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Experimental Study on Flow Transition in Dual Bell Nozzles

Chloé Nürnberger-Génin* and Ralf Stark†
DLR, German Aerospace Center, D-74239 Hardthausen, Germany

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The dual bell nozzle is a concept of altitude-adaptive nozzles. The flow adapts to the altitude by separating at the wall inflection at low altitude and flowing full at high altitude. To understand the phenomenology of the flow by the transition from sea-level to high-altitude mode, a series of tests have been made under subscale cold flow conditions. Three nozzles with different geometries have been tested. Two of them were successively shortened and driven under the same conditions for each extension length. This study yields the influence of the geometric parameters of the base and extension on the transition conditions. Furthermore, a prediction of the transition conditions is given.

Nomenclature

L'	=	relative extension length, L_e/L_{tot}
L''	=	length ratio, L_e/L_{init}
M	=	Mach number
P	=	pressure, bar
R	=	nozzle radius, mm
t	=	transition duration, s
X, Y	=	axial and radial coordinates
α	=	contour inflection angle, deg
γ	=	heat capacity ratio

Subscripts

0	=	total conditions
a	=	ambient conditions
b	=	base nozzle
e	=	extension nozzle
init	=	initial nozzle length
retrans	=	retransition from high-altitude to sea-level mode
sep	=	separation conditions
th	=	throat
tot	=	total
trans	=	transition from sea-level to high-altitude mode

I. Introduction

THE use of a parallel configuration for current launchers, like the European Ariane 5, imposes the functioning of the main engine from sea level up to vacuum conditions. The area ratio has to be limited to avoid the flow separation phenomenon in the nozzle at sea level, thus limiting the high-altitude performances. The rocket engine nozzle, therefore, came into focus as one of the subsystems with the most promising performance gain.

A European research group [1–3] was initiated to study flow in both conventional bell nozzles and altitude-adapting rocket nozzles such as plug nozzles, dual bell nozzles, or nozzles with extendible exit cones. With its simple geometry and its good altitude adaptation, the dual bell was identified as the most promising concept.

The concept first appeared in the literature in 1949 in a study by Foster and Cowles [4] on the conditions and consequences of flow separation in supersonic nozzles. Rocketdyne patented the concept in the 1960s as the dual bell nozzle. A conventional bell nozzle is the base nozzle and is linked to the extension nozzle with an abrupt wall inflection angle (see Fig. 1). The dual bell operates with a well-defined separation characteristic under sea-level conditions as well as under high-altitude conditions.

The wall inflection offers a one-step altitude adaptation without any moving part. In sea-level mode, the wall inflection forces the flow to separate from the wall in a controlled and symmetrical way. High-separation side loads are avoided and the small effective area ratio of the base nozzle generates increased sea-level thrust. At a certain altitude during launcher ascent, nozzle transition conditions to high-altitude mode are reached. The flow attaches abruptly in the whole extension to the wall, down to the exit plane. The full area ratio is now used and leads to optimized high-altitude thrust generation.

The first studies on this altitude-adaptive nozzle concept were done in the early 1990s in the United States, with tests conducted at Rocketdyne by Horn and Fisher [5] and in Europe within a technology development program [6]. Experimental and numerical studies have been conducted to better understand the dual bell flow behavior. The feasibility criteria were investigated both experimentally (e.g., by Hagemann et al. [7]) and numerically (e.g., by Martelli et al. [8] and Nasuti et al. [9]).

II. Motivation

A fundamental understanding of the flow phenomenon in dual bell nozzles is necessary for application to a rocket engine. As the transition nozzle pressure ratio (NPR; P_0/P_a) defines the altitude of operating mode change, it has to be predicted precisely to ensure the safe rocket launcher ascent. Former tests conducted at the cold flow facility P6.2 [2,10,11] have pointed out the existence of a hysteresis effect between the two operating modes. It ensures the stability of the flow mode transition against NPR fluctuations. The influence of the various geometrical parameters on the transition NPR, its duration, and the hysteresis were studied with a series of cold flow subscale tests on test bench P6.2.

Three nozzle contours were designed with different geometries (contour inflection angle α and base nozzle length L_b) and tested under similar conditions. The nozzles were then progressively shortened. These additional configurations yield information on the influence of the relative extension length L' on the flow transition behavior [12]. L' was defined as the ratio of the extension length L_e to the total nozzle length L_{tot}. Additionally, the shortened nozzles allowed the observation of the flow evolution with schlieren optics for a better understanding of the transition process.

III. Test Conditions

A. Test Rig

The dual bell tests were conducted at the cold flow test bench P6.2 [11]. The horizontal test rig, used for this study, features sea-level conditions. Dry nitrogen is chosen as the driving gas.

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*Research Scientist, Nozzle Group, Institute of Space Propulsion, Langer Grund.

†Head of Nozzle Group, Institute of Space Propulsion, Langer Grund.

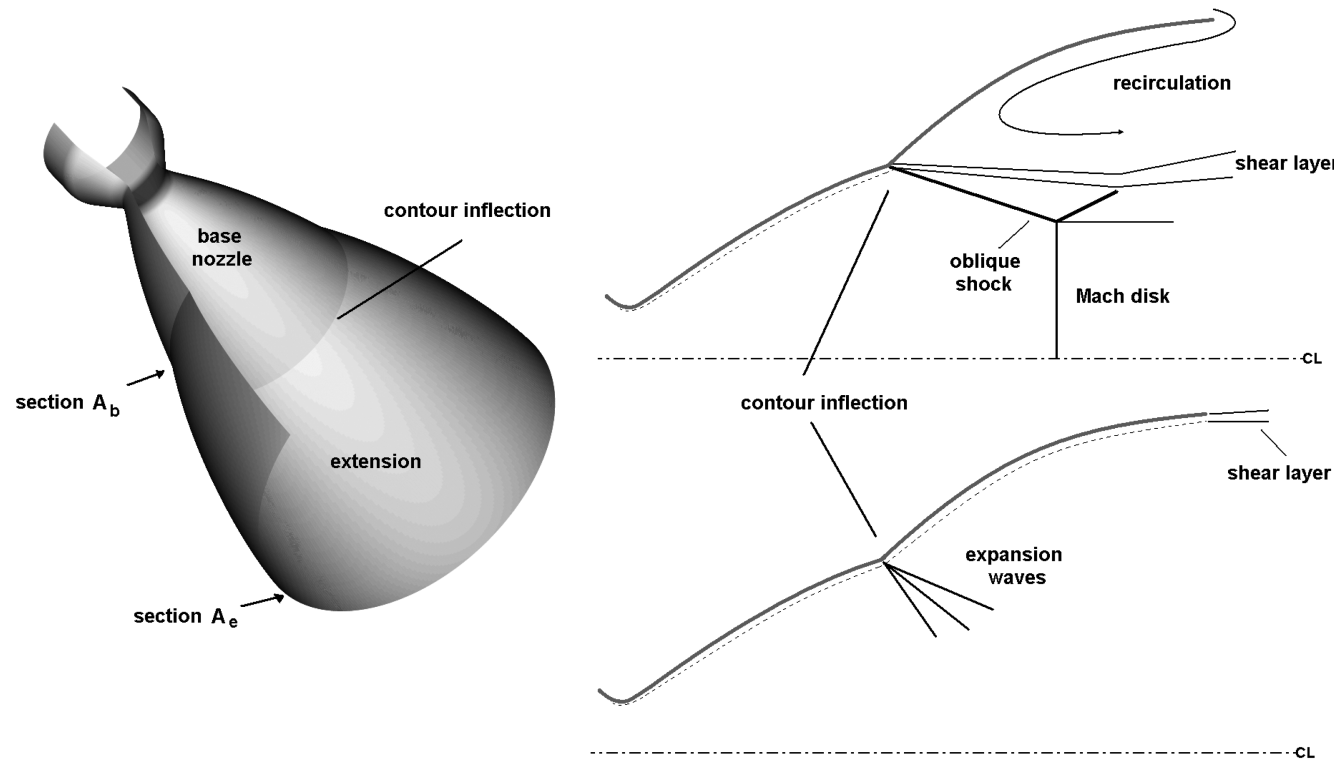

Fig. 1 Dual bell nozzle.

The nozzle can be driven under constant ambient pressure P_a. The feeding pressure P_0 is variable with gradients from 0.5 to 2 bar/s. The NPR that can be reached is limited to a maximum of 55. Therefore, the studies are limited to tests on dual bell nozzle of small dimensions with a transition NPR lower than 55.

The test installations at the P6.2 bench offer 64 low-frequency (1 kHz) and 16 high-frequency (25 kHz) measurement channels. The signals were filtered to 160 Hz and 8 kHz, respectively.

B. Test Specimen

The tests were made on three subscale dual bell nozzles presenting different geometric parameters: contours DB1, DB2, and DB3. The common base nozzle was designed as a truncated ideal nozzle, which prevents the generation of internal shocks. The contour was designed using an in-house program based on the method of characteristics [13].

The nozzle extension was designed for a constant wall pressure. The contour was defined by a freejet isobar leaving the last point of the base nozzle. This design isobar can be found by increasing the wall inflection angle defining a Prandtl–Mayer expansion. As the resulting design wall Mach number and pressure cross the chosen flow separation criterion, the isobar is reached. This procedure assures a flow transition at the desired NPR.

The geometric parameters studied were the base length L_b, the extension length L_e, and the inflection angle α (see Fig. 2). In a first step, only α and L_b were studied, and all three contours use the same value of $L_e/R_{\mathrm{th}} = 8.3$. The geometric parameters of the three tested nozzle contours (DB1, DB2, and DB3) are summarized in Table 1.

The extensions of the nozzles have been successively shortened (DB1, DB2 in four steps and DB3 in six steps) and tested under same conditions for each length to study the flow in the extension before and during the transition process. A parametric study was performed on the extension length influence on the flow behavior. Table 2 summarizes the relative extension lengths $L' = L_e/L_{\mathrm{tot}}$ for each nozzle configuration.

Table 1 Geometry of the three tested nozzles in their design configuration

		Contour DB1	Contour DB2	Contour DB3
Throat radius	R_{th}	10 mm	10 mm	10 mm
Area ratio	ε_b	11.3	11.3	9.4
	ε_e	27.1	24	25.6
Base length	L_b/R_{th}	6.2	6.2	5.2
Total nozzle length	$L_{\mathrm{tot}}/R_{\mathrm{th}}$	14.5	14.5	13.5
Inflection angle	α	7.2 deg	5 deg	7.2 deg

C. Instrumentation

Pressure measurements have been made at the nozzle wall following a streamline from the throat to the exit (see Fig. 3). A better resolution in the vicinity of the contour inflection was reached by using further measurement positions in the other quadrants (addressed as Q1–Q4). In addition, the last cross section in the extension has been equipped in each quadrant to detect potential asymmetry of the flow during transition. The sensors in the base nozzle were recorded with a low scan rate (1 kHz) and the ones in the extension with a high scan rate (25 kHz) to resolve the flow transition with better precision. The pressure ports are labeled from P_{wb1} to P_{wb7} in the base nozzle and from P_{w1} to P_{w12} in the extension. The transducers used were XT-154-190M from Kulite Semiconductor, Inc., with an accuracy attained in the operating range of 0.5% related to the measurement range upper limit. To ensure this measurement

Table 2 Successive relative extension length L'

	Contour DB1					
Series		1	2	3	4	
L'		0.57	0.53	0.49	0.41	
	Contour DB2					
Series		1	2	3	4	
L'		0.57	0.48	0.39	0.23	
	Contour DB3					
Series	1	2	3	4	5	6
L'	0.61	0.56	0.49	0.41	0.3	0.16

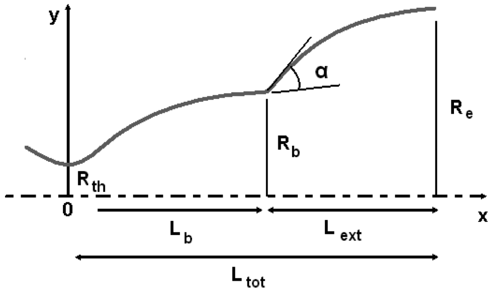

Fig. 2 Geometrical parameters of a dual bell nozzle.

accuracy for the whole measurement range, all sensors were calibrated statically before the test and an adjustment polynomial was determined. The sensitivity of the sensors were 0.97 V/MPa.

A black and white schlieren optics installation, using a high-speed camera with a frequency of up to 2 kHz, was implemented to study the flow evolution during the transition process. The recording of the shock system was triggered on the pressure drop at a chosen measurement position in the middle of the extension.

IV. Results

A. Sneak Transition

Figure 4 depicts the pressure distribution at the nozzle wall measured for various NPR values. The results obtained with a low total pressure gradient indicate an additional flow condition between sea-level and high-altitude modes. As the NPR increases, the pressure at the extension wall first drops at the positions P_{w1} and P_{w2}, located downstream of the inflection. Because of viscosity effects, the pressure gradient has a finite value at the inflection: the wall pressure gradient is negative in the vicinity of the contour inflection, defining the inflection region [9]. Figure 5 illustrates the theoretical and experimental wall pressure distributions in the vicinity of the inflection for high-altitude mode.

The extension nozzle can be divided into two zones: the inflection region, where the wall pressure gradient is negative, and the residual part of the extension, where the wall pressure is constant. For a

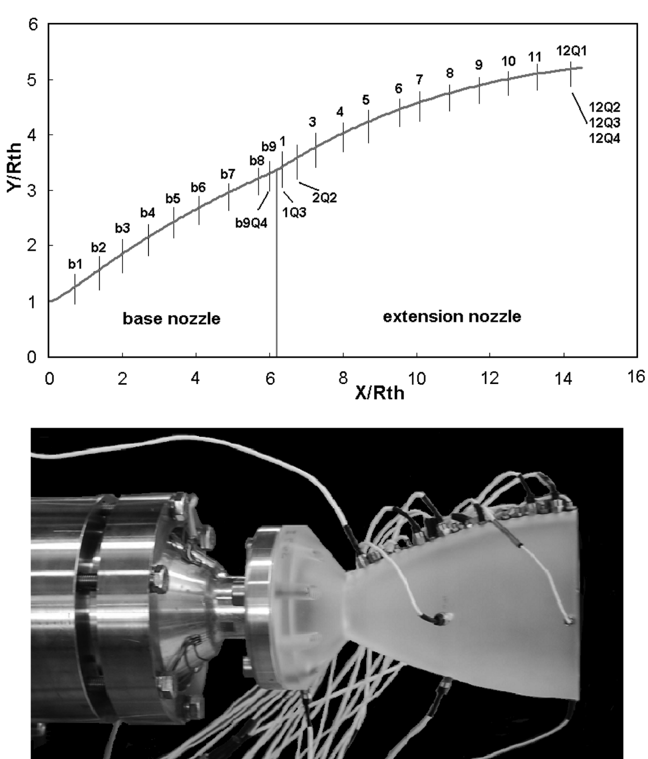

Fig. 3 Setup: a) pressure ports, and b) nozzle mounted on the test rig.

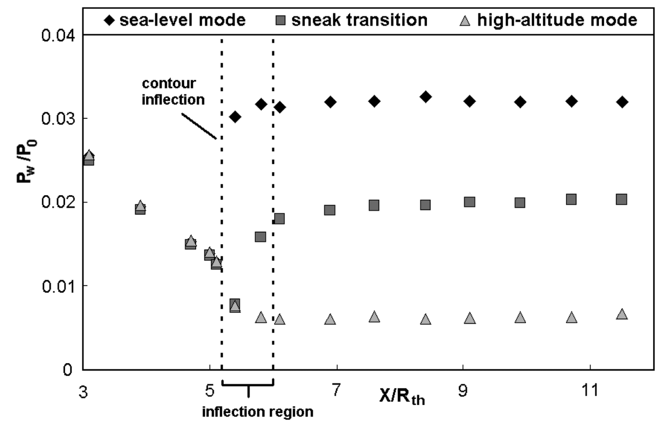

Fig. 4 Wall pressure distribution for different NPR conditions.

certain interval of NPR, the flow separation can find a stable position within the inflection region. With a continuous increase of the total pressure, the transition NPR is reached. The separation position jumps abruptly to the nozzle end. The transition from the sea-level to the high-altitude mode is completed as the residual nozzle part shows a constant wall pressure profile. This flow evolution preceding the actual transition is hereafter addressed as the "sneak transition."

Schlieren pictures were recorded for various settings to observe the flow evolution in the dual bell nozzles. The schlieren pictures were superimposed with the nozzle contour grid, and the position of the shock system and Mach disk were extracted (see Fig. 6a). It was possible to obtain the position of the flow separation point using the intersection of the wall contour and the extrapolated oblique shock.

The evolution of the shock system is represented in Fig. 6b for the short configuration of nozzle DB2 ($L' = 0.23$) at different instants before and during the transition. Three phases can be discerned during the flow evolution:

First phase: sea-level mode is reached. The flow separation is fixed at the inflection. As the NPR increases, the jet widens (the angle between the jet and nozzle axis decreases). The flow accelerates around the contour inflection point.

Second phase: the flow separation starts moving into the extension. The sneak transition takes place.

Third phase: the flow separation reaches the residual constant wall pressure zone. The actual transition takes place and the flow attaches abruptly to the extension wall down to the exit plane.

In a real application, the total pressure is constant during the ascent of the launcher. The variation of the pressure ratio P_0/P_a is only due to the decreasing ambient pressure. This decrease is very slow, so that the sneak transition will be a critical effect for rocket nozzle main engine application.

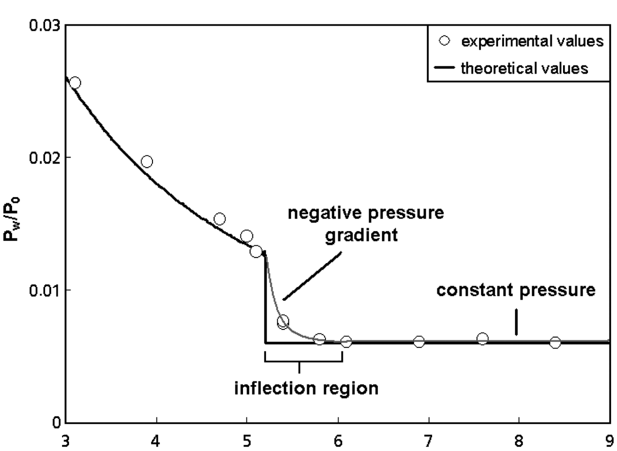

Fig. 5 Theoretical and experimental wall pressure distribution for high-altitude mode.

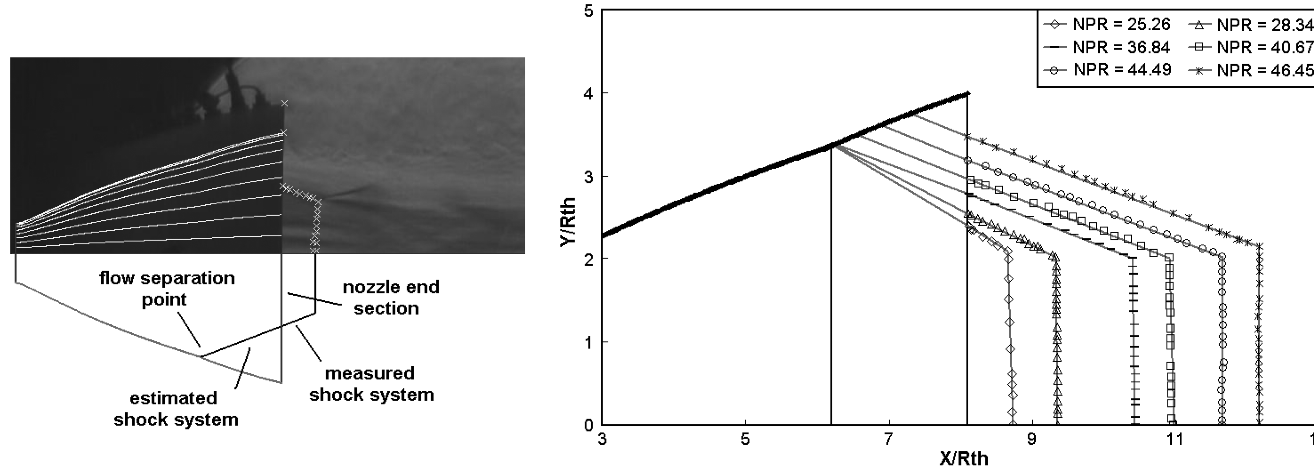

Fig. 6 Measured shock system and flow evolution before and during actual transition.

B. Influence of the Geometric Parameters

For each test, wall pressure measurements have been made along the nozzle wall. The actual transition was defined by the instant when the wall pressure dropped abruptly along the extension wall. With every change of mode, the ratio P_0/P_a has been determined and averaged for each nozzle configuration in $\mathrm{NPR}_{\mathrm{trans}}$, with a maximum statistical variance of $\pm 1\%$. Figure 7 summarizes the transition conditions for all the measured configurations as a function of the relative extension length L'. Nozzle configuration DB1 appears in all four configurations, nozzle DB2 is depicted in the three longest configurations, and nozzle DB3 is depicted in the five longest configurations. The results do not include the short configurations ($L' = 0.16$ for contour DB3 and $L' = 0.23$ for contour DB2), because for these configurations, the nozzles presented no clear definable transitions.

The estimation of the transition duration is crucial for structure lifetime prediction. During the transition from one mode to the other, the flow presents significant asymmetries that lead to high side loads. To prevent damages to the nozzle structure, the transition duration has to be minimized. The high-frequency pressure measurements allow the study of the transient flow evolution along the extension wall and its time needed to attach in the complete nozzle extension. The total transition duration, t_{tot}, corresponds to the time between the instant at which the flow separation first moves into the extension and the instant at which it reaches the nozzle exit (the duration of actual transition plus sneak transition). The start of the total transition is determined by the distinct pressure drop at the first sensor position inside the extension (P_{w1}).

Figure 8 represents the averaged total transition duration for various configurations of nozzle models DB3 and DB2. The durations of contour DB2 is presented for three feed pressure gradients: 2, 1, and 0.5 bar/s. The tests of nozzle DB3 were conducted with a constant feed pressure gradient of 2 bar/s. The total duration increases for a decreasing feed pressure gradient. This effect has to be taken into account for flight as the NPR increase due to ambient pressure decrease is very small. In contrary to the accepted results, the total transition duration t_{tot} decreases linearly with an increasing extension length. One reason for this is the significantly strong increase of the maximum transition front velocity compared to extension length increase. A minimal value seems to be common for all NPR gradients. This indicates the existence of an optimal transition time, corresponding to a relative extension length of about 0.63. At identical pressure gradients, nozzles DB2 and DB3 show comparable characteristics. This denotes that neither the base nozzle length nor the inflection angle have a significant influence on the total transition duration t_{tot}.

The difference between the transition and retransition NPRs is crucial for the stability of the flow mode during ascent. A large value of hysteresis ensures that a small NPR variation, for example, due to combustion instabilities (P_0) or buffeting effects around the rocket (P_a), does not lead to an oscillation from one flow mode to the other [11]. To estimate the stability of a dual bell flow, the value of the hysteresis is calculated as the ratio of the NPR difference over the transition NPR:

$$\text{hysteresis} = \frac{\mathrm{NPR}_{\mathrm{trans}} - \mathrm{NPR}_{\mathrm{retrans}}}{\mathrm{NPR}_{\mathrm{trans}}} \cdot 100\% \tag{1}$$

The transition and retransition NPRs were determined and the percentage of hysteresis calculated for each nozzle configuration. A second nondimensional parameter is introduced to define the extension length: $L'' = L_e/L_{\mathrm{init}}$, where L_{init} represents the total length of the nozzle in its initial configuration, before shortening. Figure 9 gives the hysteresis data for all nozzle configurations as a function of L''. For all nozzle configurations tested, the hysteresis behaves linearly with increasing L''. For this study, reference values

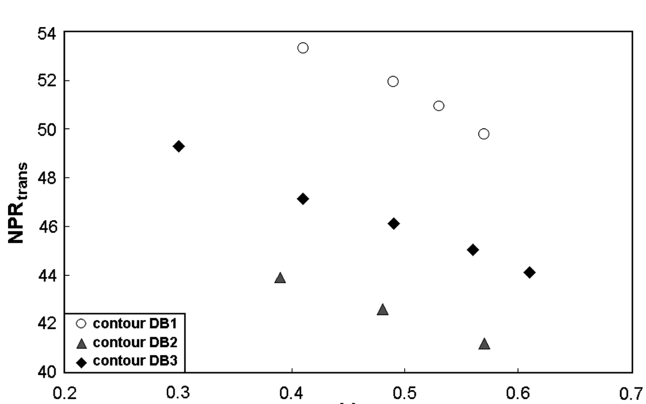

Fig. 7 $\mathrm{NPR}_{\mathrm{trans}}$ for the various nozzle configurations.

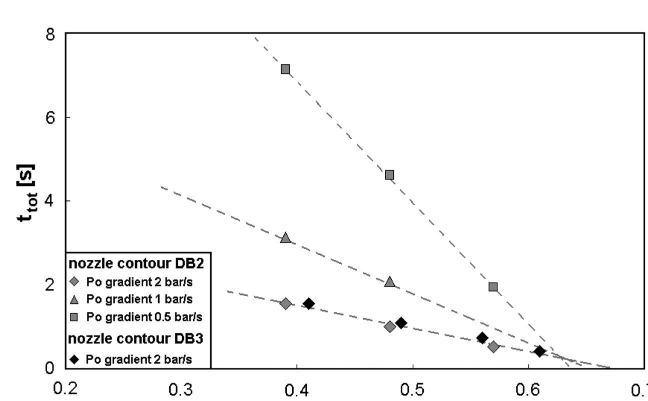

Fig. 8 Transition duration as a function of the relative extension length for various pressure gradients.

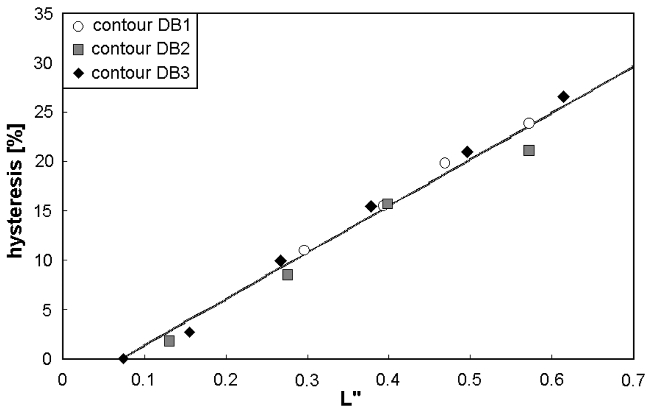

Fig. 9 Hysteresis effect as a function of the length ratio L''.

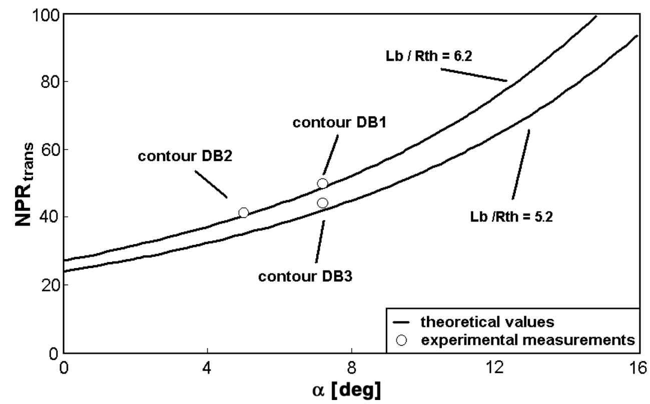

Fig. 11 Theoretical values and experimental data of transition NPR as a function of the inflection angle.

for L'' are used that correspond to a very small extension wall exit angle (less than 4 deg), defining the initial total nozzle length during design process. For future nozzle design applications, the reference initial nozzle length used should be the contour with an extension exit wall angle equal to zero.

The extension length L_e was found to be the outstanding parameter to improve the dual bell flow stability. Thus, two of the decisive parameters for dual bell concept optimization can be enhanced by lengthening the dual bell extension: the hysteresis between the transition and retransition NPRs can be increased, and the total transition duration can be reduced. However, the NPR gradient has to be high enough to significantly reduce the transition duration. In real flight applications, throttling down the combustion chamber pressure before the transition condition is reached and a following delayed abrupt reincrease back to nominal value ensures a high NPR gradient resulting in short transition duration.

C. Transition Prediction

The base nozzle geometry defines the wall pressure ratio P_b/P_0 and the wall Mach number M_b at the base nozzle end, and the contour angle α of the wall inflection defines the Prandtl–Meyer expansion between the base nozzle and extension. To each possible value of α corresponds a constant wall Mach number M_e within the extension and a constant wall pressure ratio P_e/P_0, as illustrated in Fig. 10.

The inflection angle α is related to the flow conditions by

$$\alpha = \nu_e - \nu_b \tag{2}$$

The angle ν_b is calculated using the Prandtl–Meyer relation as a function of M_b, the wall Mach number at the base nozzle end, and ν_e as a function of M_e, the wall Mach number within the extension during high-altitude operation. The Prandtl–Meyer relation is given for the general case:

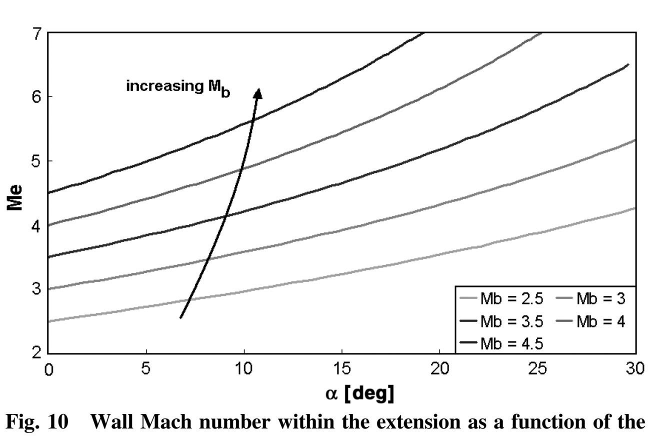

Fig. 10 Wall Mach number within the extension as a function of the inflection angle α.

$$\nu = \sqrt{\frac{\gamma+1}{\gamma-1}} \arctan \sqrt{\frac{\gamma-1}{\gamma+1}(M^2-1)} - \arctan \sqrt{M^2-1} \tag{3}$$

The remaining thermodynamical properties within the extension can be calculated using the isentropic relations. The ratio of the wall pressure at the extension P_e to total pressure P_0 can be obtained using

$$\frac{P_0}{P_e} = \left(1 + \frac{\gamma-1}{2} M_e^2\right)^{\frac{\gamma}{\gamma-1}} \tag{4}$$

The theoretical value of the transition nozzle pressure ratio (NPR_{trans}) is determined using the Stark separation criterion [14], $P_{sep}/P_a = 1/M_{sep}$:

$$\begin{aligned} NPR_{trans} = P_0/P_{a,trans} &= \frac{P_0}{P_e}\frac{P_{e,sep}}{P_a} = \frac{P_0}{P_e}\frac{1}{M_e} \\ &= \frac{1}{M_e}\left(1 + \frac{\gamma-1}{2} M_e^2\right)^{\frac{\gamma}{\gamma-1}} \end{aligned} \tag{5}$$

The design transition NPR can be calculated for the two studied base nozzle geometries: contours DB1 and DB2 with length $L_b/R_{th} = 6.2$, and contour DB3 with $L_b/R_{th} = 5.2$ (which defines M_b). Furthermore, contours DB1 and DB3 feature identical inflection angles of $\alpha_1 = 7.2$ deg, and contour DB2 features an inflection angle of $\alpha_2 = 5$ deg (which defines M_e). Both theoretical values and experimental data are depicted in Fig. 11. The experimental data of the nozzle models in their design configuration show very good agreement with the theoretical calculated values.

The choice of the contour inflection angle α influences two decisive optimization parameters: on the one hand, the transition flight altitude, at which higher angles lead to higher transition altitudes, and on the other hand, the possible high-altitude impulse gain, at which higher angles lead to enlarged expansion ratios. An optimization process is necessary.

V. Conclusions

The influences of several geometric parameters of a dual bell nozzle have been studied. The extension length defines the dimensions of the recirculation area at sea-level mode and, hence, determines the transition NPR. The stability between the two operating modes and the transition duration can be improved by increasing the extension length. In its design configuration, the transition of a dual bell can be predicted using the base nozzle geometry and the chosen contour inflection angle. The sneak transition has been observed with pressure measurements and schlieren optics observations. This intermediate state of the flow between sea-level mode and transition to high-altitude mode may cause higher structural and thermal loads in the vicinity of the inflection. The duration of the sneak transition can be shortened by higher NPR gradients or geometry improvements, such as taking into account the boundary-layer viscosity during the extension design process.

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