Influence of the Test Environment on the Transition of Dual-Bell Nozzles

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The dual bell nozzle offers a simple and efficient altitude adaption through its contour inflection, which insures symmetrical and controlled separation at sea level and a large area ratio at high altitude. The understanding of the transition from one operating mode to the other is the key to its prediction. Intensive cold flow investigation has led to an empirical criterion for a precise transition prediction. However, the testing conditions may have a great influence on the actual transition. The temperature of the flow and the nozzle wall, especially when driving test series, can shift the nozzle pressure ratio leading to the transition. A test campaign in a high altitude chamber has also shown the dependence of the transition condition with the chamber pressure, i.e. with the density of the separated backflow. For a reliable prediction of the dual-bell nozzle flow behavior, both on test facility and in real flight conditions, all these influences have to be identified and taken into account.

Key Words: Nozzle Flow, Dual-Bell Nozzle, Flow Separation

Nomenclature

\[ \alpha \] : contour inflection angle, \(^{°}\)

\[ \epsilon \] : area ratio

\[ \gamma \] : isentropic exponent

\[ \rho \] : density, \([kg/m^3]\)

\[ L' \] : normalized extension length, \(L_e/L_{tot}\)

\[ M_a \] : Mach number

\[ NPR \] : Nozzle pressure ratio, \(P_0/P_a\)

\[ p \] : pressure, \([MPa]\)

\[ T \] : temperature, \([K]\)

\[ x \] : axial position

Subscripts

\(0\) : total conditions

\(a\) : ambient

\(b\) : base

\(e\) : extension

\(sep\) : separation

\(tot\) : total

\(tr\) : transition

\(w\) : wall

1. Introduction

Altitude adaptive nozzles are an interesting alternative for performance gain of launcher main engines. The flow adapts to the flight altitude for an optimized thrust, circumventing the area ratio limitation of conventional nozzles.

The dual-bell concept was first investigated in the early 90’s by Horn and Fisher\(^1\) at Rocketdyne. In Europe, a series of investigations has been conducted in the frame of the FESTIP program\(^2,3\) on various altitude adaptive nozzles. The dual-bell nozzle came out to be the most promising concept.

A contour inflection links the base nozzle to the extension, forcing the flow to a symmetrical and controlled separation at sea level. Dangerous side loads due to unsymmetrically separated flow are avoided and the small area ratio leads to increased thrust at low altitude. During the flight, as the ambient pressure decreases, the separation front moves rapidly toward the extension down to the nozzle exit: the transition to high altitude mode takes place. The dual-bell flows then full for an increased altitude thrust. Figure 1 is a schematic of the two operation modes of a dual-bell nozzle.

![Fig. 1. Dual bell nozzle in sea level (top) and high altitude mode (bottom).](image-url)
features the same base nozzle: a truncated ideal contour, with a design Mach number of 5.8, in two different lengths. The extension is designed as an isobar, featuring an inflection angle to the base of 7.2° for contour DB1 and DB3 and 5° for contour DB2. The geometrical parameters are summarized in Fig. 2 and in Table 1.

Table 1. Nozzle model characteristics.

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>DB1</th>
<th>DB2</th>
<th>DB3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflection angle, α</td>
<td>7.2°</td>
<td>5°</td>
<td>7.2°</td>
</tr>
<tr>
<td>Base Mach number, Ma</td>
<td>3.64</td>
<td>3.64</td>
<td>3.58</td>
</tr>
<tr>
<td>Area ratio, εb</td>
<td>11.3</td>
<td>11.3</td>
<td>9.4</td>
</tr>
<tr>
<td>Area ratio, εe</td>
<td>27.1</td>
<td>24</td>
<td>25.6</td>
</tr>
</tbody>
</table>

Using the geometrical parameters, the Prandtl-Meyer relation and an empirical flow separation criterion (identified by Stark4 as $P_{sep}/P_a = 1/M_a$), the nozzle pressure ratio (NPR = $P_0/P_a$) leading to the transition can be defined as:

$$NPR_{tr} = \frac{1}{Ma_e} \left( 1 + \frac{\gamma - 1}{2} \frac{Ma_e^2}{Ma} \right)^{\gamma - 1}$$  \hspace{1cm} (1)

The criterion is valid for an extension with constant wall pressure (CP extension). A CP extension implies that the wall pressure $P_e$ and Mach number $Ma_e$ are constant along the extension wall. Figure 3 is a comparison of the experimental transition NPR for the three nozzles with the predicted values. The criterion shows very good agreement for the transition prediction.

This empirical criterion must be adapted to take the test conditions into account. Therefore, further campaigns have been conducted under different conditions: with warm flow and in a high altitude chamber, offering a low density environment.

3. Experimental Setups

3.1. High altitude chamber

In addition to its outside horizontal rig, on which the first campaign was conducted, the cold flow test facility P6.2 features also a high altitude chamber (see Fig. 4).

Up- and down ramping tests on a dual bell model led to transition from one operating mode to the other. The chamber was evacuated at various pressures to modify the nozzle environment (see also Verma et al.5). Driving gas for this campaign was dry nitrogen.

3.2. Warm gas conditions

Warm flow conditions were obtained at test complex M11 (Fig. 5). It features oxygen/hydrogen burners heating pressurized air. The operation points are steady in pressure and temperature. The maximal attainable values are 3 MPa and 1300 K. Depending on the chosen operation point, the flow was composed of about 95% air and 5% water damp6.

A dual-bell nozzle model was designed for the test facility and tested in steady conditions for a matrix of temperature and pressure operating points.
3.3. Test specimen

All dual bell nozzles were designed with an in-house code based on the method of characteristics. The base nozzles were defined on a truncated ideal contour (TIC). In each case, the extension was designed as an isobar, leading to a constant pressure extension.

The cold flow test specimens were made of acrylic glass, with a wall thickness of 10 mm. The warm flow specimen was made of heat resistant steel. The extension and the part of the base near the inflection were thin walled (<3 mm).

3.4. Instrumentation

Dynamic wall pressure measurements were made for all nozzle configurations through pressure ports distributed along the wall. When allowed by the wall thickness, the transducers were directly screwed into the wall and connected to the fluid via 0.5 mm orifices. In the case of the thin walled nozzle, short pipes were welded to the wall and linked to the transducers through small Teflon tubes.

Total conditions in pressure and temperature were also measured during each test.

4. Results and Discussion

Three main influence parameters for the transition behavior have been identified: the extension geometry (in particular its length), the temperature of both flow and nozzle walls, and the density of the flow.

4.1. Nozzle extension geometry

The three initial nozzles, presented in section 2 as DB1, DB2 and DB3, were successively truncated and tested under the same conditions (up- and down-ramping of the NPR). The normalized extension length \( L' = \frac{L_e}{L_{tot}} \) is given for the successive steps in table 2. The picture of Fig. 6 is an illustration of one of the nozzle models mounted on the test rig for three different lengths.

![Fig. 6. Nozzle model in various lengths.](image)

<table>
<thead>
<tr>
<th>Series</th>
<th>DB1</th>
<th>DB2</th>
<th>DB3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.57</td>
<td>0.57</td>
<td>0.61</td>
</tr>
<tr>
<td>2</td>
<td>0.53</td>
<td>0.48</td>
<td>0.56</td>
</tr>
<tr>
<td>3</td>
<td>0.49</td>
<td>0.39</td>
<td>0.49</td>
</tr>
<tr>
<td>4</td>
<td>0.41</td>
<td>0.23</td>
<td>0.41</td>
</tr>
</tbody>
</table>

The transition NPR are represented as a function of \( L' \) in Fig. 7. The transition is shifted to higher NPR values when decreasing the extension length. The velocity of backflow depends on the geometry of the recirculation area; it increases with decreasing angle between jet and wall and with decreasing extension length. When shortening the nozzle extension, the backflow velocity decreases and the backpressure increases in the separated extension. The transition criterion does not directly apply for shortened extensions.

![Fig. 7. NPR for various nozzle geometries and extension lengths.](image)

The transition criterion is valid for an extension in full length, which corresponds to the length of the isobaric leaving the last point of the base nozzle before the wall angle tends to zero.

For a shorter nozzle extension configuration, the transition NPR varies linearly with the relative extension length. So it is possible to adapt the criterion knowing the linear coefficient between extension length and recirculating backflow pressure.

4.2. Flow properties

Various operation points in temperature and pressure were chosen for the warm flow investigation. The total temperature of the flow has a significant influence on the flow behavior in the nozzle extension. A representative pressure port was chosen in the middle of the extension. Figure 8 represents the value of the measured non-dimensional wall pressure \( \frac{P_w}{P_0} \) in high altitude mode for various total temperatures. The pressure in the extension strongly depends on the flow temperature. Two effects may be responsible for these variations: the variation of the isentropic coefficient with the temperature and the deformation of the nozzle wall under heat loads.

![Fig. 8. Wall pressure in the extension: experimental measurements and calculated values with influence of \( \gamma \) only.](image)
The theoretical wall pressure has been calculated by taking only the influence of the variation of the heat capacity ratio $\gamma$ into account. The values are compared to the measurements in Fig. 7. It can be seen, that the influence of $\gamma$ on the wall pressure exists, but is not the dominant effect. The wall pressure in the extension slightly decreases with increasing flow temperature.

The decrease of the wall pressure is mainly due to variations of the contour geometry. As the nozzle wall is heated up by the flow, the base nozzle contour buckles leading to a higher expansion of the flow and hence to lower wall pressure values. The variations in the base nozzle are more significant as in the extension, so that the inflection angle increases with the temperature.

![Fig. 9. Influence of the total temperature on the transition NPR.](image)

This effect also shifts the transition NPR for increasing flow temperature. Figure 9 illustrates the dual bell operating mode reached for various pressure and temperature conditions. The transition NPR is represented by the straight line separating the two modes. Increasing the temperature leads to an increased transition NPR.

Former cold flow investigations had already shown this effect in a smaller order of magnitude, as shown in Fig. 10. The contraction of the nozzle contour under low flow temperatures leads to higher wall pressure and hence to lower transition NPR.

![Fig. 10. Influence of the total temperature on NPR in cold flow tests.](image)

In order to precisely predict the transition, it is necessary to take the contour variation due to temperature variation into account. This will be an important parameter for hot flow dual bell using a cooling system.

4.3. Recirculating backflow

The tests in the altitude chamber simulated various altitude conditions. The chamber was evacuated with an ejector system before the test start to reach different altitude chamber pressure.

The specimen chosen for the test campaign was the nozzle contour DB1. The transition and retransition conditions for this dual bell nozzle are $\text{NPR}_{tr} = 49.5$ and $\text{NPR}_{retr} = 38.6$ under sea level conditions. Figure 11 represents the transition and retransition NPR as a function of the pressure in the altitude chamber.

It can be seen that by decreasing the pressure in the chamber, the values of the NPR leading to both transition and retransition linearly increase. In high altitude conditions ($Pa < 0.02 \text{ MPa}$), the transition NPR increase is in the order of 10%, and the retransition NPR in the order of 15% in comparison to the values obtained under ambient conditions.

![Fig. 11. Transition and retransition conditions as a function of the pressure in the high altitude chamber.](image)

Figure 12 illustrates the flow density at the end of the base nozzle shortly before the transition takes place. Its value was calculated using isentropic relations for the wall pressure obtained out of the last pressure measurement port in the base nozzle. For density higher than 0.04 kg.m$^{-3}$ the transition NPR correspond to the sea level value ($\text{NPR}_{tr} = 49.5$).

![Fig. 12. Flow density at the end of the base nozzle before transition start as a function of NPR.](image)

When the chamber is evacuated down to low pressure
values, sea level mode is reached already for very low NPR values. This corresponds to a low density of the nozzle flow. The opening angle of the jet decreases as well, leading to a delayed transition to altitude mode. The transition NPR increases linearly when the flow density decreases, i.e. when decreasing the chamber pressure. The variation of the transition NPR toward the theoretical value is due to the lower pressure and hence density of the flow in altitude conditions.

In flight condition, the combustion chamber remains constant, while the ambient pressure decreases with the altitude. The pressure and the density of the nozzle flow do not vary during flight. So the variation of the transition conditions seen in the tests is only an experimental effect due to the high altitude chamber and will thus not take place in real application.

5. Conclusion

A criterion is given for the flow mode transition in dual bell nozzles. The prediction is accurate for ideal conditions: nozzle in its full length, no wall deformation due to temperature influence and under ambient conditions. Experimental studies have shown that the transition NPR increases with decreasing extension length, with increasing flow temperature and with decreasing pressure in the high altitude chamber. However, for an optimized extension geometry and in flight conditions, the transition can be well predicted with the proposed criterion.

References

6) Genin, C. and Stark, R., Hot flow testing of dual bell nozzles, 49th Aerospace Science Meeting, 4-7 Jan. 2011, Orlando, FL.