P6.2 COLD GAS TEST FACILITY FOR SIMULATION OF FLIGHT CONDITIONS – CURRENT ACTIVITIES

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Abstract

New developments like advanced nozzles, unexpected events during flight or the development of reusable systems drive again the question how to qualify rocket engines and propellant systems. It's getting more and more necessary to test rocket engines closer to original flight conditions.

The test position P6.2 has been developed and erected in the field of gas dynamic studies in cold gas conditions. The objectives for P6.2 are basic research in altitude simulation for rocket engines and in flow separation phenomena of advanced nozzles. A special task for the P6.2 facility is the simulation of transient environmental pressure conditions similar to the flight conditions of a launcher during lift off.

Several techniques were tested to visualise the flow of over expanded nozzles.

1 Introduction

From the very beginning in the 1960s, DLR Lampoldshausen has been involved in all European launcher programs and one of its main tasks has always been high altitude testing of rocket engines.

To maintain the experience of the test facility engineering and to improve the altitude simulation especially the development of rocket steam generators and the simulation of flight conditions the department of engineering was founded in 1996 within the institute of space propulsion.

In 1998 the P6.2 test facility was developed and erected for the improvement of the altitude simulation and for basic research in flow separation of over expanded nozzles. The main task was the development of an altitude simulation with variable pressure conditions. The pressure should be regulated from $p = 1$ bar at sea level down to $p < 10$ mbar in altitude. The objectives were the investigation of flow separation and transition phenomena of nozzles like dual bell or plug type nozzles.

2 Flight Conditions ARIANE 5

Let's consider the ARIANE 5 to demonstrate the basic flight conditions (table 1). For the main stage engine VULCAIN it's the transition from sea level to altitude conditions and for the upper stage engine AESTUS it's the operation in high altitude.

Table 1: Flight Conditions ARIANE 5

	Time t	Height h	Velocity v	Pressure p	Acceleration a
	s	**km**	**m/s**	**mbar**	**m^2/s**
Start-Up VULCAIN	**-2**	**0**	**0**	**1000**	**9,81**
Ignition Solid Booster	**7**	**0**	**0**		
Mach 1	**50**	**7**	**325**	**400**	
max g	**112**	**39**	**1600**		**43**
Shut-Down Solid Booster	**140**	**65**	**2050**		**43⇒5**
Shut-Down VULCAIN	**585**	**140**	**7620**	**10^{-6}**	**32⇒0**
Separation Upper Stage	**590**	**150**	**7790**	**≈ 0**	
Ignition AESTUS	**595**	**152**	**7790**		
Shut-Down AESTUS	**1500**	**1650**	**8500**		**3⇒0**
Separation payload	**1690**	**1950**	**-**		

The basic operational conditions for the VULCAIN 1 main stage engine are:

- Ignition and Start-Up at sea level conditions (P = 1 bar). Transient pressure conditions during operation from sea level down to vacuum. Shut-Down in vacuum conditions (P = 10^{-6} bar.)
- Dynamic pressure conditions driven by the aerodynamic like buffeting and transonic conditions.
- Operational conditions like accelerations, flight control operations, Gimballing of the engine, rolling of the launcher, acoustic loads at sea level, etc.

The basic operational conditions for the AESTUS upper stage engine are:

- All operational phases with ignition, Start-Up, Steady-State, Shut-Down, Ballistic-Phases and Re-Ignition are in vacuum conditions.
- Flight control operations and changing acceleration conditions down to 0 g.

3 P6.2 Cold Gas Test facility

At DLR in Lampoldshausen there are investigations to improve the flight simulation for rocket engines. The main topics are:

- Improvement of the altitude simulation for the transient engine operations during Start-Up and Shut-Down.
- Simulation of flight conditions for the investigation of advanced nozzle.

The investigations are performed at the cold gas test position P6.2 concerning diffusers, ejectors and other components for altitude simulation and for advanced nozzle designs like dual bell nozzles.

The use of dry nitrogen gas at ambient temperature for operation gives easy handling. With similar Mach and Reynolds numbers (Re ~ 10^7) the results can be transferred to original conditions. For the understanding of the phenomena and the validation of CFD models different visualisation methods were developed.

The P6.1 consists of a vacuum chamber combined with exchangeable super- or subsonic diffusers and optional an ejector system.

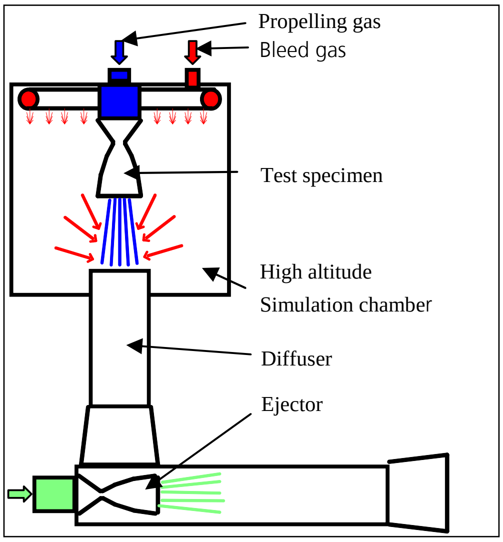

Fig. 1: Principle P6.2

The principle (fig. 1) allows the regulation of the pressure inside the vacuum chamber depending on the behaviour of the diffuser, ejector and the bleed gas injection. The pressure can be adjusted between 1 bar and <10 mbar. The P6.2 conditions are mentioned in table 2.

Table 2: P6.2 Conditions

Conditions	Description
Supply system	N2 cold gas, m ≈ 2.8 kg/s (optional 4.2 kg/s), pressure regulated from P = 10 – 40 bar (optional 55 bar)
Test time	> 60 s with full flow
Altitude simulation	Vacuum chamber < 10 mbar – 1 bar, adjustable for the research of transition phenomena
Measurement and control system	64 LF channels up to 1 kHz, 16 HF channels up to 100 kHz, 32 digital I/O, 4 GB capacity

The characteristic of the pressure inside the vacuum chamber (fig. 2) can be controlled with respect to the requested profile, parameters are:

Diffuser characteristics:

- Sub sonic diffuser (1 to 0,5 bar) or super sonic diffuser (1 to 0,05 bar)
- Different types (Tube Diffuser, Second Throat Diffuser, Centre Body Diffuser)

Geometrical conditions:

- Distance nozzle to diffuser inlet, gap between nozzle and diffuser, volume of the vacuum chamber, etc.

Additional conditions:

- Extractions of boundary layers, use of ejector stages, bleed gas characteristic and conditions, etc.

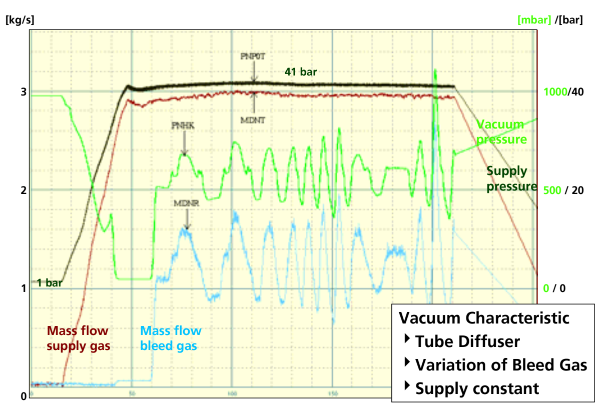

Fig. 2: Pressure Characteristic P.6.2

4 Visualisation Techniques

Different visualization techniques were developed and tested, examples are:

- Pressure Sensitive Paint (PSP)
- Backflow Frosting (BFF)
- Infrared Thermography (IRT)
- Schlieren Optic

4.1 Pressure Sensitive Paint (PSP)

With the PSP it's possible to visualize two dimensional pressure distributions on surfaces by application of a pressure sensitive paint. The PSP technique is based on the process in which photo chemically excited molecules are deactivated by oxygen. This makes different degrees of luminosity recognizable on the surface. The fluorescent image can be visualised by cameras.

The principle test setup for flow separation is using the reaction of the PSP with the oxygen of the ambient air within the backflow region. The nozzle flow itself supplied by nitrogen doesn't react with the PSP until the separation zone. The PSP surface coating (fig. 3, left) and test support are done by DLR Göttingen.

The brightness change marks the separation of the flow to a free jet (fig. 3, right). It is reciprocally proportional to the partial pressure of oxygen. 'Light' means nitrogen flow and 'dark' means ambient oxygen.

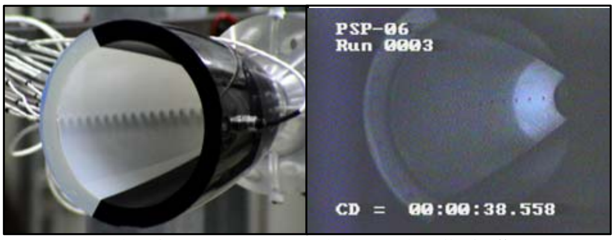

Fig. 3: Pressure sensitive Paint "PSP"

Due to the marginal PSP intensity the signal had to be integrated over 4 seconds and the test stand was darkened perfectly. For the interpretation of the PSP the results has to be verified and analysed by the wall pressure measurements and the general behaviour of the flow separation.

4.2 Backflow Frosting (BFF)

Backflow Frosting (BFF) uses the behaviour of nearly saturated air at the dew point. The test set up is demonstrated in figure 4.

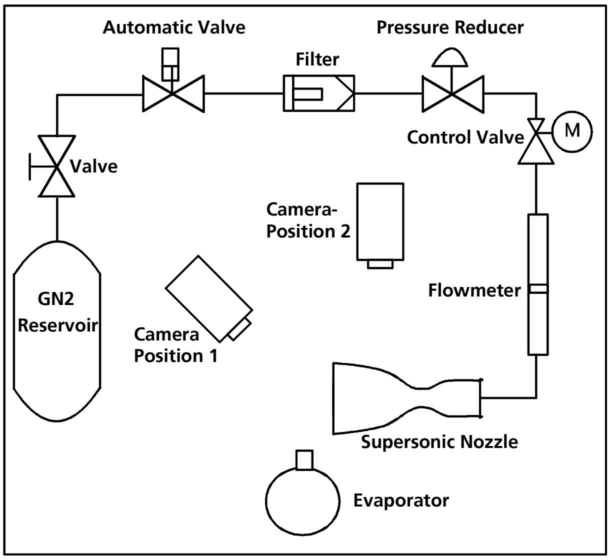

Fig. 4: Principals Test Conditions "BFF"

The nitrogen stored at ambient temperature expands to operational pressure. The temperature decreases depending on the expansion ratio. The cold N2 cools down the nozzle wall. With special material of low heat conduction the local wall temperature is directly linked to the local flow conditions (fig. 5).

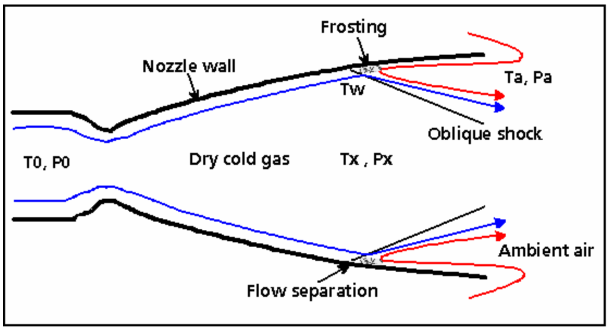

Fig. 5: Principals Flow Separation, "BFF"

The saturated ambient air will frost or condense inside the back flow zone near the wall. The effect can be improved by using an evaporator. The frosting area follows the separation zone. For transparent wall material the effect can be visualized (fig. 6) by cameras or pictures are taken at the nozzle exit (fig. 7).

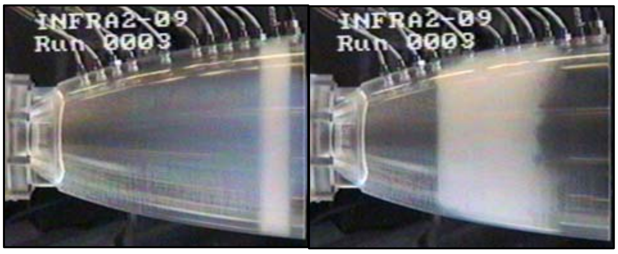

Fig. 6: "BFF" view thru transparent nozzle

Fig. 7: "BFF" view to the nozzle

For the interpretation of the BFF the results has to be verified and analysed by the wall pressure and temperature measurements and the general behaviour of the flow separation. Additionally an overlaid nozzle contour is useful for interpretation (fig. 8).

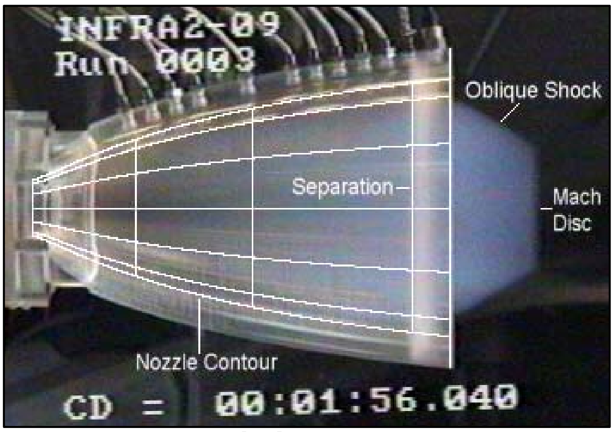

Fig. 8: Back Flow Frosting "BFF"

4.3 Infrared Thermography (IRT)

Infrared Thermography (IRT) is used to visualize wall temperature distribution. The measurements were performed with an ‘Inframetrics 600’- Scanner working in the range from -20 up to 400°C with 2° accuracy.

The IRT result (fig. 9) has to be verified and analysed by temperature measurements and interpretation of the flow conditions.

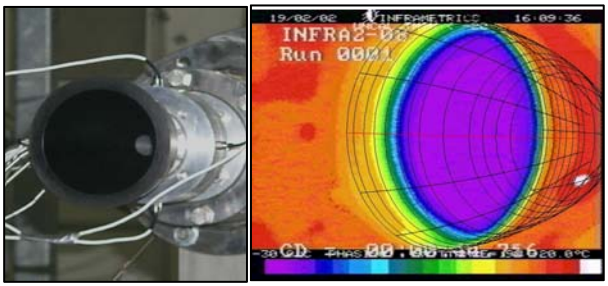

Fig. 9: Infrared Thermography

The nozzle is made of a material with low heat conduction to have a direct link between local flow conditions and local wall temperature. Good experiences were made with acrylic glass nozzles, painted matt black.

4.4 Schlieren Optic

Schlieren optic is used to verify the principle flow characteristic. Shocks and boundary layers are visible (fig. 10).

The results are used to verify the CFD modelling and for the interpretation of the measurements.

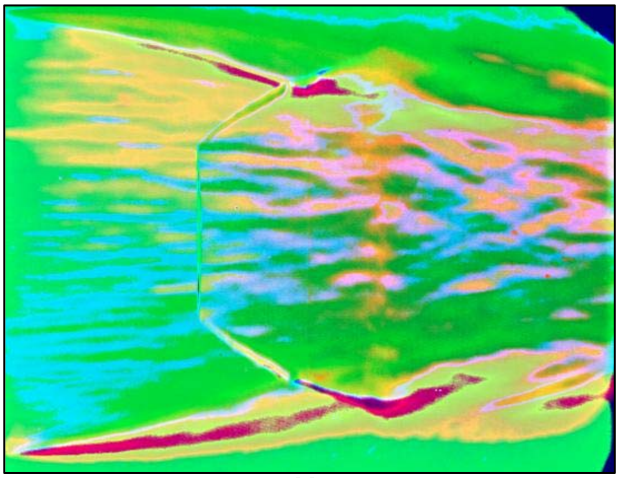

Fig. 10: Schlieren Optic

5 Current activities

Actual there are two activities:

- First activity is the improvement of the vacuum pressure regulation for simulation of flight conditions.
- Second activity is the improvement of the test conditions for dual bell nozzle.

5.1 Regulation of the vacuum pressure

One possibility to regulate the pressure inside the vacuum chamber P_{Vc} is the variation of the ejector supply pressure P_{Ej}. In order to simulate the flight profile a pressure regulation sequence was installed to control the ejector supply pressure and also the vacuum chamber pressure directly within certain limits. In a wide region the vacuum pressure have a static functional dependency of the ejector supply pressure (fig. 11). In these regions the vacuum chamber pressure can be regulated directly.

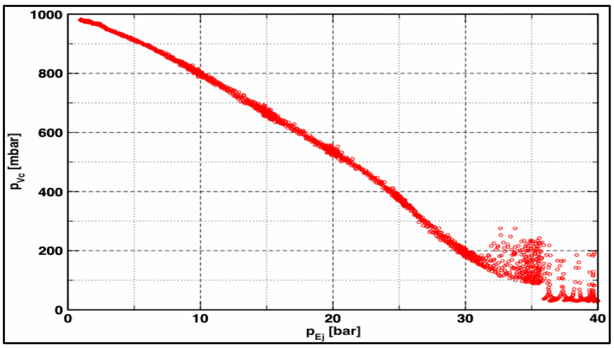

Fig. 11: Vacuum Pressure with Ejector System

An adapted PID regulation was used to perform this operation. The valve opening S_{valve} is calculated directly.

$$S_{valve} = S_{valve}(t_{-1}) + G_0 e(t) + G_1 e(t_{-1}) + G_2 e(t_{-2})$$

The function $e(t)$ is depending on the set point deviation and G_0, G_1 and G_2 are PID parameters:

$$G_0 = K_R\left(1+\frac{T_D}{T}\right)$$

$$G_1 = -K_R\left(1+\frac{2T_D}{T}-\frac{T}{T_I}\right)$$

$$G_2 = K_R\left(\frac{T_D}{T}\right)$$

The parameters where determined experimentally and depends on the reaction time of the regulation valve as well as on the fluid system. The error function *e(t)* is calculated with the set point deviation and a function of depending of the real value, where p_{sp} is the pressure set point.

$$e(t) = -\frac{(p_{sp} - p_{Vc})}{C + p_{Vc}}$$

The constant *C* was also experimentally determined. The closed loop regulation fails at pressure values p_{Vc} below 200 mbar. These points can only be reached by an open loop regulation of the ejector supply pressure p_{Ej}.

The P6 altitude simulation with ejector supply pressure regulation allows vacuum pressure adjustment with an accuracy of 3% relating to a pressure of 1 bar also with mass flow starting from the test specimen.

5.2 Dual Bell Testing

With the new regulation loops a test campaign for a dual bell nozzle was performed. The objective was the analyzing of the flow transition from the first bell to the second bell without feedback from the altitude simulation. The flow "jumping" reacts into a strong momentum change, which has to be compensated by the suction system to prevent the direct "back jumping".

The nozzle was tested without diffuser (fig. 12). Only the ejector system was used.

Fig. 12: Dual Bell Nozzle

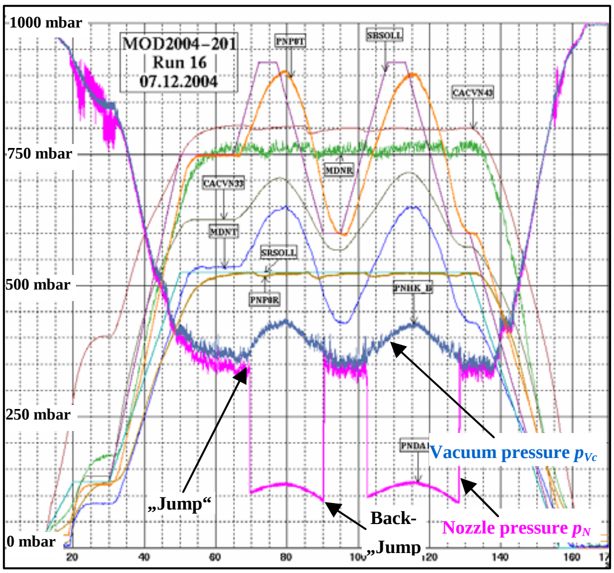

Fig. 13: Dual Bell Test

The ejector system was adapted to subsonic conditions. The flow "jumping" of the nozzle was driven by increasing of the supply pressure. The "jumping" behaviour is as expected (fig. 13) without direct "back jumping", but there was a pressure oscillation of 585 Hz.

The jumping of the dual bell was with a pressure ratio of p_N/p_{Vc} = 90 -93 (supply pressure of the nozzle p_N and vacuum pressure p_{Vc}). The back jumping of the nozzle was with a pressure ratio of about 70 (hysteresis).

By implementation of a pieced tube (fig. 14) between nozzle and ejector the oscillation could be influenced to 1885 Hz and reduced amplitude.

Fig. 14: Pieced Tube

6 Conclusion and Forecast

With the test position P6.2 it's possible to investigate advanced nozzle design by simulated flight conditions.

For the next dual bell nozzle tests the oscillation will be investigated. The use of damping devices is foreseen to exclude completely the feedback of the altitude simulation.

The "jumping" will be driven by reducing the vacuum pressure according to a flight profile for the investigation of the sensitivity and reproducibility of the dual bell nozzle behaviour.

Future developments of the flight simulation system will include the flow conditions around the nozzle too. Possible test conditions are under investigations.

References

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