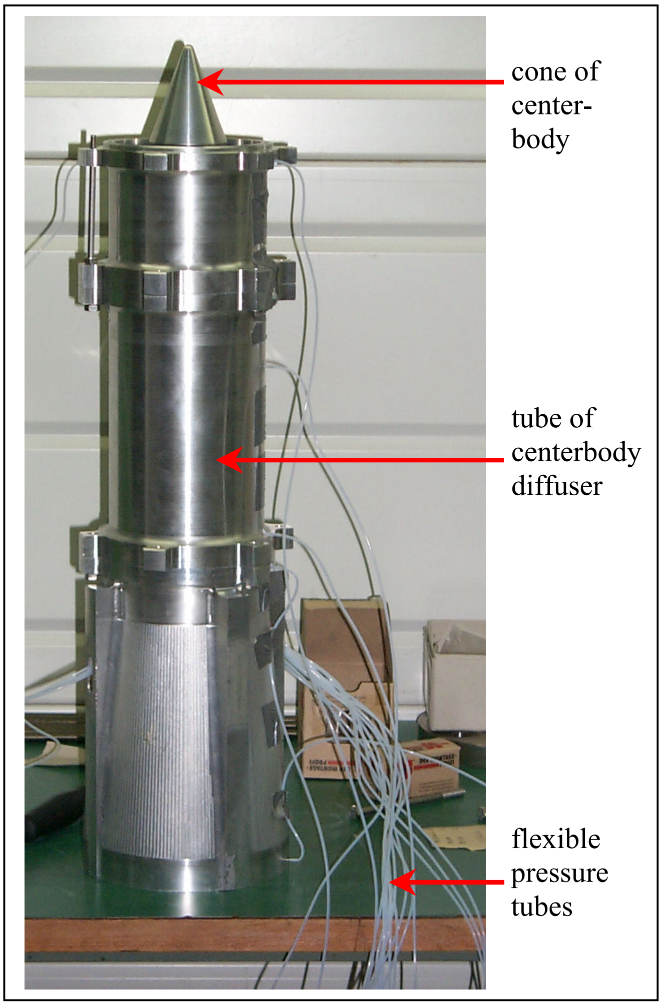

Figure 16: Centerbody in assembly

As seen in Figure 15, the calculated results are close to the test results. This is a really good verification of our mathematical models.

Visualisation Possibilities

Among the normal measurement of pressures and temperatures with the transducers, it is also possible to visualise flow patterns in- and outside the nozzle.

Schlieren Technique:

Schlieren methods are very well known measuring techniques for the visualisation of flow fields. Light will be deflected due to a refractive index gradient (caused for example by a density gradient), which is oriented at right angle to the light beam. This deflected light is separated from the undisturbed light by means of a Schlieren stop (e.g. in black/white Schlieren or monochrome Schlieren by a knife edge), which is placed in the cut-off plane. In black/white Schlieren, the image of the investigation object in the camera shows these gradients as different shades of grey. With a Colour Schlieren technique these refractive index gradients are visualised by different colours, which are easier to distinguish for a human eye than the different shades of grey, see Ref. [8]. At the SSTF P6.2 in Lampoldshausen it is possible to use even Colour Schlieren Technique.

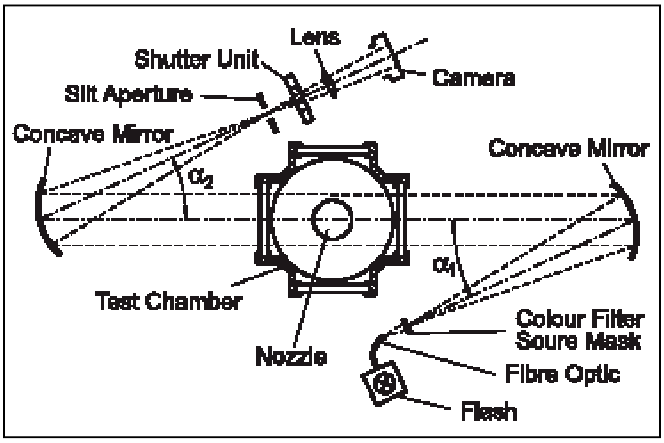

Figure 17: Colour-Schlieren set-up

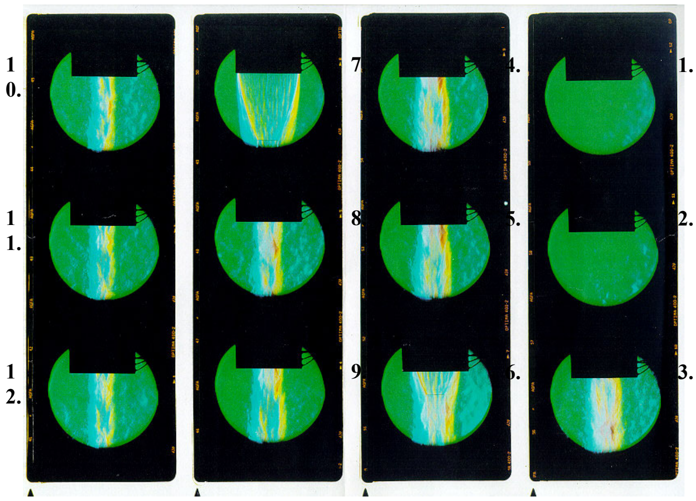

Figure 18: Colour Schlieren of a cone nozzle

Figure 18 shows the flow visualisation via Colour Schlieren of a starting (top right), full flowing and shut down (bottom left) cone nozzle.

Infrared camera measurement:

Research of the influence of the separation pattern on the wall heat transfer and both separation patterns, free- and restricted shock separation, have been the subject of investigation. The local wall temperatures have been measured by infrared thermography. Furthermore, the formation of vortices near the wall has been observed [6], see Figure 19 and Table 3.
For the investigation of the inner nozzle wall temperature an “Inframetrics 600” camera was used. This type of camera works in the wavelength region of 8-14 µm (IR long wave). This region is almost free of absorption by water vapour and enables a high thermal contrast. Due to a cryogenic nitrogen vessel the mounting of the infrared camera was limited in horizontal and vertical positions. Therefore it was mounted inside the open altitude chamber (sea level conditions) beside the diffuser with a mirror attached to it, to enable a view on the inner nozzle surface.

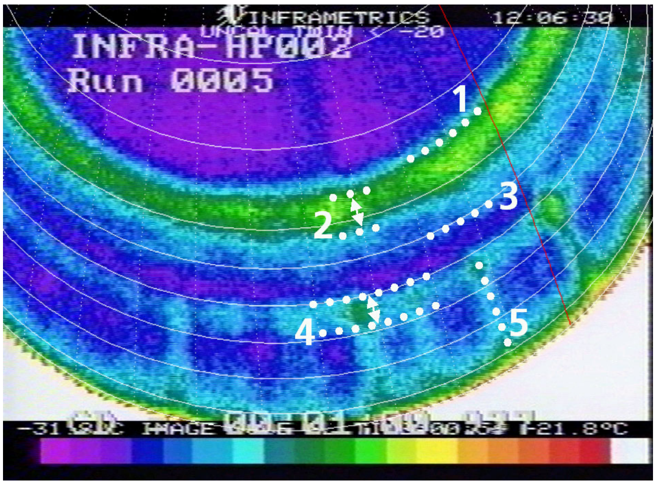

Figure 19: Infrared image, pressure ratio p_c / p_a = 21.8 during shut-down, temperature range: 241 – 295 K

N°	illustration:
1	Incipient separation line
2	Closed re-circulation zone in RSS
3	Re-attachment line
4	Hypothetical second re-circulation zone
5	Trace of vortex

Table 3: legend to Figure 19

At the given pressure ratio of p_c / p_a = 21.8, the incipient separation starts at x / r_t = 6.7. The flow physically separates at $x / r_t \approx 7.2$. Here, the wall temperature reaches a plateau value, and then decreases again further downstream. In between, a closed re-circulation zone is established. Further downstream of the initial detachment line, the flow re-attaches to the nozzle wall, thereby inducing a wall pressure peak significantly higher than the ambient pressure. This re-attachment which closes the re-circulation zone occurs at x / r_t = 9.2 [6].

Video camera:

A video camera is used to observe the tests. Single pictures can also taken to compare numerical and test results. This was for example done in the BUBBLE campaign [6].
To investigate the flow pattern in the plume behind the nozzle, experiments using threads were made in order to visualise the flow direction. A horizontally mounted wire with a diameter of 0.5 mm was placed behind the nozzle with 13 threads attached to it, at 10 mm intermediate distances. The middle thread was positioned on the symmetry-axis of the test set-up. Experiments were conducted with the wire positioned at different locations. It must be taken into account, that the wire certainly disturbs the exhaust plume. To minimise the flow disturbance, only one wire was used for a test run. The drag of the wire in the flow caused the wire to be displaced up to approximately 1 cm, which was considered further in the evaluation. Nevertheless the results clearly show the presence of a stable re-circulating flow region in the TOP nozzle plume by the threads which are clearly directed upwards. For more information see Ref. [6].

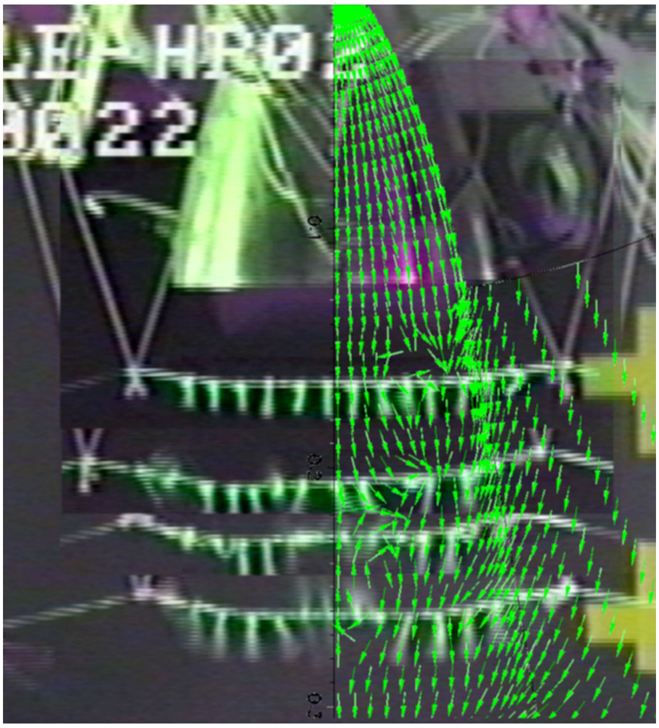

Figure 20: Superposition of experimental and numerical results for the plume flow structure of the TOP nozzle, pressure ratio p_c / p_a = 60

Side load measurement

Side loads are forces perpendicular to the nozzle axis. Usually it is very hard to directly measure them. Instead, most experiments measure the resulting torque with respect to a cardan point. In the SSTF, a simple set-up without moving parts has been realised. Upstream of the convergent nozzle part a bending tube is mounted, on which strain gauges are placed, two in each quadrant. The bending tube has very thin walls, but is made of a special aluminium alloy, so it can withstand the forces of the high pressure inside, it is still sensitive with respect to lateral forces. Two full Wheatstone bridges are used to get strain gauges signals for both lateral directions, where only bending displacements are measured. All other displacements, such as the ones due to the pressure inside or the longitudinal nozzle forces, are compensated by the wiring. The strain gauge voltage is proportional to the extension of the tube due to bending, i. e. the response of the structure to the applied bending torque. For static problems, there is a proportionality between the structural response and the bending torque. However, if a dynamic lateral force acts, the connection between voltage and torque gets much more difficult, and the consideration of the whole dynamic system is necessary to recalculate the applied torque from the measured system response. This requires the determination of the transfer function, see [6].

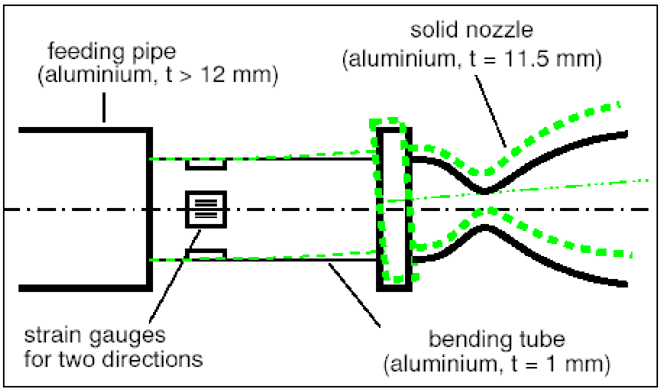

Figure 21: Bending tube used to measure the side load torque

TIME SCHEDULE OF P6.2

At the SSTF a lot of work will be done in the next months, see Figure 22.

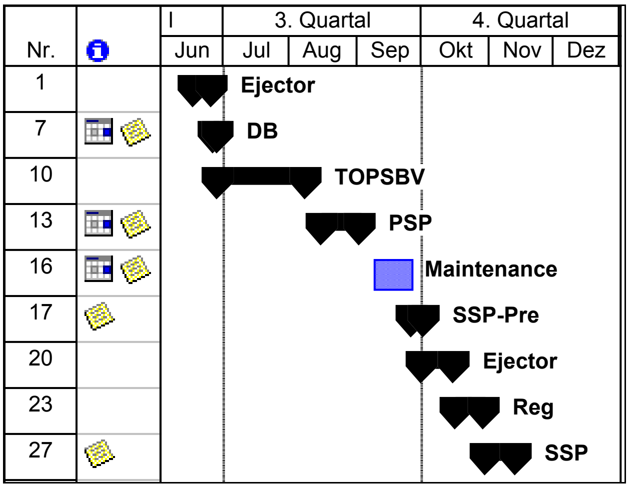

Figure 22: Allocation of P6.2 until nearly the end of this year

SUMMARY AND OUTLOOK

This short review shows, that a lot of work was done on the Cold Gas Subscale Test Facility P6.2 at the German Aerospace Center in Lampoldshausen in the last 3 and a half years. Plenty of know-how was won in the field of flow separation in nozzles, diffuser technology and similarly will be done in the field of ejector systems especially for rocket altitude test facilities.

One thinks also about to upgrade the P6.2 with a preheating unit for the gaseous nitrogen. Further it is possible to extend the know how in diffuser technology with a moveable centerbody diffuser. Also the field of advanced nozzle technology, like plug or dual bell nozzles types, is wide open.

REFERENCES

[1] M. Frey, G. Hagemann: *Status of Flow Separation Prediction in Rocket Nozzles*, AIAA 98-3619, Cleveland, July 1998

[2] M. Frey, G. Hagemann: *Flow Separation and Side-Loads in Rocket Nozzles*, AIAA 99-2815, Los Angeles, June 1999.

[3] M. Frey, R. Stark, H. K. Ciezki, F. Quessard, W. Kwan: *Subscale Nozzle Testing at the P6.2 Test Stand*, AIAA 2000-3777, Huntsville, Alabama July 2000

[4] G. Hagemann, M. Terhardt, D. Haeseler, M. Frey: *Experimental and Analytical Design Verification of the Dual-Bell Concept*, AIAA 2000-3778, Huntsville, Alabama July 2000

[5] W. O. H. Mayer: *Cryogenic rocket engine research within the National Technology Program TEKAN at the German Aerospace Center*, Aerosp. Sci. Technol. 5 (2001) 273-282, Éditions scientifiques et médicales Elsevier SAS

[6] R. Stark, W. Kwan, F. Quessard, G. Hagemann, M. Terhardt: *Rocket Nozzle Cold Gas Test Campaigns for Plume Investigations*, 4th European Symposium on Aerothermodynamics for Space Vehicles, Capua, Italy, Oct. 15 – 18, 2001

[7] Gross, O. Haidn, R. Stark, W. Zeiss, C. Weber, C. Weiland: *Experimental and Numerical Investigation of Heat Loads in Separated Nozzle Flow*, AIAA 2001-3682, Salt Lake City, UT

[8] H. Ciezki: *Entwicklung eines Farbschlierenverfahrens unter besonderer Berücksichtigung des Einsatzes an einem Stoßwellenrohr.* Diploma Thesis, Technical University Aachen, Germany

[9] *European Seminar on Rocket Nozzle Flows*, organised by CNES, October 12-14 1998, Paris, France