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PERFORMANCE OF SUPERSONIC FIRST-THROAT IN LOWER MACH NUMBERS

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Abstract. *The Pilot Transonic Wind Tunnel (TTP) of the Institute of Aeronautics and Space (IAE) is a facility with two sets of first-throat to achieve different test configurations. One sonic throat with only-convergent geometry to perform tests up to Mach number 1.0, and one supersonic throat characterized by a convergent-divergent geometry and with a specific area ratio to perform tests at Mach number 1.3. The first-throat design consists of two lateral panels with specific geometry which are manually replaceable just before the test section of the tunnel. The use of specific nozzle geometries to accomplish determined Mach number condition is a must in supersonic wind tunnels with solid test section walls. However, for transonic wind tunnel, where semi-open walls are required, the behavior of the test section is more complex. For example, with convergent-only geometry in a solid wall tunnel it is impossible to achieve Mach number higher than 1 at the test section. However, experience shows that slots act in such a way to allow reaching higher Mach numbers depending on pressure ratio. With solid walls and convergent-divergent first-throat the flow regime reaches supersonic condition at the test section, according to the area relation. Similarly, experience shows that it is possible to establish continuous Mach number control with convergent-divergent nozzle, counting on a complex behavior of test section semi-open walls. As the replacement of the first-throat panels is a cumbersome task, many times during tunnel operation it has been decided to keep the convergent-divergent nozzle to accomplish subsonic and even continuous supersonic regimes. The present work shows recent experiment undertook in TTP to assess the pressure distribution in the test section using the convergent-divergent first-throat in various operational situations and comparing them with results obtained with both first-throat geometries.*

Keywords: *transonic wind tunnel, first-throat, nozzle performance, transonic flow*

1. INTRODUCTION

The Aerodynamic Division (ALA) of the Institute of Aeronautics and Space (IAE) has built a transonic facility in 1988, denominated Pilot Transonic Wind Tunnel (TTP). The tunnel is a scaled down 1:8th from an industrial facility idealized by the Institute in 1985 to support the aeronautical development of the country. Due to financial restrictions only the pilot facility was built and made operational in 2000 (Falcão Filho et al., 2009). Figure 1 shows the aerodynamic closed circuit of the installation, where it is possible to observe the upper tubing connecting the circuit to auxiliary compressors installed in other building.

The tunnel is continuously driven by a main compressor of 830 kW of power, and works in a Mach number range from 0.2 to 1.1 related to its test section with dimensions 0.30 m of width and 0.25 m of height. It can also run intermittently with the help of a mass injection system which operates in combined action with the main compressor for at least 30 s, achieving Mach numbers up to 1.3. Automatic control systems for Mach number, stagnation pressure (from 50 kPa to 125 kPa), stagnation temperature and humidity allow stable conditions at the test section to guarantee similarity with real flight conditions (Falcão Filho and Mello, 2002).

Figure 2 shows a diagram of the tunnel circuit, where one can see its main functional parts. The circuit has four corners. Generally the region between the corners 4 and 1 is known as the test leg, where the test section is located and the region between corners 2 and 3 is known as the back leg, which consists of elements to redirect the flow with renewed energy level to reach the test leg. The back leg elements are almost all with large areas and low speed in order to diminish pressure losses. On the other hand, the test leg has the test section, the component with the highest speed and pressure loss. To achieve stable and uniform flow condition inside the test section there are specially designed components to settle the flow. The high temperature that comes from the compressor is decreased and controlled in the cooler. Just after the cooler there is the stagnation chamber with three screens and one honeycomb. The honeycomb cancels transverse components of velocity and the screens smooth the longitudinal speed component. Both the cooler and the stagnation chamber are the elements with the biggest area in order to keep low pressure losses.

(a) (b)

Figure 1. (a) TTP's aerodynamic closed circuit (with 17 m long and 4 m wide), and (b) the Plenum Chamber open showing its internals (test section with red structure).

As the flow is uniform and has its temperature controlled, it can be accelerated to reach desirable conditions at the test section. This is accomplished initially by means of the main contraction sector which accelerates the flow while changing the shape of the cross sections, from a cylindrical section to a rectangular section at the first-throat entrance. The first-throat, the test section and the second throat are involved by the plenum chamber that equalizes the pressure in all slots of the test section walls.

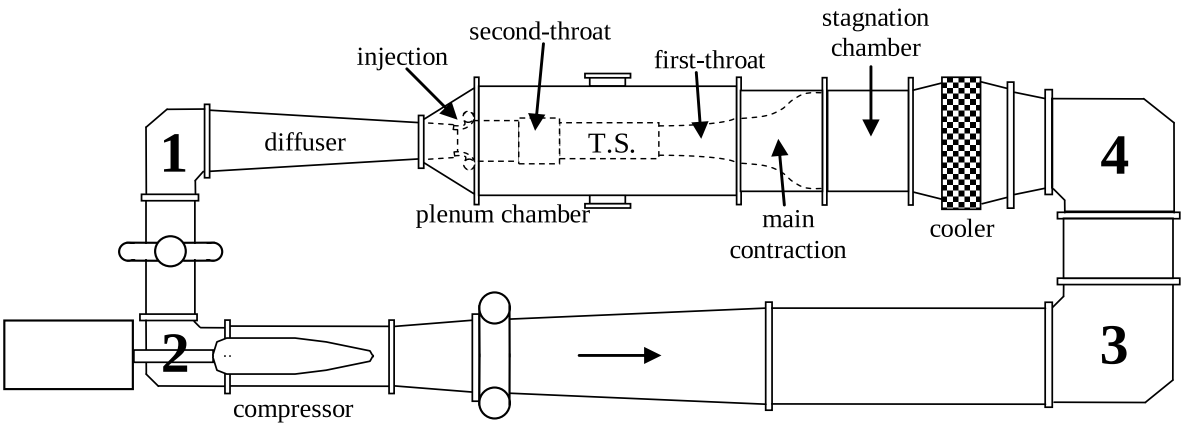


Figure 2. Diagram of the tunnel's aerodynamic circuit, showing the main components.

In the first-throat the flow is still accelerated by changing the lateral walls geometry while keeping constant the height of this element. Figure 3 shows the plenum chamber open with its internal elements: first-throat, test section, second-throat and injection section. The lateral walls of the first-throat are replaceable to change the geometry. The tunnel has two sets of first-throat panels, one subsonic with only-convergent geometry and one supersonic with convergent-divergent geometry to accomplish tests at Mach number 1.3.

In some wind tunnel installations, the first-throat has flexible walls, which allow adjusting them to any Mach number condition. This is not the case for the TTP, which has fixed geometry first-throat panels. As the replacement of the first-throat panels is a cumbersome task, many times during tunnel operation it has been decided to keep the supersonic convergent-divergent nozzle to accomplish subsonic and even other supersonic speed regimes than Mach number 1.3 tests. Certainly some prejudice is expected with this, since the nozzle was not predicted to work in this situation. However, it is possible to quantify the error by adopting this idea and admit it for certain types of tests.

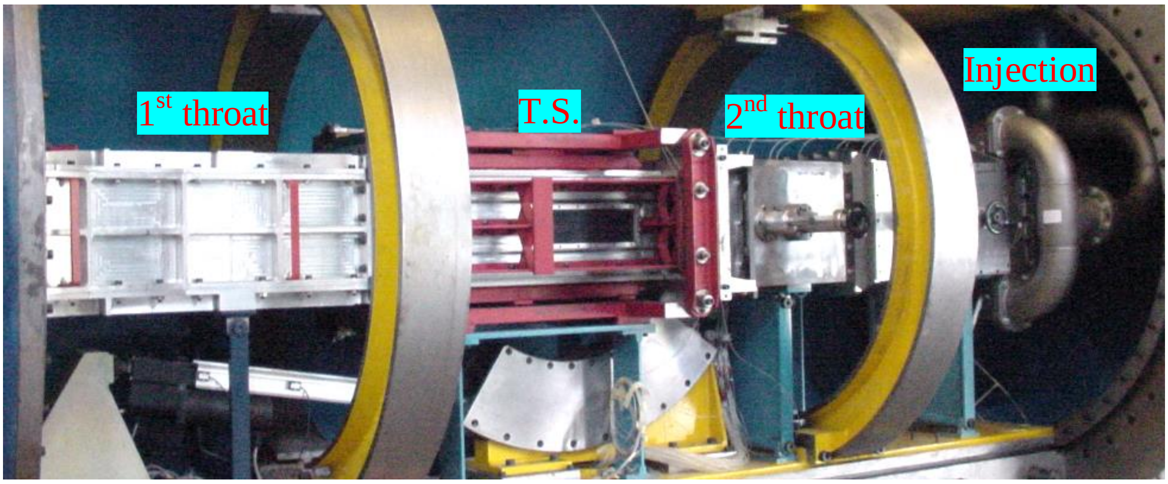


Figure 3. Plenum chamber open showing its internal elements.

Figure 4 shows diagrams of subsonic (only-convergent) and supersonic (convergent-divergent) nozzles. The subsonic nozzle is quite simple where the final area is the throat area being reached at the test section entrance. Theoretically for solid walls the maximum Mach number at the test section is 1.0 (Pope and Goin, 1978).

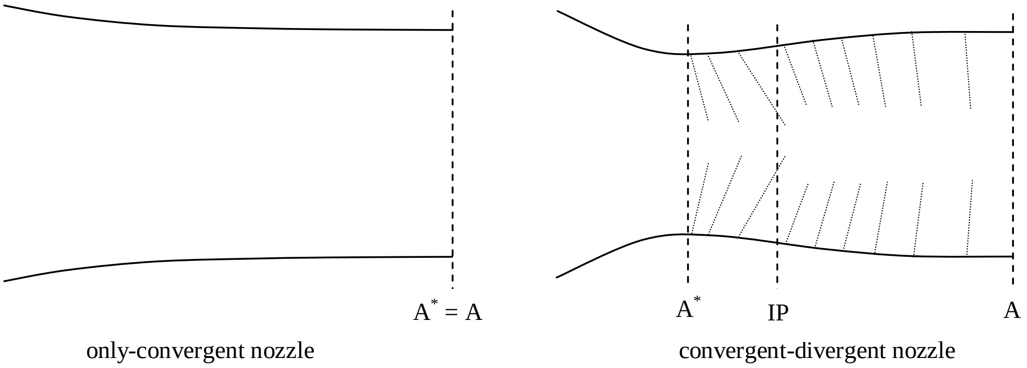


Figure 4. Diagram of subsonic (only-convergent) and supersonic (convergent-divergent) nozzles.

Supersonic nozzle has a more sophisticated design as it has been studied for many decades in the last century. It is necessary to create a section called throat with minimum area and the element will work up to the throat as an only-convergent nozzle at maximum speed, *i. e.*, Mach number 1.0. Thus the nozzle is choked. After the throat the flow is accelerated to supersonic conditions provided that the supplied pressure ratio is sufficient. The Mach number (*M*) achieved at the end in this case depends on the area ratio, which can be given by Eq. 1 (Anderson, 2007).

$$\frac{A}{A^*} = \frac{1}{M}\left[\frac{1+\frac{\gamma-1}{2}M^2}{1.2}\right]^{\frac{\gamma+1}{2(\gamma-1)}} . \qquad (1)$$

Convergent-divergent nozzles may operate at other flow regimes depending on the pressure ratio provided (Anderson, 2003). According to Eq. (1), the designed area ratio for a convergent-divergent nozzle for Mach number 1.3 is 1.06631 and the nozzle will work in a chocked condition, with Mach number 1.0 at the throat and supersonically downstream. However, this same area ratio corresponds to the subsonic solution for Mach number 0.7432. This means that the same area ratio will allow subsonic behavior with Mach number 1.0 at the throat and Mach number 0.7432 at the test section, making the nozzle work in a special fashion known as Venturi regime.

For supersonic regime inside the nozzle, the wall geometry of the region after the throat should be constructed in such way to avoid compression and/or expansion waves into the test section area. This is due to the supersonic flow behavior. Just after the throat as the walls open (increasing of wall inclination) expansion waves appear until the inflexion point (IP) is reached see Fig.4. From this point on, the wall inclination decreases and then compression waves appear. To avoid that these expansion and compression waves, which will reflect indefinitely on the walls, reach the test section, a mathematical procedure is developed to create the geometry after the inflection point based on the method of the characteristics. This geometry will create compression waves in such points to precisely cancel the expansion waves generated before the inflexion point. Thus, the geometry at the end of the nozzle will be expansion/shock-free (Crown, 1948).

For subsonic flow operation, or Venturi operation, there is no expansion or compression waves. For supersonic flow if this cancellation is not attained, the flow in the test section may be affected by these expansion and compression waves which were not adequately treated. This will be also the case for geometry that was not precisely designed for a particular Mach number regime. For example, the nozzle for Mach number 1.3 may give poor results for other Mach numbers. This is why in many tunnels the first-throat has flexible walls shaped by the action of jacks alongside for definite Mach number condition. For supersonic wind tunnels where the walls are solid it is fundamental that the nozzle geometry is adjusted for precise Mach number.

On the other hand, the slots in the test section act extending the behavior of the nozzle, as it allows streamlines to extend beyond the test section walls resulting in a smooth continuous changing of Mach number depending on pressure ratio, or the main compressor rotation. This is true even with only-convergent subsonic nozzle. For example, it is possible reaching Mach number 1.1 with reasonable flow quality by increasing the main compressor rotation. For supersonic convergent-divergent nozzle it is possible to use Mach number 1.3 nozzle for other Mach number conditions as well.

The next section will show some important experimental results to quantify the deviation present when typical models are tested.

2. MACH NUMBER CORRECTION

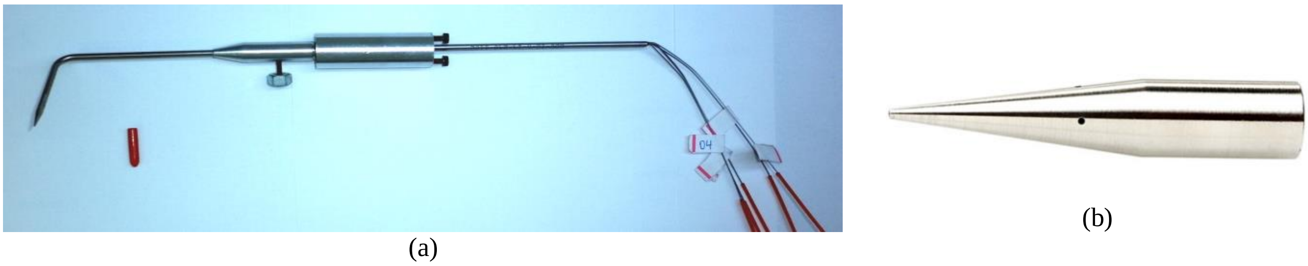
The Mach number at the test section is determined from the relation between total pressure and static pressure at its entrance by the isentropic relation expressed by Eq. (2) (Anderson, 2007).

$$M = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{p_0}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}, \qquad (2)$$

However, it is difficult to measure total pressure into the test section because installing a Pitot probe inside the test section would disturb a lot the flow in transonic range. For high speed wind tunnels up to Mach number 1.6 it is observed that the total pressure loss between the stagnation chamber and the test section entrance (see Fig. 2) is very low (Pope and Goin, 1978). In TTP total pressure is measured at the wall of the stagnation chamber. The decrease in the pressure read at the stagnation chamber, being interpreted the pressure at the wall as a total pressure, practically compensates the decrease in stagnation pressure between stagnation chamber and test section, being a good candidate.

However, if the convergent-divergent supersonic nozzle will be used at test section Mach number, for example, 1.2, shock waves inside the solid walls of the first-throat will produce a wrong value, as shock wave will cause decrease in total pressure. Thus, for Mach number higher than 0.75, it is expected some correction in Mach number read by the above procedure.

To correct Mach number values using a supersonic convergent-divergent first-throat, a conical probe was installed into the test section to compare total pressure measurements with the pressure measured at the stagnation chamber. Figure 5 (a) shows the conical probe used in the experiments. A special holder shown in Fig. 5 (a) was adapted to fix the probe outside the test section in such way to introduce its head through the test section wall longitudinal slot. Figure 5 (b) shows the probe head with one of four pressure taps visible. At its tip the probe has the total pressure tap, which pressure level should be corrected at supersonic regime.



(a) (b)

Figure 5. Conical probe assembly (a) with a holder to fix it outside the test section, and (b) probe head showing one of four circumferentially distributed pressure tapes.

Figure 6 shows the result in terms of Mach number correction obtained with the Conical probe. Observe that although the nozzle geometry predicted difficulties above Mach number 0.7432 as discussed in section 1., one can see that up to Mach number 0.8 there is no need of correction in the Mach number. Maybe this comes from the fact that the slots are always working to alleviate the effect of possible expansion and compression waves reflections on the wall. By the way, this is exactly one of the slots purpose (Goethert, 2007). It is interesting to note that from Mach number 0.8 to 0.9 the need for correction increases. The next singular region goes up to Mach number 1.05, when the correction is practically the same and from this point on, the correction increases again.

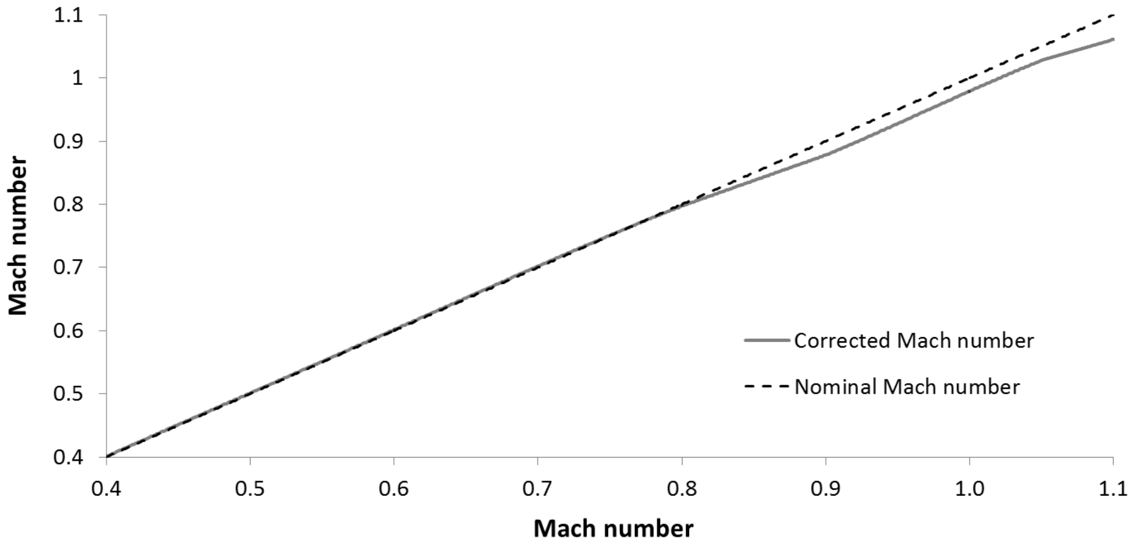


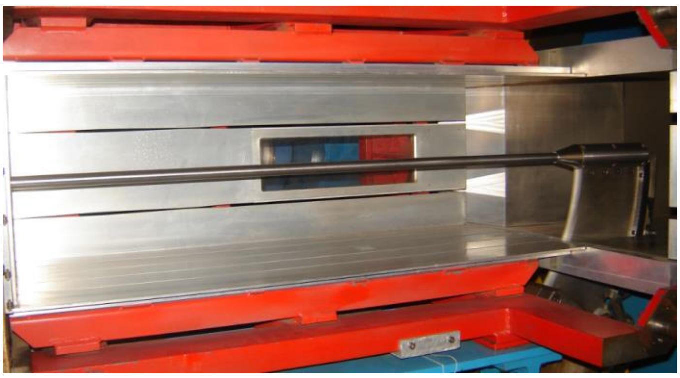
Figure 6. Mach number correction prescribed for using supersonic first-throat geometry.

The result presented in Fig. 6 was expressed in terms of Mach number correction for nominal Mach number (M), being divided in four distinct regions, as given by Eq. (3).

$$\begin{array}{ll} \Delta M = -2.3569M^4 + 5.2243M^3 - 4.2781M^2 + 1.5364M - 0.20327, & for \quad M < 0.8 \\ \Delta M = -0.1942M + 0.1527, & for \quad 0.8 \leq M < 0.9 \\ \Delta M = -5.817M^3 + 16.886M^2 - 16.306M + 5.2161, & for \quad 0.9 \leq M < 1.05 \\ \Delta M = -0.33869M + 0.33358 & for \quad 1.05 \leq M \leq 1.10 \end{array}, \qquad (3)$$

The Mach number correction will be verified and results will be shown for two distinct assessments: (1) centerline Mach number distribution and (2) drag force measured with a typical model installed in the test section.

The centerline Mach number distribution was assessed by a centerline probe installed in the test section, as shown in Figs. 7 (a) and (b). In these figures the lateral wall of the test section was removed.



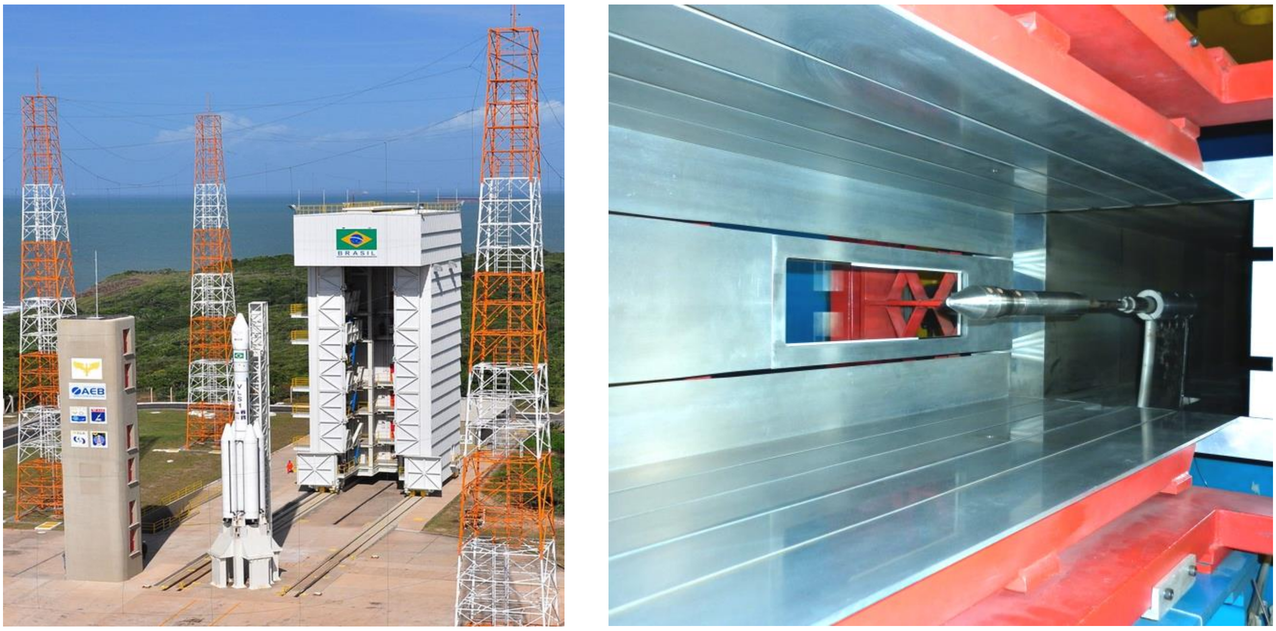
(a)

(b)

Figure 7. Tunnel's test section without lateral wall showing (a) the pressure probe installed in centerline and fixed at the sting holder, (b) the front part of the probe which is 0.12 m inside the divergent part of the first-throat.

The cylindrical probe, installed at the model sting support (see Fig. 7 (a)), has an ogive at the tip with 17.2 mm outer diameter representing 0.3% of blockage area and with an orifice for total pressure measurement. The probe total length is 1.24 m and it has 33 static pressure orifice stations alongside distributed. Close to the region called the nominal test section, where the model is to be installed because it is expected the best flow quality, the measuring points are distant 10 mm, and in other regions 20 mm of distance was adopted. Each station has four orifices circumferentially distributed and connected to a single pressure measurement sensor. The tip is prolonged 0.12 m inside the divergent part of the first throat. Results using this pressure probe will be shown for only-convergent and convergent-divergent nozzles.

In order to verify drag results with both nozzles it was selected a typical vehicle model. In this case, it was chosen the VLS-1 (Brazilian Satellite Launcher Vehicle), as shown in Fig. 8. The real vehicle at the launch platform is shown in Fig. 8 (a). The vehicle is quite complex with four stages, and the first stage comprising four lateral strap-on boosters. The vehicle is configured with a hammer-head fairing to ship larger pay-loads. The fairing comprises a frustum-cone to geometrically accommodate cylindrical parts with different diameters, called boat-tail (Moraes, 1990). In order to investigate aerodynamic behavior of the front part of the vehicle varying boat-tail angle, it was constructed a special model with the front of the VLS-1 truncated at 10 diameters from the model tip (Medeiros, 2014). The model has a scale 1:37 from the real vehicle with the biggest diameter of 32 mm, guaranteeing small blockage area in relation to the test section area (1.1%).



(a) (b)

Figure 8. The vehicle VLS-1: (a) at the launch platform, and (b) model of the front part of the vehicle in scale 1:37 installed at the TTP's test section.

3. RESULTS

Figure 9 shows results of the Mach number uniformity at the centerline of the test section using the centerline pressure probe and they were already presented in another article, as they will be soon referenced. In Fig. 9 (a) we can see the result using the only-convergent first throat geometry. Because of shortage of pressure measuring channels the first measuring points near the test section entrance were not selected.

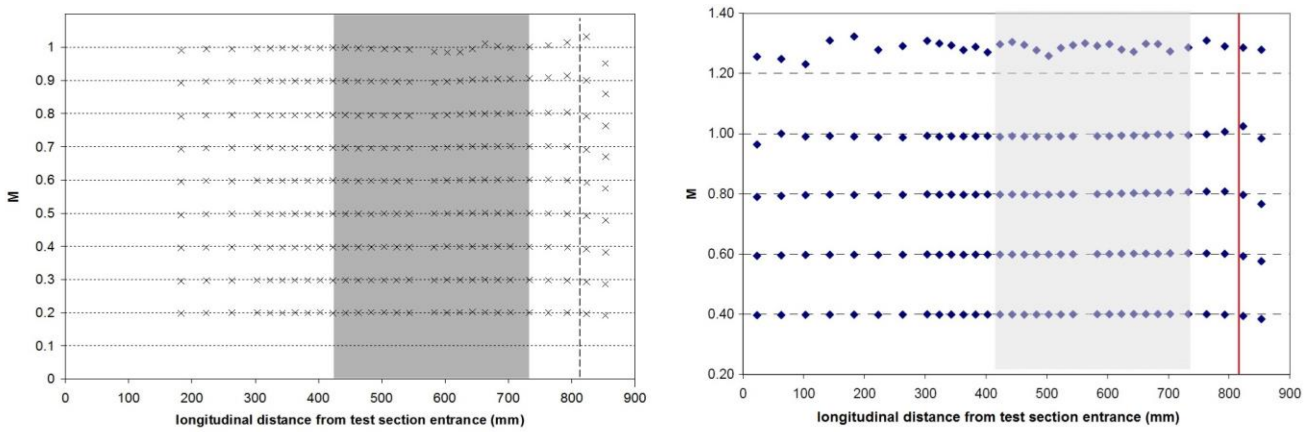
In the graphics, the region called the nominal test section where the model is to be installed is shadowed, and a vertical line marks the end of the test section. Thus, two measuring points are located in the reentry-flaps region. One measuring point almost at the medium of the nominal test section read wrong values during various test runs because it was clogged and its value was not shown.

The results for only-convergent first-throat (Fig. 9 (a)) were taken only up to Mach number 1.0, and they revealed good uniformity properties for the flow, mainly in the nominal test section. The Mach number deviation observed in most Mach number conditions was of approximately 0.002 (Falcão Filho and Ubertini, 2011).

The results obtained for convergent-divergent first-throat (Fig. 9 (b)) were taken for the designed first-throat Mach number of 1.3 and also for some off-design conditions (Mach numbers 1.0, 0.8, 0.6 and 0.4) (Reis *et al.*, 2012). It is important to observe that the Mach numbers are taken as nominal values and they were not corrected at this point.

It is impressive how disturbed seems to be the Mach number distribution for 1.3. In the nominal test section the Mach number standard deviation was 0.013. Reis *et al.* (2014) compare the results for Mach number 1.3 with data from continuous operated transonic wind tunnels of ARA 9ft x 8 ft with perforated walls, Langley 8 ft, Langley 16 ft and AEDC 1 ft, these three with slotted walls. TTP's standard deviation compares well with the small wind tunnel from AEDC 1 ft, but these values are about three times the standard deviation observed in large installations.

For Mach numbers 1.0 and below, the results were very good, and at the same quality obtained with the only-convergent first-throat.



(a) (b)

Figure 9. Mach number distribution in the test section and reentry-flaps region using (a) only-convergent sonic first-throat, and (b) convergent-divergent Mach number 1.3 first-throat.

Figure 10 shows the results using an internal balance to measure drag force in the VLS-1 model with zero angle of attack. In order to suppress errors due exclusively to the internal balance, the values in Fig. 10 were made non-dimensional by the value obtained at Mach number 0.6. The only-convergent first-throat points are only for Mach numbers 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 0.95. It is clear that these results (points marked with black circle) do not compare well with those obtained with the convergent-divergent first-throat considering the Mach number without any correction (points marked with diamonds). After the correction of the Mach number values the new curve (represented by points with squares) goes to the left, as indicated at one point with a red arrow. Thus, one can see how well these new corrected values compare with those obtained with the only-convergent first-throat.

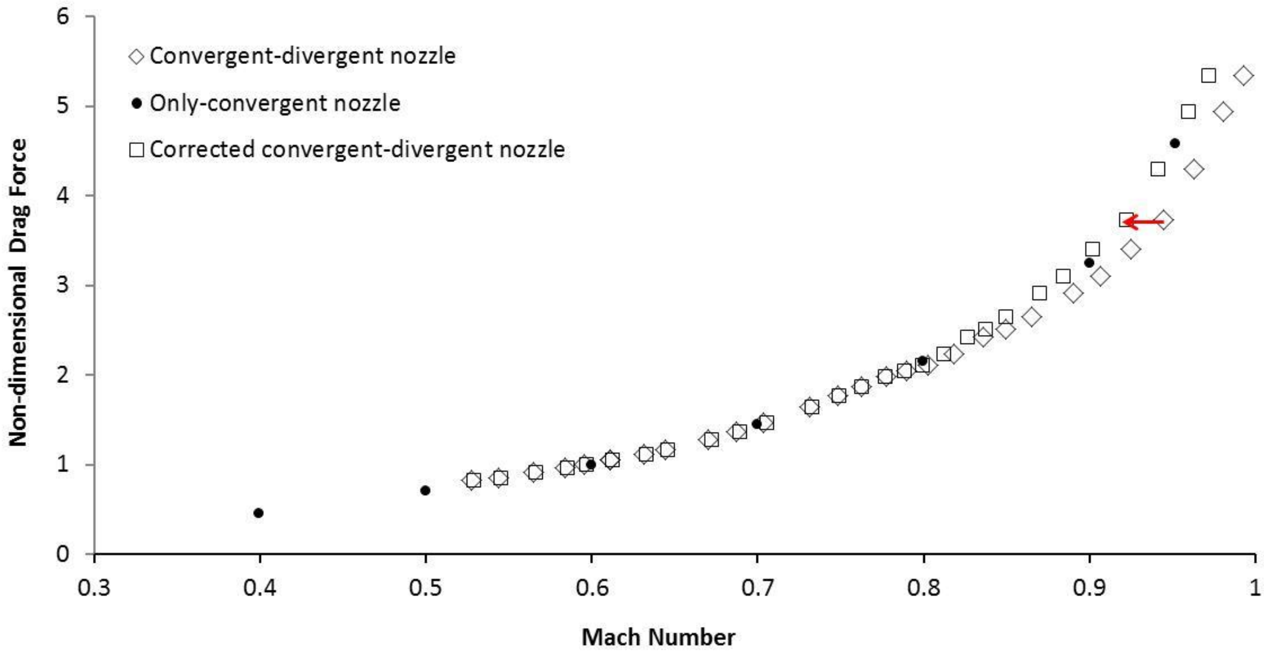


Figure 10. Diagram of subsonic (only-convergent) and supersonic (convergent-divergent) nozzles.

4. CONCLUSION

This paper highlights the possibility of using a convergent-divergent nozzle, operating as a first-throat in a transonic wind tunnel, at other Mach number values than the one of the design point. The great advantage of this is found in fixed geometry first-throat designs which demands great, time consuming, effort to change their lateral panels.

A particular problem was addressed and the results were reported by using the Pilot Transonic Wind Tunnel of IAE, where tests were undertaken to determine correction in Mach number values due to discrepancies aroused by using the convergent-divergent nozzle at off-design operational point.

The tunnel was verified in terms of Mach number distribution at the centerline of the test section indicating that both first-throats had similar standard deviation for Mach number range from 0.4 to 1.0.

A model of the front part of the vehicle VLS-1 in scale 1:37 with 1.1% of blockage area was tested in the TTP using an internal balance to measure drag force. A correction in the Mach number was applied to the results obtained with the convergent-divergent first-throat and they had good agreement when compared with the results obtained with the same model using the only-convergent first-throat.

Further analysis to assess spatial Mach number distribution and the use of other models with higher blockage area are being considered in order to determine the operational limits for using the convergent-divergent first-throat at off-design operational points.

5. ACKNOWLEDGEMENTS

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