COLD FLOW TESTING OF DUAL-BELL NOZZLES IN ALTITUDE SIMULATION CHAMBERS

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As the stage design of today's launchers has changed from classical tandem to a parallel configuration and the main stage engine therefore has to fulfill a wider range of operation conditions during ascent of the launcher the rocket nozzle comes into focus as the sub system with the most promising performance gain.

Common main stage rocket nozzles are designed to be full flowing under sea-level conditions to avoid flow separation and undesired side loads. But these requirements limit the expansion ratio and result in performance losses as ambient pressure decreases during ascent. A promising way out is the use of altitude adapting rocket nozzles such as plug nozzles, dual-bell nozzles or nozzles with an extendible exit cone.

The dual-bell nozzle (fig. 1) operates under sea-level and high altitude conditions. Its characteristic wall inflection offers a one-step altitude adaptation, without any moving parts. In sea-level mode the flow separates controlled and symmetrical at the wall inflection, dangerous side loads are avoided and due to a smaller effective area ratio sea-level thrust increases. During ascent of the launcher, at a certain altitude, the nozzle flow attaches to the wall of the nozzle extension until the exit plane and the full area ratio is used. Due to a higher expansion ratio an increase in vacuum thrust is achieved.

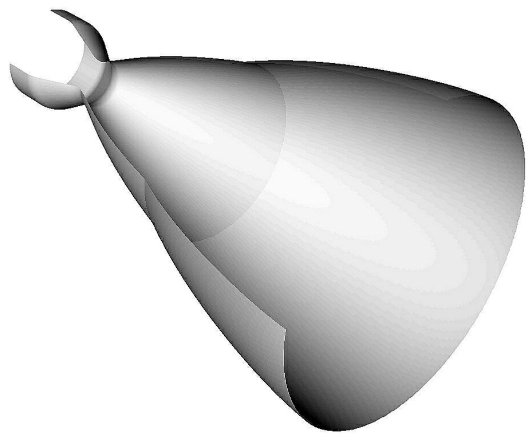

Fig. 1, dual-bell nozzle

With its classical bell design of base nozzle and nozzle extension less changes on existing rocket engines become necessary compared to other advanced nozzle concepts.

First dual-bell tests were published by Horn and Fisher [6], recalculated by Goel and Jensen [4]. Kusaka et al. [7] performed subscale hot firing tests and Wong and Schwane [9] investigated the dual-bell transition numerically. At DLR, Frey and Hagemann started with analytical and numerical studies [3] followed by subscale cold flow test of various dual-bell nozzles, performed at DLR's test facility P6.2 [5].

To fulfill future test requirements the test facility was modified. This paper gives an overview about the upgrading and its results.

P6.2 Test Facility

DLR's cold gas subscale test facility P6.2, located at Lampoldshausen test site in Germany, went into service in 1998. It bases on a closed high altitude simulation chamber (HASC) combined with a supersonic diffuser or a subsonic guiding tube. For a short time an additional ejector system is available.

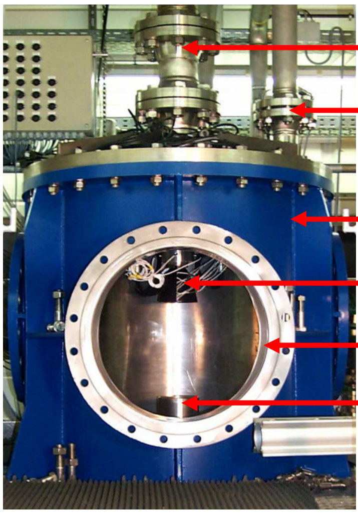

Fig. 2, HASC P6.2 (front view)

Different kind of test specimen can be mounted inside the HASC in vertical position. A propelling gas line provides gaseous nitrogen at pressures up to 4 MPa (opt. 5.5 MPa). Nitrogen is used instead of air to prevent condensation. Using the momentum of the nozzle exhaust jet for evacuation the HASC acts as a self-sustaining system, decreasing the nozzle back pressure. As the diffuser becomes supersonic over its full area the inside altitude chamber pressure decouples from the ambience and pressures down to 40 mbar can be achieved.

A second nitrogen line feeds a ring shaped manifold at the top of the HASC to adjust the altitude chamber condition without varying the specimen feeding pressure. Feeding pressure to altitude chamber pressure ratios p_0/p_{alt} up to 1200 can be realized.

If the additional ejector system is used the specimen can be started under low pressure conditions. The ejector system is supplied with gaseous nitrogen too, with pressures up to 4.5 MPa.

Table 1

Features of P6.2

- Gas supply:	
Max. feeding pressure p_0	4 MPa (opt. 5.5 MPa)
Max. ejector system pressure p_{ejc}	4 MPa (opt. 5.5 MPa)
Min. altitude chamber p_{alt} without ejector	< 4000 Pa
Min. altitude chamber p_{alt} with ejector	< 2500 Pa
N_2 feeding gas mass flow rate	2.8 kg/s (opt. 4.2 kg/s)
N_2 ejector mass flow rate	2.8 kg/s (opt. 4.2 kg/s)
N_2 bleed gas flow rate	2.8 kg/s
- Data acquisition:	
High frequency system (HF)	16x 50 or 8x 100 kHz
Low frequency system (LF)	64x 1 kHz
Anti-aliasing filter for LF/HF	50x
- Altitude camber (inside)	
Axial length	1000 mm
Diameter	800 mm
Window access	1x Ø500 mm (acrylic glass) 2x Ø400 mm (mit 210 mm quartz glass)

The P6.2 facility is a cost-efficient, secure and easy to handle configuration to perform tests and studies in the field of altitude simulation and flow separation of nozzles. If it is necessary to avoid possible HASC effects a second free-standing horizontal test position is available.

For dynamic nozzle wall pressure measurements 'Kulite Semi-conductor Inc.' - Transducers are used (model XT-154-190M). These transducers, with a pressure-sensitive area of 0.4 mm² and an outer case area of 12 mm², have a natural frequency of 50 kHz. The accuracy is within 0.5% in the operating pressure range of 0.1 MPa, with a sensitivity of typically 0.97 V/MPa. The transducers are screwed into the nozzle wall. A small orifice connects transducer and flow. This configuration has a resonance frequency of 8 kHz. Measurement frequencies are 1 kHz for LF- and 25 kHz for HF-Applications. The related filter cut-off frequency is 160 Hz and 8 kHz, respectively.

Dual-Bell Nozzle Performance in Altitude Simulation Chambers

A dual-bell base nozzle is designed as a conventional Rao type nozzle using the methods of characteristics (MOC). As length and expansion ratio are reduced the sea-level mode impulse increases compared to conventional main stage engine nozzles. The flow separates symmetrically and stable.

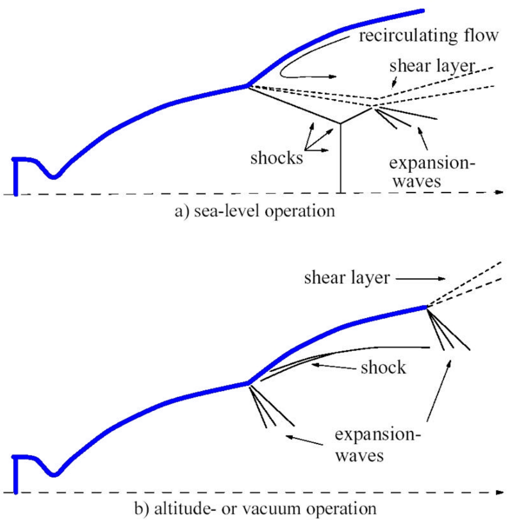

Fig. 3, flow pattern of dual-bell nozzles under sea-level and high altitude operation, taken from [3]

The exit area of the base nozzle marks the wall inflection where a Prandtl-Mayer expansion is applied.

The design requirement of the nozzle extension is a profile of constant wall pressure. This guarantees a certain jump of the separation from the wall inflection to the nozzle exit with a full flowing nozzle extension in high altitude mode (fig. 3). It is achieved by applying MOC once again.

Under sea-level operation ambient air is sucked into the separated flow region of the nozzle extension causing a difference between ambient and inside wall pressure downstream of the wall inflection. The pressure difference results in a thrust loss in sea-level mode that has to be considered as an aspiration drag. The specific sea-level impulse can be estimated as follows:

$$I_{sp} = w_{e,B} + \frac{(p_{e,B} - p_{alt}) \cdot A_B}{\dot{m}} - \frac{\Pi \cdot p_{alt} \cdot (A_e - A_B)}{\dot{m}},$$

Where $w_{e,B}$ and $p_{e,B}$ is the averaged velocity respectively the averaged pressure in the base nozzle exit plane. A_B and A_e are the exit areas of base nozzle and nozzle extension, p_{alt} is ambient pressure and Π is the dimensionless pressure difference between ambient and averaged inner nozzle extension wall pressure $(p_{alt}-p_{e,w})/p_{alt}$.

If the dual-bell nozzle switches to high altitude mode the aspiration drag collapses. The exit area and the averaged exit velocity increases. The averaged exit pressure decreases. Combined the overall specific impulse decreases:

$$I_{sp} = w_{e,e} + \frac{(p_{e,e} - p_{alt}) \cdot A_e}{\dot{m}},$$

The switch in operation mode can be triggered by increasing the ratio of nozzle feeding and nozzle back pressure p_0/p_{alt}.

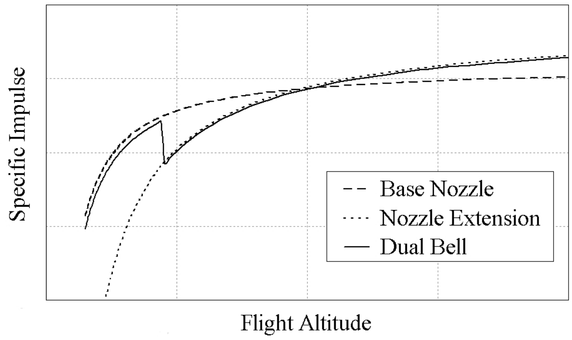

Fig. 4, dual-bell impulse as a function of altitude

In a closed system like a HASC the nozzle exhaust plume contributes with its suction performance to the chamber pressure and therefore to its own back pressure. Strong effects occur if the HASC is designed to evacuate as a self-sustaining nozzle/chamber system. The chamber pressure will rise simultaneously with falling nozzle impulse after an operation mode switch. This causes an immediate rebound of the flow to the wall inflection, followed again by a rise in nozzle impulse.

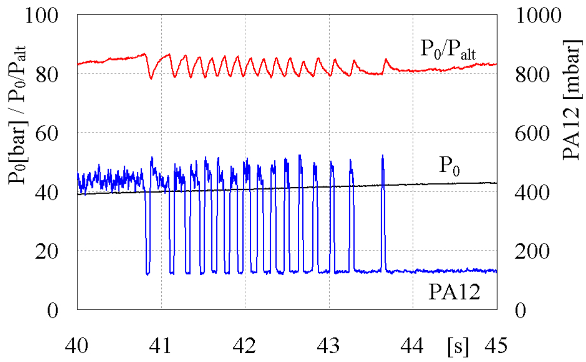

Fig. 5, flip-flop behavior of a dual-bell

If the nozzle pressure ratio p_0/p_{alt} is increased with a small gradient a period of successive transitions and re-transitions follows (commonly called 'Flip-Flop'). A dual-bell nozzle alternating between separated and full flowing nozzle extension is given in fig. 5. Fifteen rebounds are provoked by a small pressure gradient dp_0/dt. The wall pressure transducer PA12, located on a cross section in the middle of the nozzle extension, shows a wall pressure alternating between attached and back flow condition, pressure ratio p_0/p_{alt} pulsates.

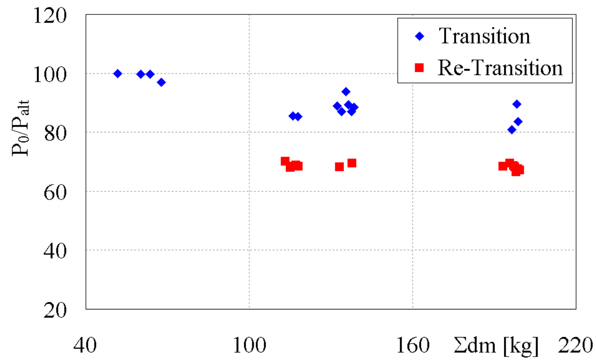

Fig. 6, hysteresis behavior of dual-bell nozzle (mix of explicit transitions and flip-flops)

Dual-bell nozzles feature a hysteresis that partly counteracts an immediate rebound as the necessary re-transition pressure ratio is lower than the one for a transition. An impression is given in fig. 6 where transition and re-transition criteria are shown as a function of the overall mass flow Σdm. A second effect appears after first transition: The temperature impact of the attached flow deforms the nozzle extension. Here, in cold flow tests, the nozzle shrinks. The reduced exit area causes a stabilization as the averaged pressure in the nozzle exit plane $p_{e,e}$ increases. Consequently the transition pressure ratio of following transitions decreases. The hysteresis in combination with an altitude chamber being able to buffer mass flow fluctuations or a primary evacuation system being insensitive for these fluctuations avoids flip-flops.

Tests and Results

To exclude undesired rebounds the guiding tube and the exhaust baffle of the HASC were replaced by a closed ejector system (fig. 7). In literature the characteristic frequency of the separation shock passage is stated to be 400-500 Hz [2]. Test performed on separated nozzle flows at the horizontal P6.2 test position indicate frequencies around 300 Hz. As the HASC dimensions feature resonances in a comparable order of magnitude an additional semi-permeable decouple device (DCD) was installed to prevent a possible coupling between nozzle exhaust jet and internal chamber flow.

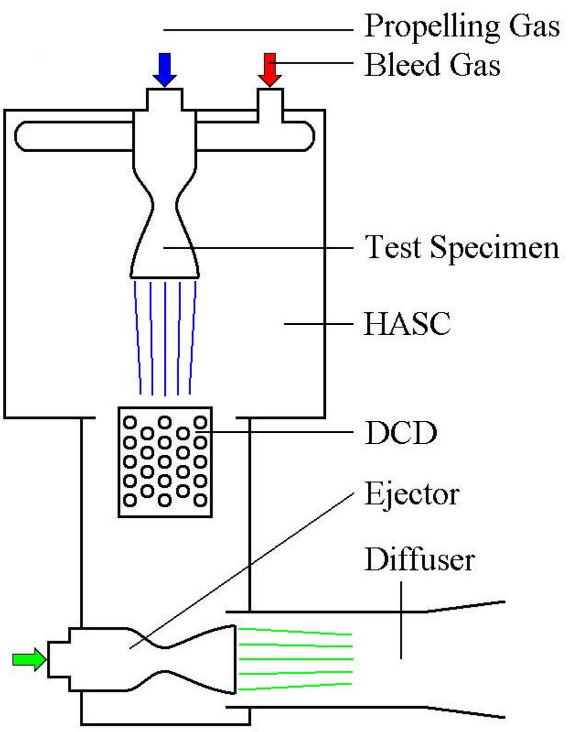

Fig. 7, extended high altitude simulation chamber P6.2

With this setup a unique dual-bell transition as well as a unique re-transition was achieved, without any flip-flop tendency. Fig. 8 gives the response of transducer PA12. Once the transition criteria p_0/p_{alt}>91 is reached and the separation jumps from the wall inflection to the nozzle exit the wall pressure decreases from back flow to attached flow value (top). If the re-transition criteria p_0/p_{alt}<68 is fulfilled a single rebound takes place (bottom). In both cases the hysteresis feature prevents a flip-flop.

To visualize the transition and the plume deflection black and white high speed Schlieren images with a frame rate of 2 kHz were taken (fig. 10). The typical duration of transition was ~2.5 ms, for a nozzle extension length of 0.1 m.

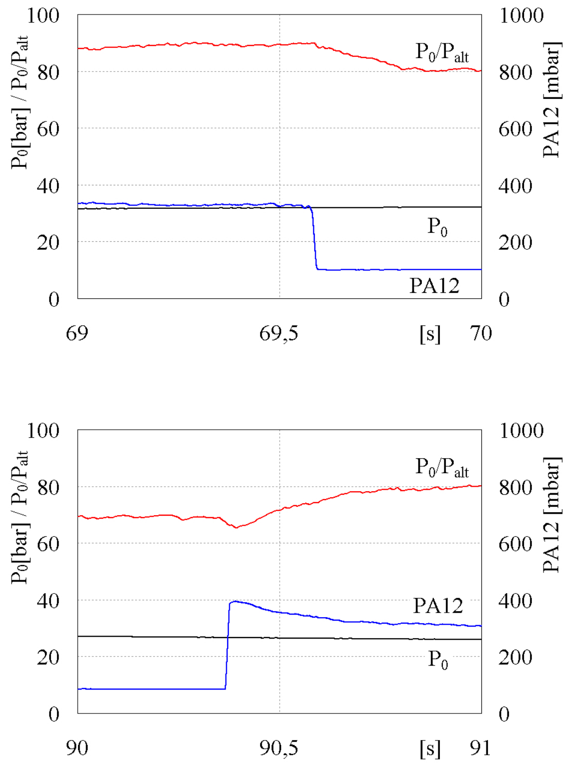

Fig. 8, transition (top) and re-transition (bottom)

The increasing Mach disc tilt angle indicates an accelerated separation front (fig. 10d to 10f). If a wall Mach number of 4.8 and an axial velocity of 685 m/s is assumed the separation front moves during transition with an averaged velocity of approximately 0.28 Ma.

The delay of the asymmetric transition can be determined from images 10f/g to be lower than 0.5 ms (fig. 9). The maximum Mach disc tilt angle taken from images is approximately 8 degrees and occurs at the end of transition.

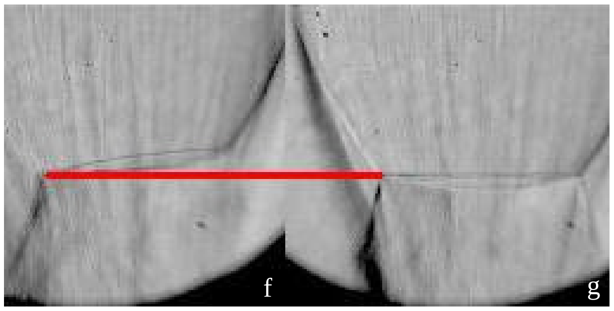

Fig. 9, delay, end of transition

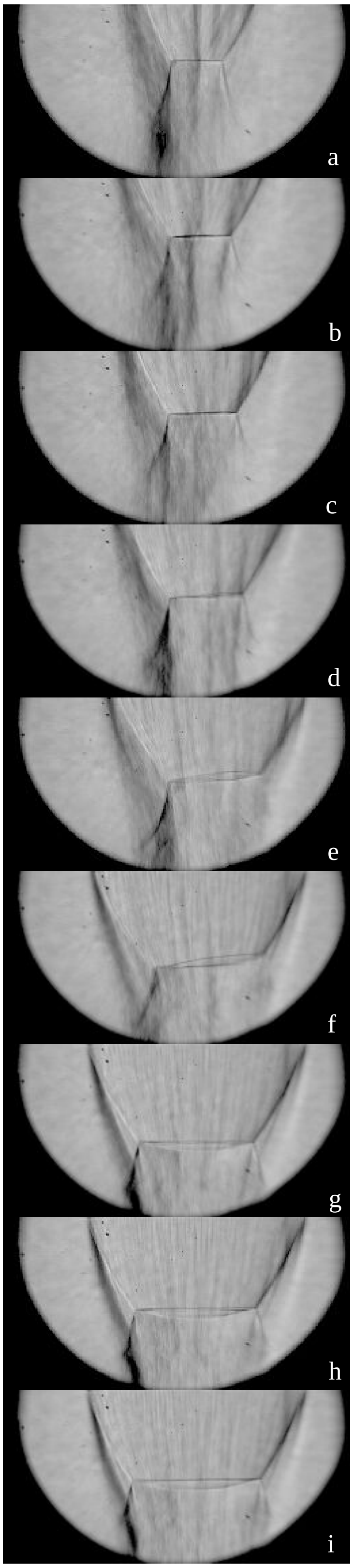

Fig. 10, Schlieren images of dual-bell transition, frame rate 2 kHz

Conclusions

One focus of future dual-bell nozzle tests will be on the influence of total and back pressure fluctuations during transition regime. As big scaled back pressure fluctuations can only be achieved with surrounding chamber systems it is mandatory to decouple the transition process and the described nozzles impulse decay.

The presented tests demonstrate: The applied P6.2 modifications (removing of guiding tube and exhaust baffle, integration of ejector system and decouple device) exclude undesired flip-flops. The dual-bell transition is a result of specified pressure ratio changes $d(p_0/p_{alt})/dt$.

The test bench is ready to install pressure fluctuation generators for both feeding and back pressure fluctuations.

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