Dual-Bell Nozzle Design

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Abstract The dual-bell nozzle is an altitude adaptive nozzle concept that offers two operation modes. In the framework of the German Research Foundation Special Research Field SFB TRR40, the last twelve years have been dedicated to study the dual-bell nozzle characteristics, both experimentally and numerically. The obtained understanding on nozzle contour and inflection design, transition behavior and transition prediction enabled various follow-ups like a wind tunnel study on the dual-bell wake flow, a shock generator study on a film cooled wall inflection or, in higher scale, the hot firing test of a thrust chamber featuring a film cooled dual-bell nozzle. A parametrical system study revealed the influence of the nozzle geometry on the flow behavior and the resulting launcher performance increase.

1 Introduction

The dual-bell nozzle is an altitude adaptive nozzle concept. It consists of a conventional bell shaped base nozzle, linked to an extension nozzle by an abrupt change in wall angle at the contour inflection. This nozzle concept permits to circumvent the area ratio limitation of conventional nozzles: under high ambient pressure conditions, at low altitude, the flow is attached in the base nozzle and separates at the inflection point. Indeed the contour inflection ensures a controlled and stable flow separation during the sea-level mode. During the launcher ascent, the ambient pressure decreases, and at some point the nozzle pressure ratio (combustion chamber pressure over ambient pressure, NPR) necessary for the flow transition is reached.

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The flow separation moves then quickly from the inflection point to the end of the extension; the nozzle is then flowing full and the dual-bell nozzle has reached its altitude mode. The higher area ratio experienced by the flow leads to a higher thrust under high altitude conditions. The concept was proposed in the late 1940's but the first investigations and the proof of concept took place in the 1990's [8]. Various studies, both experimental and numerical, were conducted to verify the potential of the dual-bell nozzle, and to investigate the flow behavior. In particular the transition from one operation mode to the other was of interest, see for example the works conducted in Europe or in Japan in [7, 11, 13, 15, 21]. Many studies were conducted at the German Aerospace Center DLR in Lampoldshausen in the past two decades [3–5, 16, 17]. The flow behavior and the transition from one operation mode to the other were studied for cold flow and hot flow conditions, first experimentally and then simulated numerically using the DLR intern developed Navier–Stokes solver TAU.

1.1 Method of Design

For the design of dual-bell nozzle contour a DLR in-house tool based on the method of characteristics is used [22]. Usually the base nozzle is chosen as a truncated ideal contour as it generates a flow without strong shock, as a thrust optimized contour (TOP) would. This is important because a strong intern shock may cause a restricted shock separation in the extension nozzle. The contour is defined by the gas properties and the design Mach number imposed. The length of the base nozzle should be chosen to ensure attached flow at all time under sea-level condition. Starting from the last right-running characteristic, a Prandtl–Meyer expansion of the supersonic nozzle flow is calculated. As the chosen wall inflection angle is reached, the expansion is stopped, and the resulting static pressure introduces an isobaric streamline that defines the extension contour. The obtained nozzle section is a so-called CP extension, yielding a constant wall pressure along the nozzle extension length. In order to achieve a fast transition from one operation mode to the other, the extension nozzle is defined as CP or PP, corresponding respectively to a constant or positive wall pressure gradient along the extension. This condition is essential to avoid any stable position of the flow separation point between sea-level and altitude mode, as it would lead to an increase in side load generation.

1.2 Parameters of Influence

In the last years various studies have focused on identifying and optimizing the different parameters of influence of the dual-bell nozzle, see for example Refs. [4, 14]. The geometrical parameters of interest are illustrated in Fig. 1 (right). As stated earlier, the shape and the length of the base nozzle will define the thrust and the flow

Fig. 1 Correlation between L' and hysteresis amplitude for different nozzle geometries (left) and relevant geometrical parameters of a dual-bell nozzle (right)

condition under sea-level mode. The only limitation is to ensure a full flowing base nozzle at all time. The extension length has a significant impact on the transitional behavior. For an easier comparison of the observations obtained for different configurations, the relative length of extension nozzle (ratio of extension length over total nozzle length $L' = L_e/L_{tot}$) can be introduced. The stability of the operation modes is ensured by a hysteresis effect between transition and retransition NPR. Each operation mode is stable toward small pressure fluctuations, either due to instabilities in the combustion chamber or to ambient pressure variations. An increase of the relation length leads to a higher amplitude of the hysteresis (see Fig. 1, left). Unfortunately, it is not possible to increase the value of L' past a certain value as it has a negative impact on the amplitude of the side load peak generated during the transition. A compromise has to be found between stability of the modes and the risk for the structural integrity of the nozzle (and the engine). A good rule of thumb is to design the extension with a comparable length as the base nozzle ($L' \simeq 0.5$) corresponding to a hysteresis amplitude of $\pm 20\%$ with a CP extension.

The inflection angle, i.e. the wall angle difference between extension and base contours at the inflection determines the transition NPR. The inflection angle should be at least 5° as a value too low will not guarantee the fixation of the separation point at the inflection between sea-level mode and the start of the transition. If the inflection angle is too high (typically for values higher than 25°) the length of the extension will grow exponentially, increasing the mass of the structure, or the wall angle at the end of the inflection will be very high, leading to increased diverging losses.

The transition NPR can be predicted for a CP extension using the following equation:

$$\text{NPR}_{tr} = P_0/P_{a,tr} = \frac{1}{M_e} \left(1 + \frac{\gamma - 1}{2} M_e^2 \right)^{\frac{\gamma}{\gamma - 1}} \quad (1)$$

Where M_e is the Mach number reached on the extension wall (constant in the case of a CP extension). More details are given in [4]. In the case of a PP extension it is not possible to predict the value of the transition NPR analytically, but it will always be lower than for the corresponding CP extension. It is also important to note that a dual-bell with a PP extension will yield hysteresis amplitude higher than the corresponding CP, provided the wall pressure gradient of the PP is monotonous. The limit for the gradient of the wall pressure possible for a PP extension is the necessity to keep a positive wall pressure angle at all points of the contour.

2 Optimization Studies

Many studies have been conducted in the past to evaluate the potential gain brought by the implementation of a dual-bell nozzle as main stage engine (see for example [9]). The application of a dual-bell nozzle to the European main stage engine Vulcain 2 confirmed the potential payload gain (see [19] for more details). For this study, the nozzle contour of Vulcain 2 was recalculated and its mass approximated. Then, starting from this redesigned contour, a great number of alternative dual-bells were generated and evaluated. The original contour was shortened at various positions, corresponding to five area ratios: ϵ_b 33, 38, 45, and 58. The contours obtained were considered as base nozzles. The shortest configuration presents a base nozzle area ratio of 33, which corresponds to the limitation imposed by the position of the TEG injection manifold in the original contour. The longest contour corresponds to the full length Vulcain 2 contour. Further restrictions in the contour geometries (total length and exit diameter) were imposed by the launch pad configuration of Ariane 5 at the Space Center site in French Guiana. The second parameter of influence taken into account for this study was the angle of inflection and five values were considered between $\alpha = 5^\circ$ and $\alpha = 25^\circ$ for each base nozzle generated. The extensions were all designed as CP extension. The sea-level and altitude thrust, and specific impulse were calculated for each contour, as well as the transition NPR and corresponding transition altitude. Two methods were used to evaluate the resulting payload mass, an analytical one based on the rocket equation and a detailed one using launch vehicle trajectory simulation. The values obtained with both methods were in good agreement. The results were very different from one contour to the other: from a significant payload gain to a detrimental effect of the additional nozzle mass despite the thrust gain in altitude. The optimum configuration features a base nozzle with an area ratio of 50 with an inflection angle of 15° , designated here as 50alp15, and yielded a potential payload gain of 490 kg. The contour is illustrated in Fig. 2 (left) together with other variations of the extension.

The evolution of the generated thrust with altitude is illustrated in Fig. 2 (right) for the original Vulcain 2 contour, the optimized dual-bell contour 50alp15 and three other dual-bells presenting the same inflection angle $\alpha = 15^\circ$ with different base lengths (i.e. base area ratios): 33alp15, 38alp15 and 58alp15. All contours present a transition before the optimum altitude and hence yield a partially lower thrust at low

Fig. 2 Various dual-bell contours based on Vulcain 2 nozzle (left) and generated thrust over altitude for redesigned Vulcain 2 and optimized dual-bell (right)

altitude. However, this deficit is compensated by the higher altitude thrust once the dual-bell nozzle operates in altitude mode. As this study was based on the redesign of an existing nozzle for a given engine, launcher and launch pad configurations, some of the geometrical parameters were imposed. A complete redesign of the nozzle starting at the convergent part would lead to shorter and lighter configurations. Combining this geometrical optimization with a trajectory optimization would lead to even larger payload gain for the Ariane 5 launcher.

3 Film Cooling

Dual-bell nozzles have been intensively studied at DLR in Lampoldshausen, both experimentally and numerically, under cold and hot flow conditions. In the past years, two topics have retained the attention of the authors: the impact of the film cooling and the influence of the outer flow on the transitional flow behavior.

3.1 Dual-Bell Nozzle Film Cooling

A hot flow test campaign has been conducted at the P8 facility of DLR Lampoldshausen. A dual-bell nozzle contour has been designed for LOX/H₂ combustion.

Figure 3 illustrates the thrust chamber assembly in exploded view with the cylindrical combustion chamber (CC) and nozzle throat segment (NT) made out of cooper alloy, the base and extension nozzles made out of Inconel. The slot for the film injection is situated in the base nozzle, slightly upstream to the inflection position. The combustion chamber and throat region were water cooled with a conventional regenerative circuit. The second part of the base nozzle was cooled with GH₂ flowing through cooling channels that accelerated and injected the flow as a cooling film for

Fig. 3 Sketch of the film cooled dual-bell nozzle

Fig. 4 Picture of the film cooled dual-bell nozzle mounted and instrumented at test bench P8

the extension nozzle. Preparatory works to the test campaign are presented in more details in [18, 20].

In order to reach the transition from sea-level to altitude mode and back, the cooling film mass flow rate was set and the combustion chamber pressure was varied for each test. To reduce the total number of tests, a test could feature a series of combustion pressures ramps with each time a different value of cooling film mass flow rate.

The instrumentation of the experiments consisted of wall pressure and temperature measurements, high speed video of the outer flow and acoustic measurements with a microphone array placed around the jet. Figure 4 is a snapshot of the nozzle jet during a typical test in sea-level (left) and altitude mode (right).

The test data are currently being analyzed as the campaign just ended.

3.2 Film Cooling Study in Shock Tunnel

In the framework of a cooperation within the Special Research Field Transregio 40 of the German Research Foundation, a dual-bell nozzle design was realized for an application in the shock wave laboratory [10] at the RWTH Aachen University. The objective was to study the behavior of the coolant film passing over the inflection point in supersonic flow.

The design constraints were to use the existing conical nozzle, to shorten it and use as base nozzle of the new dual-bell. The extension is a new design. The test specimen is then instrumented with pressure and heat flux sensors to determine the pressure distribution (i.e. nozzle operation mode) and the cooling efficiency.

The flow conditions correspond to a total pressure between 3 and 5 MPa with a total temperature around 3700 K. The main flow is composed mainly of water damp and the Mach number is in the range of 3.3. The cooling medium can be chosen as Helium, nitrogen, carbon dioxide or argon for this facility; its injection Mach number lies between 1.6 and 1.8.

A series of different contours has been generated, and the flow behavior was studied. Figure 5 illustrates a few of the contours considered and the Mach number distribution calculated with the in-house design tool for the contour retained for the study. In this case, the position of the inflection point, and hence the length of the base nozzle, has been varied, as well as the inflection angle between 12° and 14° . The contours were designed for a transition NPR in a range of 130 to 250, which lies within the installation capability.

Fig. 5 Variation of base length and inflection angle in contour design (left) and Mach number distribution inside the chosen contour (right)

4 Wake Flow with Dual-Bell Nozzle

Past experiments did not take into account the outer flow. Transition was obtained experimentally by varying continuously the feeding/combustion chamber pressure. Under flight conditions, the variation of the NPR is due to the change of altitude, hence the progressive decrease of the ambient pressure. Furthermore, the impact of the fluctuating ambient pressure and the wake flow could not be taken into account under sea-level test conditions. The following section describes some works conducted recently to investigate this aspect.

4.1 Flow Fluctuation Experiment

A cold flow test campaign was conducted inside the DLR Lampoldshausen altitude chamber of the P6.2 test facility. A dual-bell nozzle was designed and tested in the modified altitude chamber equipped with fast opening valves to simulate ambient pressure fluctuations. Through the programming of the valves it was possible to vary the amplitude and frequency of the fluctuations [6].

Figure 6 illustrates the evolution of NPR and wall pressure in the extension as a function of time. An abrupt drop in the extension wall pressure indicates the flow transition (i.e. attached flow along extension wall), as it can be seen for frequency values below 2 Hz.

The transition is more sensitive to fluctuations of lower frequencies, which is partly due to the transition inertia: the transitional front does not have time to start moving in the transition before in one half time period; and partly to the inertia of the altitude chamber itself: the perturbation is applied at the top of the chamber and the time needed to reach the nozzle end can be greater than the perturbation half period. This last effect can be seen in Fig. 6 for a perturbation frequency of 3 Hz, the NPR variation does not follow the valves opening and closing.

Fig. 6 Evolution of NPR and wall pressure inside the nozzle extension towards fluctuations of different frequencies in the altitude chamber

Fig. 7 Dependency of transition and effective NPRs with Mach number of ambient flow

In addition to the experiment a numerical study has been conducted on a dual-bell nozzle with an outer flow applied. The Mach number of the outer flow was set for values between 0 and 4. Figure 7 illustrates the transition NPR dependency with the velocity of the ambient flow. The transition to altitude mode takes place to much lower values of NPR in presence of an outer flow with high Mach number. This effect poses a problem for the transition prediction in a real flight application. For this reason an effective NPR, NPR_{eff} value has been introduced as the ratio of combustion chamber pressure over the pressure experienced by the flow at the nozzle end. This NPR value is constant at all outer flow conditions.

4.2 Interaction Between Afterbody and Dual-Bell Nozzle Flow

Another cooperation took place in the framework of the project founding with the universities of Braunschweig, Aachen (RWTH) and the German Armed Forces University to study the transitional flow behavior of dual-bell nozzles in interaction with wake flow.

The University of Braunschweig focuses on base flow interaction with propulsive jets [1]. The experimental studies are conducted on 3d test models. A first dual-bell nozzle was designed based on a TIC with a design Mach number of 3 and a CP extension. The transition NPR was evaluated around 13 during the design phase using the semi-empiric relation presented earlier, validated for test environment without wake flow. In reality the transition took place for much lower values of NPR, and a so-called flip-flop effect was observed. This effect can have multiple causes like the very low feeding and ambient pressures potentially leading to laminar flow separation or an insufficient hysteresis amplitude to withstand the ambient flow fluctuations. A

Fig. 8 Generic launcher configuration considered for the numerical simulations [12]

second nozzle contour was designed for the study, taking into account the limitations of the test environment. Accent was put on the optimization of hysteresis effect. In order to increase the hysteresis amplitude, various geometrical parameters were changed: the relative extension was increased and the extension contour was changed from CP to PP design. If the test conditions would have permitted it, an increase of the inflection angle would have also led to an increase of stability.

The German Armed Forces University also performed tests on a sub-scale planar dual-bell nozzle model [2] to study the nozzle flow interaction with the wake flow. In this case four contours were designed by varying various parameters: design Mach number for the base nozzle (between 2.5 and 2.8), throat radius, relative extension length and inflection angle (between 12° and 18°). Similar to the previous case, the transition NPR evaluated analytically was much higher than the value experienced with wake flow. In the second phase of the cooperation, the extension was changed to a PP to increase the hysteresis amplitude.

In addition to the performed tests, numerical simulations of the experiments were also realized at RWTH Aachen University [12]. Figure 8 illustrates the configuration considered for the calculations. A generic axisymmetric space launcher was investigated in a turbulent wake flow using a zonal RANS/LES approach. The influence of the dual-bell nozzle jet on the wake flow was investigated. The simulations were performed for transsonic freestream condition.

5 Conclusion

Over a decade of dedicated study, analytically, experimentally and numerically, on dual-bell nozzle flow behavior has led to a validated method for contour design and transition prediction. The influence of wake flow has shown to be critical in the flow behavior and further work will be necessary to ensure a safe and predictable transitional behavior.

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