THE ALTITUDE ADAPTIVE DUAL BELL NOZZLE

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The dual bell nozzle has been found out to be one of the most promising concepts for altitude adaption of the nozzle jet. The wall contour inflection linking the base nozzle with the extension provides two stable operating modes, circumventing the area ratio limitation inherent to conventional main stage engine nozzles. During the past decade, numerous experimental as well as analytical investigations have been conducted at the German Aerospace Center for a better understanding and the qualification of the dual bell concept for main stage engine application. Cold and hot flow tests aimed to point out the influence of the geometrical parameters on the flow behavior. The conditions for the transition from sea level to altitude mode and back, the hysteresis between these values, the duration of the transition and the resulting side load generation were of particular interest. The contour optimization results in a trade-off between the transition duration, stability and side load amplitude, all depending on the extension length. Out of the experimental work, it was possible to define the parameters for realistic dual bell nozzle geometries and to conduct an analytical study of the nozzle behavior during ascent of a parallel staged heavy launcher. The additional loss in sea level, the so-called drag effect, was evaluated for the chosen nozzle using DLR's CFD in-house code Tau. The present paper gives an overview on current experimental and analytical dual bell research activities.

1. Introduction

The concept of a nozzle featuring a contour inflection was first proposed in 1949 by Foster and Cowles [1], to circumvent the area ratio limitation of main engine nozzles, which have to withstand a wide range of ambient pressures. The dual bell nozzle (patented in 1968 by Rocketdyne) offers two operating modes. At sea level, the high ambient pressure forces the flow to separate. The contour inflection insures a controlled and symmetrical separation, therefore limiting the generation of high side loads known for separated flows in conventional nozzles. The area ratio of the base nozzle is smaller than a reference main engine nozzle and leads hence to increased thrust at low altitude. During ascent, the ambient pressure undergoes the transition condition. The separation point leaves then the inflection and moves rapidly down to the nozzle exit plane. The altitude mode is reached and the high area ratio of the nozzle extension provides increased thrust. Figure 1 gives a principle schematic illustrating the two operating modes of a dual bell nozzle.

The first feasibility studies on dual bell nozzle both experimental (e.g. Horn and Fisher [2]) and analytical (e.g. Hagemann et al. [3]) were conducted in the 1990's. All performance analyses have confirmed the potential performance gain for a launcher with parallel configuration (like the European Ariane 5) presenting a dual bell as main engine nozzle. The main stage of such an engine operates in a wide range of altitude – from sea level to about 150 km, for the Vulcain 2, imposing the nozzle area ratio limitation to insure attached flow at all time. The dual bell nozzle offers two operating modes, i.e. two altitudes at which the engines can be optimized. The small area ratio at the end of the base nozzle offers safe operation at sea level and an increased thrust. After the transition to altitude mode, the flow attaches in the extension, using the whole area ratio of the nozzle for higher altitude thrust. The potential performance gain obtained out of these studies strongly depends on the chosen reference engine and the various assumptions made on the flow behavior in a dual bell nozzle. Frey and Hagemann [4,6] predicted a potential payload gain up to 72% if a dual bell nozzle was applied to the FSS1 engine. Immich and Caporicci [5,6] indicated a payload gain up to 33% or 1400 kg depending on the launcher application. An increase of the specific impulse of 10 s was calculated by Miyazawa [7]. A study conducted in China by Zheng et al. [8] indicates an impulse gain of 1.8% averaged over the flight of the engine. An effective mass decrease of 3% was calculated by Manski et al. [9]. Additional losses are generated in sea level mode due to the aspiration drag of the separated extension (in the range of 3%) and in altitude mode due to the contour inflection (0.1 to 1.2% compared to an optimized nozzle) [5].

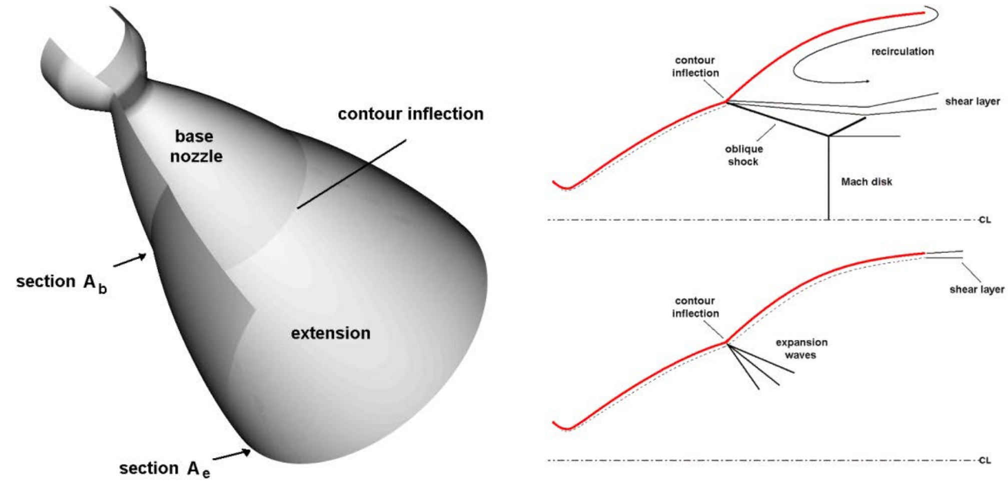

Fig. 1. Principle sketch and the two operating modes: sea level (top) and altitude mode (bottom)

The present work summarized the status of the research on dual bell nozzles, in particular the experimental results of the parametrical studies. Starting from these geometrical limitations, a contour has been defined for a main stage engine of an Ariane 5 ECA like heavy launcher. The performance over the flight is presented together with a first evaluation of the sea level losses, calculated with CFD method.

2. Experimental study

The influence of the various geometrical parameters of a dual bell nozzle on its flow behavior has been investigated in intensive experimental studies. For this reason, cold flow tests have been conducted by the German Aerospace Center at the P6.2 test bench [10,11]. Three subscale nozzle models, featuring different geometries (and designated here as contour DB1 to 3), were tested under sea level conditions. The transition from one operating mode to the other was reached by varying the nozzle pressure ratio (NPR = P_0/P_a) through the up- and down-ramping of the feeding pressure with constant gradients. Wall pressure measurements along the nozzle contour and schlieren optic installation enabled recording the flow evolution in the test specimens. Side load measurements were also conducted, using strain gauges mounted on a bending tube placed upstream to the nozzle throat.

Figure 2 illustrates the evolution of the NPR and the measured side loads during a typical test. While increasing the NPR, the separation point moves progressively down the nozzle contour until it reaches the contour inflection, where it remains fixed during sea level mode. As the transition condition, NPR_{tr}, is exceeded, the separation point jumps rapidly down to the extension end. Its displacement inside the extension is asymmetric and generates a high side load peak. Retransition to sea level mode takes place when decreasing the NPR under the value of NPR_{retr}. The hysteresis between transition and retransition insures the stability of both operation modes toward NPR variation, due for example to combustion chamber or ambient pressure fluctuations during the buffeting phase. It is usually given in percentage and is calculated as the difference of NPR_{tr} and NPR_{retr} over NPR_{tr}.

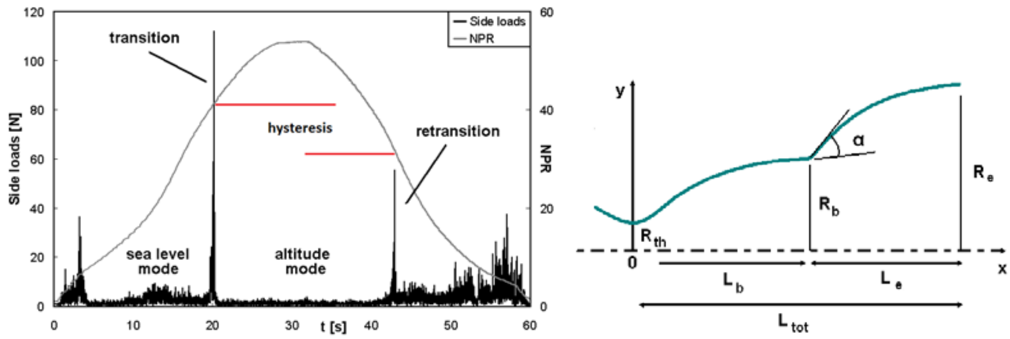

Fig. 2. Side load measurement during a typical cold flow test (left), and geometrical parameters of a dual bell nozzle (right).

The transition conditions strongly depend on the nozzle geometry (see Fig. 2 the geometrical parameters). The base contour length L_b defines the Mach number M_b direct upstream to the inflection. In case of a constant pressure extension (CP), the Mach number in the extension M_e is constant and determined by the contour inflection angle α. Figure 3 indicates also a significant influence of the extension length (here L' = L_e/L_{tot}) on the transition NPR. A transition prediction criterion (eq. 1) has been determined using isentropic relations and the flow separation criterion proposed by Stark [11,12].

$$NPR_{tr} = \frac{1}{M_e}\left(1+\frac{\gamma-1}{2}M_e^2\right)^{\frac{\gamma}{\gamma-1}} \quad (1)$$

A comparison of the transition conditions for the three tested dual bell models with the prediction criterion is given in figure 3 (left). The transition criterion was in very good accordance with the cold flow experiments and gave hence a precise prediction of the altitude at which a dual bell nozzle would operate its transition from sea level to altitude mode. However, the study has also shown a great influence of the extension length on the transition NPR, as illustrated in figure 3 (right). The test specimens featured a constant pressure extension, i.e. the extension contour was designed on an isobar. The reference length of the extension was set for a wall angle at the end of the extension toward zero. The nozzle models have been stepwise truncated to observe the effect of the extension length on the flow behavior. When shortening the nozzle extension, the transition NPR linearly increased. The proposed transition criterion can only be applied when considering the extension in its full length.

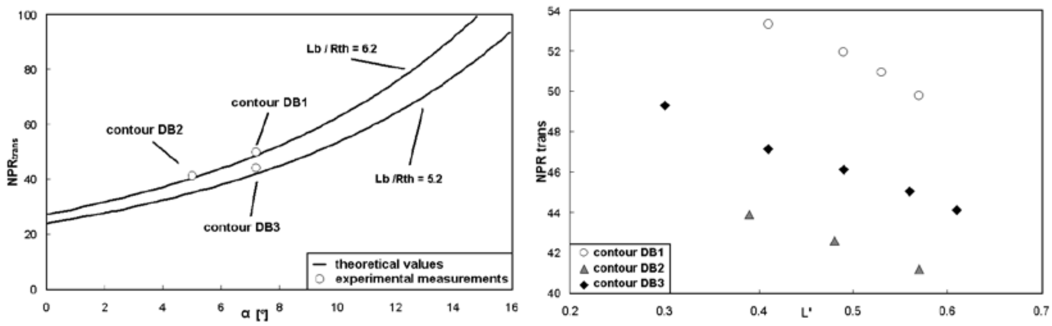

Fig. 3. Transition prediction for the three test models (left), NPR_{tr} as a function of the extension length (right).

The NPR_{retr} follows a similar trend by shortening the nozzle extension. However, the increase of NPR_{retr} is faster than the one of NPR_{tr}, leading to a rapid decrease of the hysteresis range. Figure 4 illustrates the evolution of the hysteresis value with the relative length of the nozzle extension. The truncation of the contour extension leads to a linear decrease of the hysteresis effect between transition and retransition. In real flight application, to insure the stability of the two operation modes toward pressure variations of +/-10%, the hysteresis should be at least of 20%. This corresponds to a relative extension length of at least 50% of the total nozzle length.

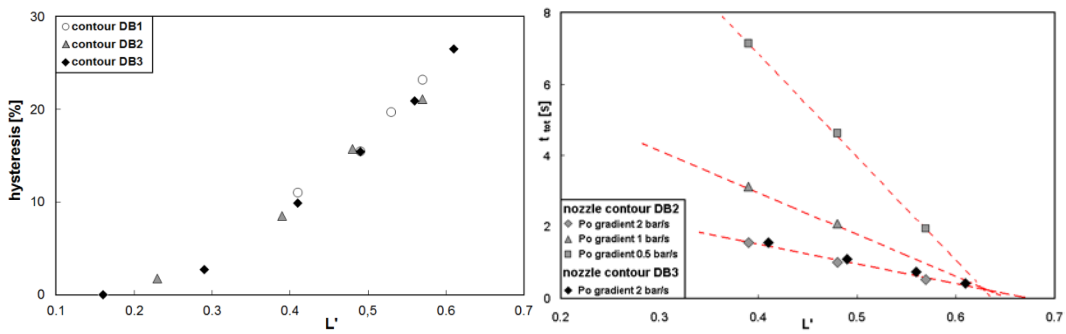

Fig. 4. Extension length influence on the hysteresis (left) and the transition duration (right).

The transition from one mode to the other is an asymmetrical phenomenon, leading to high side load peaks [13], as shown in Fig. 2. Both duration and amplitude of these loads must be limited to protect the integrity of the nozzle and the launcher structures. The transition duration depends mainly on two parameters: the extension length and the gradient of NPR variation, as illustrated in Fig. 4 (right). On the test bench, the NPR evolution is determined by the feeding pressure up- and down-ramping and can be increased to insure a faster transition. In real flight application, on the contrary, the NPR evolution follows the ambient pressure decrease during ascent, which is very slow. However, the transition duration can be reduced by increasing the extension length. Although the distance covered by the separation front during the transition increases with the extension length, the front velocity also increases. In the end, this leads to a shorter transition duration.

The extension length is the critical parameter for the flow behavior in dual bell nozzles. Figure 5 illustrates the influence of the relative extension length L’ on the transition duration and the amplitude of the side load peak generated during transition. The reduction of the side load peak amplitude can be realized by shortening the nozzle extension, leading however to an increase of peak duration. The optimization of the dual bell geometry has to be a trade-off between transition stability, duration and amplitude of the generated side loads.

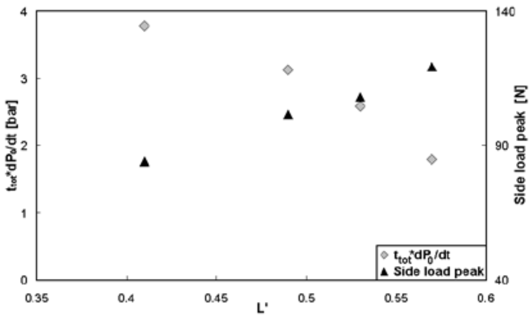

Fig. 5. Transition duration and side load generation.

3. Analysis of dual bell nozzle performance

Out of the experimental study it is possible to define a realistic range of geometrical dual bell nozzle parameters for a main stage engine application. As an example Vulcain 2 and its launch pad setting was chosen and redesigned out of literature data. Table 1 summarizes the geometry limitations and the choices made for an analytical study using the method of characteristics tool TDK94. Two dual bell designs were compared with the original performance. Both extensions start downstream the TEG injection as the film cooled nozzle extension can be easily replaced. The operating parameters of the Vulcain 2 like engine are given in table 2.

Table 1. Geometrical parameters for a dual bell nozzle as main engine

Limitations	Range	Extension 1	Extension 2
Sea level operation	$\varepsilon_b \leq 50$	$\varepsilon_b = 47.5$	$\varepsilon_b = 61$
Launch pad size	$\varepsilon_e \leq 150$	$\varepsilon_e = 147$	$\varepsilon_e = 92$
Realistic inflection angle	$5° \leq \alpha \leq 20°$	$\alpha = 17$	$\alpha = 12.8$
Max. total length	$L_{tot} \leq 4.5$ m	$L_{tot} / R_{th} = 25.4$	$L_{tot} / R_{th} = 25$
Limitation of divergence losses	$\theta e \leq 20°$	$\theta e = 18°$	$\theta e = 9°$
Operation mode stability	Hysteresis ≥ 20%	L’ = 0.48	L’ = 0.24
Transition altitude	h > 10 km or < 7 km (Buffeting)	h = 6 km	h = 1.75 km

Table 2. Operating parameters Vulcaine 2 like engine

Total pressure CC	115.5 bar
ROF CC	7.2
Injection dump cooling	$\varepsilon_{dump} = 30$
Injection TEG	$\varepsilon_{TEG} = 32.3$

The dual bell extension number one starts in the middle of the original film cooled nozzle part and ends at an area ratio of 147 with a comparable high wall exit angle of 18 degrees, whereas number two starts at the original nozzle exit, expanding the flow to an area ratio of 92 with an wall exit angle of 9 degrees. A contour comparison is given in figure 6 (left).

The resulting engine performances are presented in figure 6 (right), where the thrust, normalized by Vulcain 2 like vacuum thrust, is given as a function of the altitude. Both dual bells

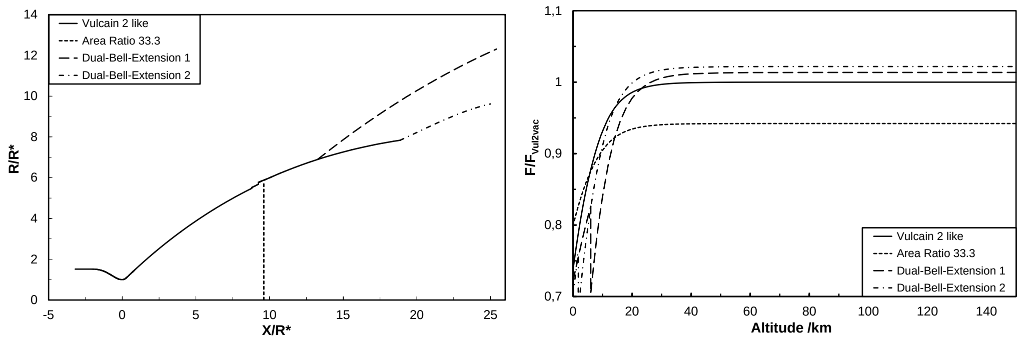

Fig. 6. Nozzle contours (left) and normalized thrust as function of altitude (right).

show sea level mode losses, caused by the drag of the separated extension as the inner wall pressure is lower than the ambient one. Extension number two generates less losses and its performance gain starts at a lower altitude. The performance gain at high altitude is 1.35 % for dual bell number one and 2.19 % for number two. Applied to a parallel staged heavy launcher like Ariane 5 ECA the potential payload gain is in the order of 145 kg and 240 kg respectively. Compared to literature this seems little. But keep in mind, the before mentioned literature studies are about engines that are designed with optimized dual bell nozzles, as the base nozzle is free to choose. To achieve a payload gain of e.g. 500 kg an increased performance of around 4.5% will be necessary.

4. Preliminary CFD Study of a Dual Bell Nozzle during atmospheric flight

Numerical simulation of a dual bell contour was also performed. The DLR finite volume flow solver TAU was chosen for its wide range of flow case applications [14]. For the present investigation, the Reynolds averaged Navier-Stokes equations were solved with a one-equation turbulence model on hybrid meshes. The original Spalart-Allmaras turbulence model was chosen for its good results on separated nozzle flows [15]. The nozzle flow was considered as a frozen mixture of perfect gases as a first attempt.

A Vulcain like configuration with a dual bell nozzle extension was simulated for a set of different ambient conditions. For all cases the combustion chamber conditions were kept constant, as shown in table 3.

Table 3. Combustion chamber conditions.

Total pressure, P_0	115.5 bar
Total density, ρ_0	5.67 kg/m³
ROF	6.14
Mass fraction O2	0.878
Mass fraction H2	0.122

Prior to the simulation, the conditions in the combustion chamber were computed for the given oxidizer to fuel ratio (ROF), the total pressure and temperature. The determined mixture of H2 and H2O was then kept as frozen flow through the whole nozzle. The ambiance consisted of a mixture of oxygen and nitrogen.

The ascent of the launcher was simulated by adjusting the ambient pressure and flow velocity in the farfield around the nozzle, corresponding to the acceleration of the rocket. Six test cases, corresponding to six altitudes, were computed for the present study. The ambient conditions are given in table 4.

Table 4. Ambient conditions for each test case.

Altitude, km	Pressure, mbar	Density, kg/m³	Velocity, m/s
0	1000	1.225	0
2	785	1.0065	180
4	609	0.8191	265
6	466	0.6597	320
8	352	0.5252	368
10	262	0.4127	417

The typical Mach number distribution in the nozzle is presented in figure 7. At sea level the flow separates at the contour inflection forming a cap shock pattern. The base nozzle is a thrust optimized nozzle. It generates an internal shock that interacts with the separation shock starting at the inflection. As the altitude increases (2 km, 2nd picture from the top), the dual bell still operates in sea level mode. The shock pattern changes from a cap shock into a typical Mach disk pattern. When further decreasing the ambient pressure, the transition to altitude mode takes place; the nozzle extension flows full. The flow pattern changes only slightly with the further increase of the altitude up to 10 km (see Fig. 7, 3rd picture).

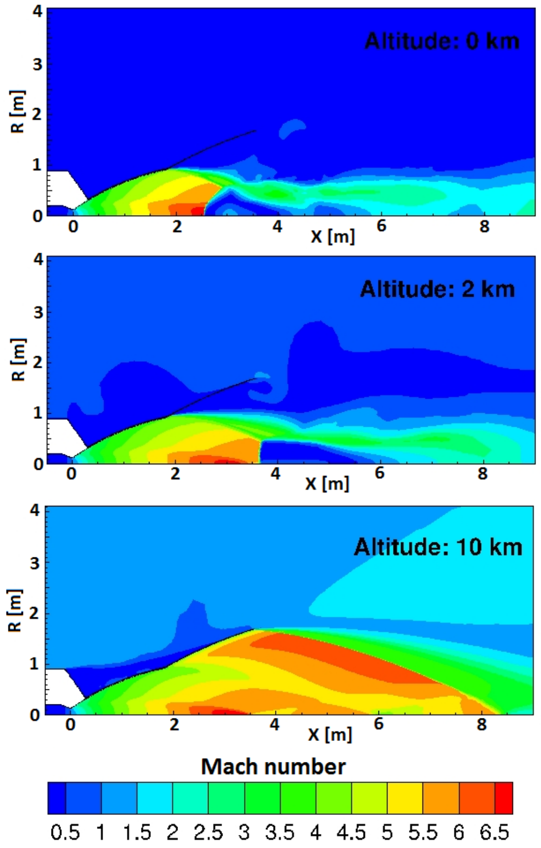

Fig. 7. Mach number distribution for various altitudes.

The evaluation of the separated inner extension shows wall pressures down to 75 % of the ambiance, depending on the altitude. This results in comparable high drag losses at low altitudes and can be explained by the suction effect of the external flow. In separated conventional nozzles the inner wall pressure decreases from nearly ambient conditions at the nozzle exit to 90%, downstream the flow separation.

The transition to altitude mode takes place for a lower altitude as the designed one. Two effects can be responsible for the discrepancy. The design of the nozzle contour was realized with the method of characteristics, which does not take viscosity effects into account. The stationary calculation with a CFD tool has shown in past studies to have difficulty to simulate the highly transient process of transition.

5. Conclusion

An intensive experimental investigation of dual bell nozzle models has shown the determinant influence of the extension length on the flow behavior. Increasing its length leads to a better mode stability (hysteresis effect) and a shorter transition duration, however, it also increases the amplitude of the side load peak generated during the transition.

The experimental results led to a realistic performance study of two Vulcain 2 like dual bell nozzles. The achievable payload gain is low. Redesigning the complete supersonic nozzle promises better results.

The reason for the poor performance at low altitude, caused by drag losses, was found by CFD to be the ambient flow, sucking out the separated dual bell extension.

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