Proceedings of ENCIT 2012
14th Brazilian Congress of Thermal Sciences and Engineering
November 18-22, 2012, Rio de Janeiro, RJ, Brazil

EXPERIMENTS IN TRANSONIC WIND TUNNEL USING A SUPERSONIC FIRST-THROAT

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Abstract. *The purpose of this work is to describe the preliminar experimental data obtained with the supersonic first-throat installed in the Pilot Transonic Wind Tunnel (TTP) of the Aerodynamic Division of the Institute of Aeronautics and Space. It is presented the main components of the wind tunnel, as well as the acquisition systems used to assess the experimental data. A special designed pressure probe with 33 measuring stations was utilized to obtain the Mach number distribution at the test section center line. It was also used 25 pressure taps distributed along the top and bottom walls of the tunnel to obtain the Mach number distribution along the test section walls. The tunnel used injection system in a combined fashion with the continuous operation of the tunnel to reach Mach number 1.3. Mass flow extraction was also used with the re-entry flaps at 5 degrees open to enhance the Mach number uniformity along the test section. The experimental results in terms of the Mach number deviation were compared with other typical wind tunnel experimental data.*

Keywords: *Supersonic flow, Transonic wind tunnel, Supersonic nozzle.*

1. INTRODUCTION

The Pilot Transonic Wind Tunnel (TTP) from the Institute of Aeronautics and Space (IAE) has financial support from CNPq/AEB to analyze numerically and experimentally the wing/fuselage interference of the SONDA III for Mach number 1.3. To reach Mach number 1.3 at the test section, it is necessary to change the standard subsonic first-throat by a convergent-divergent supersonic first-throat. The original first throat is sonic only-convergent type that allows a continuous Mach number establishment in the test section from 0.2 to 1.08. To reach supersonic regimes, a new supersonic convergent-divergent first throat is needed, theoretically with a specific geometry for each desirable Mach number. In many industrial installations rectangular first throat geometry is obtained by two flexible steel plates in opposite walls that can be bent in some points by hydraulic or electric actuators. This way it is possible to adjust a sonic geometry for the entire subsonic regime and to adjust to any specific geometry for supersonic desirable Mach number. This is a very expensive solution, however during the TTP design it was adopted a simpler design with two interchangeable lateral panels for each speed condition. Thus, now TTP has two sets of first throat lateral walls, one with convergent-only geometry which can be used in the entire subsonic regime and one with convergent-divergent geometry which was designed to establish Mach number 1.3 in the test section.

A typical convergent-divergent supersonic first-throat is composed of different regions, each one with specific functions. In the convergent region, the coming flow is subsonic and it accelerates to unitary Mach number at the smallest area of the nozzle. In the divergent region the flow continues accelerating due to area expansion in the supersonic dominion until reaching the projected Mach number. The major difficulty found in supersonic nozzle design is the expansion waves and the compression waves that may be originated at the walls, after the throat section, in the regions called initial and straightening of the divergent, respectively. The waves reflected on the walls propagate through the whole extension impairing the condition of parallelism and longitudinal uniformity of the flow at the end.

Thus TTP's technical team designed several nozzle configurations to achieve the best geometry for the supersonic first-throat of the TTP. In the research the supersonic nozzles concepts design were based on two very famous methods: the Method of Characteristics (MOC), found in Saad (1993) and Shapiro (1953), and the method of Foelsch (Foelsch, 1949). It was observed that the Foelsch's method presented the best geometric choice for the design of the first throat Mach number 1.3 to be used in TTP. More details about the application of these methods to the design problem can be found in Goffert *et al.* (2011). Later on a company was selected to fabricate the first throat to be installed in the tunnel.

It is very important the assessment of the flow characteristics in the test section region in order to determine the uniformity according to a spatial Mach number criterion. According to scientific literature (Davis *et al.*, 1986), one basic criterion to ensure a good quality of the flow in modern transonic wind tunnel is given by the standard deviation of the Mach number expressed by Eq. (1) over the region where the model is installed, *i.e.*, in the well-known nominal test section, and this accuracy must be periodically verified to guarantee the robustness and repeatability of the tests performed in the installation.

$$\left|2\sigma_M\right| \le 0.001. \tag{1}$$

Although this requirement is too demanding it is possible to observe practical values less rigid in important transonic facilities. With the original sonic first throat the achieved spatial Mach number deviation observed in tests undertaken at TTP in transonic range was about ± 0.0012 (Falcão Filho and Ubertini, 2011), and this value can be considered a goal for the new first throat design.

Some important examples of calibration and verification of the uniformity of center line Mach number distribution with possible wave reflections in important wind tunnels with supersonic flow also can be seen in Brooks *et al.* (1994) and Haines and Jones (1960). Following these procedures, the present paper presents the experimental results in terms of supersonic Mach number distribution of the TTP test section at the center line, top and bottom walls, comparing also with two-dimensional Euler numerical simulation data.

1.1 Pilot Transonic Wind Tunnel (TTP)

The Pilot Transonic Wind Tunnel (TTP) is a scaled down 1/8 from an industrial transonic facility project. The tunnel has a conventional closed aerodynamic circuit with a test section of 0.25 m x 0.30 m, with slotted walls, and with automatic controls of speed, pressure, temperature and humidity. The tunnel is continuously driven by a two-stage, 830 kW main compressor, frequency controlled, but it also operates intermittently with an injection system that provides a high speed gas jet, combined with the main compressor continuous mode of operation, to enlarge the tunnel's operational envelope without demanding extra installed power (Goffert *et al.*, 2008). The use of the injection as a power source in wind tunnels is well known; however, its use in conjunction with the main compressor represents a a difficult technological task (Falcão Filho and Mello, 2002).

Figure 1 shows the TTP's aerodynamic circuit diagram with mass injection/extraction system. Table 1 shows the nomenclature and the reference number of the main components showed in Fig.1. The basic principle of the TTP operation will be described here. The flow is accelerated by the main compressor (1) which keeps the flow running in the closed circuit. Almost all the electric power is transferred to the fluid in terms of mechanical power which will, inevitably, be transformed in heat, that must be extracted from the circuit to keep the balance and guarantee a stable temperature in the circuit. That is why the flow will pass through a cooler (2). Because of the disturbance created by the compression process, the flow must also pass through the stilling chamber (3) with screens and honeycomb to make it uniform longitudinally and transversally, respectively. The flow is now ready to be accelerated in a fixed convergent section and then to reach the first throat inside the plenum chamber. The plenum chamber (4) folds very important section: first throat, test section, flaps section, second throat and injection mixing section. For attaining Mach number 1.3 it is necessary to use the injection system because the main compressor power and pressure ratio are not enough. During injection operation high pressure air produced by piston compressors (8) and which are hold in reservoirs (7) is delivered through control valves (6) to injector beaks (5) which work in chocked condition at Mach number 1.9. The mixture of jets induces the main flow acceleration to reach the desirable Mach number condition. In TTP the injection operation is performed by stopping the normal auxiliary pressure control system because the injection mass flow is much superior the capacity of the auxiliary compressor (11) and so, its function is only directed to extract mass from the plenum chamber through control valve (12) helping the Mach number establishment in the test section. More details about the injection system operation may be found in (Goffert *et al.*, 2008).

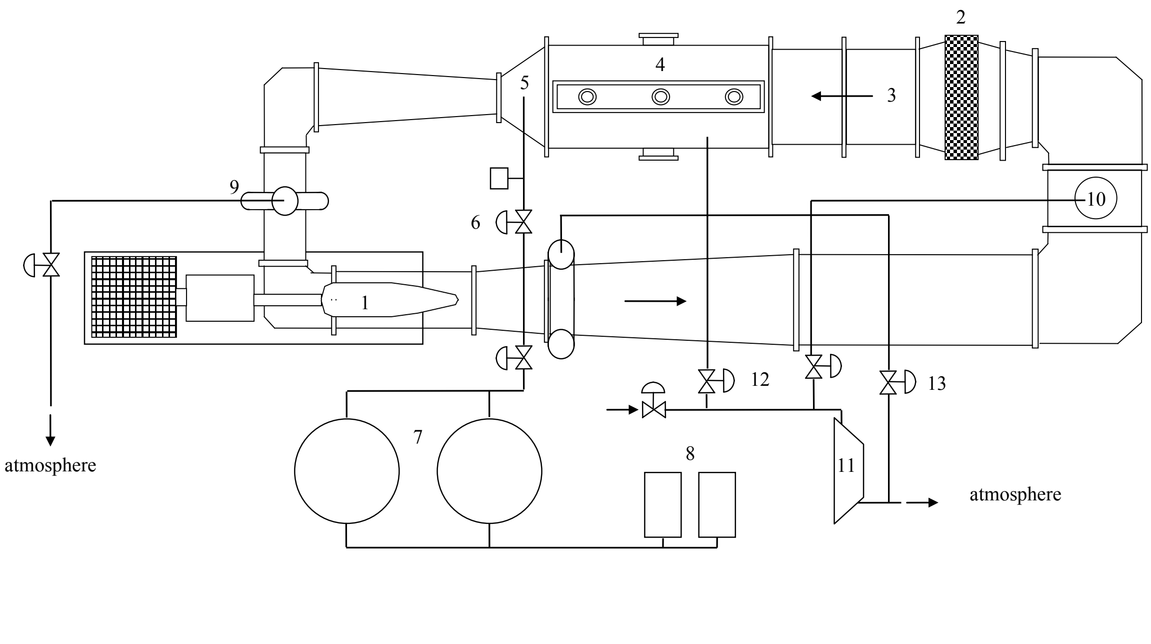


Figure 1– TTP's aerodynamic circuit with injection and extraction system.

Table 1 – Main components of TTP.

Number	Component
1	Main compressor
2	Stilling chamber
3	Cooler
4	Plenum chamber
5	Mixing chamber
6	Control valve (injection system)
7	Reservoirs (injection system)
8	Compressors (injection system)
9	Blow off section
10	Wind tunnel pressure relief valve
11	Compressor auxiliary
12	Control valve (extraction system)
13	Circuit relief pressure valve

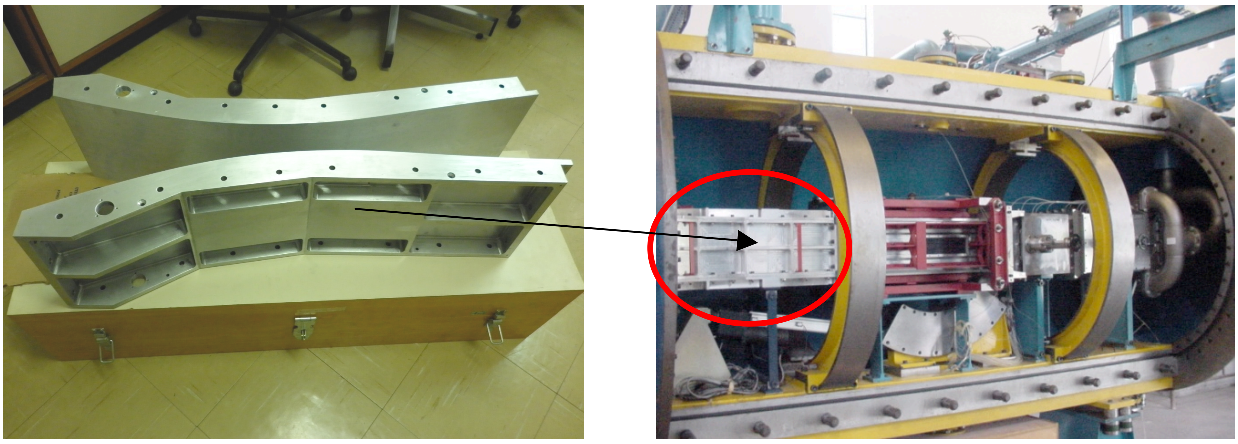
2. APPARATUS AND METHODS

TTP performed the tests with the new supersonic first-throat using the injection system to reach Mach number 1.3 in the test section. The Mach number distribution was assessed by using a pressure probe and by pressure taps along the walls. In this section it is presented the supersonic first-throat installed in TTP, and the methodologies employed during the experiments.

2.1 Supersonic first-throat

The supersonic first-throat specified in Goffert *et al.* (2011) consists of two solid blocks made of Aluminum and machined in CNC to represent with good accuracy the geometry of the panel (Fig. 2 (a)) – in one face one can see the structural design and in the other face a very smooth geometry to be mounted as a lateral wall for the main stream. The panels are installed in the proper location into the plenum chamber just before the test section (Fig. 2 (b)).

A complete geometric verification including finishing details was accomplished and showed a superior quality of the parts. The mounting procedure did not require any rework, and the panels showed to be perfectly interchangeable with the former sonic panels.

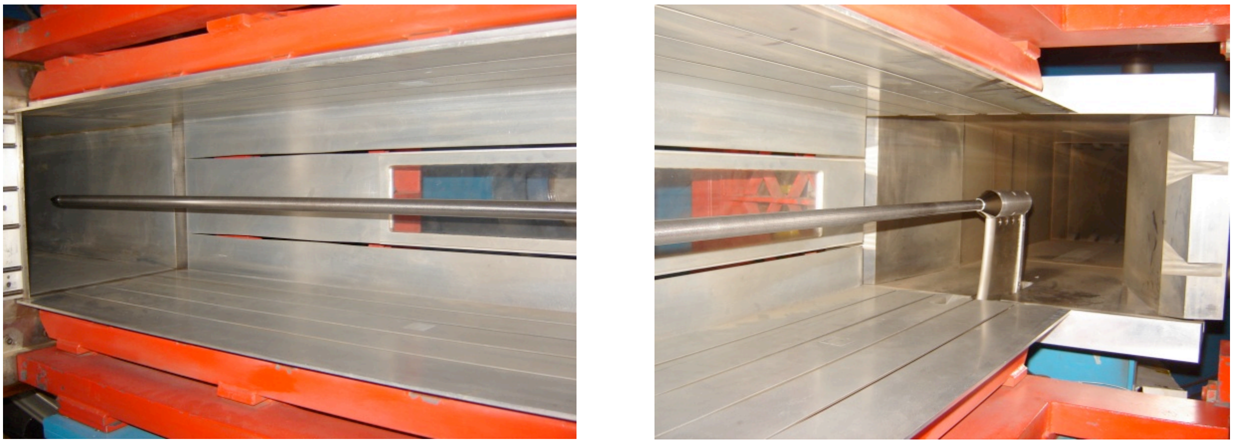


(a) (b)

Figure 2. Supersonic first-throat: (a) machined panels, (b) installed on TTP.

2.2 Pressure measurements by the pressure probe and Mach number determination

The static pressure probe design consists of an ogive tipped 17.2 cm outer diameter cylinder with 1.24 m of length that has thirty three static pressure orifices stations with four orifices connected to a single pressure measurement at each station. Its wall thickness is 2.1 mm to ensure a sufficient rigidity not to bend the probe and its diameter represents a blockage ratio of 0.3%, which is reasonably small for intruding effects. Figure 3 shows the front (a) and the rear (b) of the pressure probe whose tip is prolonged 12 cm inside the divergent part of the first throat.



(a) (b)

Figure 3. Pressure probe installed on the test section: (a) front, (b) rear.

For some tests the pressure probe was removed and 25 pressure taps distributed at the top (13) and at the bottom (12) walls of the test section were used to evaluate the Mach number distribution along the test section walls.

All the pressure taps were connected to pressure scanners with piezoresistive differential pressure sensors manufactured by Esterline Pressure Systems©, by hoses made of silicon. The device supplies responses in volts, and through calibration process the data is converted to pressure values. The atmospheric pressure is read by a reference pressure sensor to obtain the final absolute pressure value, using Eq. (2)

$$p = p_{atm} + \Delta p \tag{2}$$

where p is the absolute pressure, p_{atm} is the atmospheric pressure e Δp is the pressure obtained by the pressure device.

During the runs, the voltages referenced to the pressure taps measurements were acquired through the acquisition data board, controlled by a program in LabView®. The calibration process was the same founded in Souza *et al.* (2010). By knowing the static pressure (p) and the total pressure (p_0, read on wind tunnel control), the Mach number can be calculated simply by the isentropic relation (Anderson, 1995)

$$M = \sqrt{\frac{2}{\gamma - 1}\left(\frac{p_0}{p}\right)^{\gamma-1/\gamma}} \quad . \tag{3}$$

2.3 Mach number control

The Mach number control in continuous operation of TTP is done by adjusting the RPM of the main compressor and monitoring the resulted Mach number related to the test section entrance. The control system makes use of the isentropic relation of Eq. (3) to determine the Mach number from the static pressure read in a pressure tap at the entrance of the test section and the total pressure read at the tunnel's stagnation section (see Fig. 1, position 3). The pressure loss between the stagnation section and the test section entrance is practically negligible but even so its value is used to correct the Mach number determination.

3. RESULTS

Since the experiment represented the first attempt to reach Mach number 1.3 in the test section with the use of the injection system in a combined fashion with the continuous operation of the tunnel, it was done through some trials with progressive injection total pressure and nominal Mach number. In each case the tunnel was put to run continuously with the use of the main compressor at a nominal Mach number condition of about 0.9 at the test section, and then, the injection system was activated at a desired total pressure value. In Table 1 one can find the configuration parameters from the TTP control system for all the runs during the experiment, showing in each column: (1) the nominal Mach number read in the tunnel's control system just before starting the injection system, (2) the stagnation pressure at the injectors, (3) if it is made use of the forced mass flow extraction from the plenum chamber (PES), (4) if the pressure probe is installed in the test section, and (5) the resulted Mach number achieved in the test section with the standard deviation observed. Note that this Mach number deviation represents the temporal variation during the run. The shadowed regions in the table show the selected cases to be plotted in the operational envelope of the TTP to verify the injection system capacity in terms of increasing stagnation pressure and Mach number related to test section – in all the selected cases the pressure probe was installed. In the first three runs the Mach number just before the injection actuation was about 0.9 with injection pressure of 4, 6 and 8 bar and the resulted Mach number increase was 0.140, 0.271 and 0.326, respectively. But it was not possible to reach Mach number 1.3. So, in the runs 4, 5 and 6 the PES system was activated and the pressure probe was removed in order to decrease the pressure loss caused by it. In these three cases the final Mach number had a greater increase, reaching 1.3 when the continuous operation Mach number was higher (1.01). A final attempt to reach Mach number 1.3 was done with the presence of the pressure probe, with the PES system activated and starting with a higher continuous operation Mach number (0.99). In this case the Mach number was 1.284. The injection system was not used above 8 bar because the structural limit of the tunnel did not allow higher values of pressure. More attempts must be made in order to determine the best solution for the combined use of the injection system, exploring other Mach number starting conditions.

Nevertheless, it is worth noting the low Mach number temporal deviation observed in the test section with the use of the injection system of about 0.001, indicating a very good flow condition in the test section.

Table 2 – Operating conditions for each seven injection system study cases.

Run	Initial Mach number with continuous operation	Stagnation pressure at the injectors (bar)	Use of PES system	Pressure probe installed	Resulted Mach number at the test section
1	0.92	4	No	Yes	1.060 ± 0.001
2	0.90	6	No	Yes	1.171 ± 0.001
3	0.90	8	No	Yes	1.225 ± 0.001
4	0.89	4	Yes	No	1.087 ± 0.003
5	0.91	6	Yes	No	1.203 ± 0.001
6	1.01	8	Yes	No	1.306 ± 0.001
7	0.99	8	Yes	Yes	1.284 ± 0.001

Figure 4 shows the impact of the four selected cases in Table 2 (1, 2, 3 and 7) in the operational envelope of TTP. The envelope represents the region of operation of the tunnel with its limits. The upper limit represents the structural limit of the circuit's carcass (1.25 bar). The lower limit represents the capacity of the auxiliary pressure control system to allow stagnation pressure control in the tunnel's circuit. The left limit is the lower suggested Mach number of 0.2. TTP can operate in lower speed than this, however with low precision in the operational control. The right limit represents the power limit or the capacity of the tunnel to reach high speed with adequate first throat. The region marked as "injection" represents the region that can be reached with the injection starting at nominal continuous operation Mach number 0.6. If a lower Mach number is set and the injection system is activated it may cause a counter-rotation in the compressor – situation that must be avoided. In the envelope, the small triangle area in the right upper corner represents the region that can be reached only with the use of the injection in combination with the main compressor continuous operation. It is important to say that the injection system in the TTP is almost redundant, *i.e.*, it is possible to reach almost all the injection area in the envelope only with the continuous operation mode. This was done so to test the results with more than one mode to gain expertise for the industrial project.

It is worth note that the power limit was exceeded and the structural limit of the installation was reached in the higher Mach number run (case 7 in Table 2). It is very interesting the Mach number and total pressure increase for each study case, as shown in Fig. 4. Number 1 represents the starting condition at continuous operation and number 2 represents the final condition of Mach number and total pressure, relating to the test section.

Figure 5 shows the Mach number distribution in the test section of TTP for the first three study cases along the upper wall of the test section, with the pressure probe installed and with no PES system activation. The Mach numbers observed with the standard deviation were 1.053 ± 0.004, 1.140 ± 0.010 and 1.191 ± 0.019. It is interesting to observe that as the Mach number level increases its deviation increases considerably. It is very interesting also to observe that the supersonic first throat designed to operated mathematically well at Mach number 1.3 can produce very stable flow at Mach number 1.05 and even the same good behavior can be observed for Mach number 1.14, indicating that it can indeed work well, passing continuously in other Mach number configurations.

One question can arise from Fig. 5. Is the pressure probe responsible for the bad behavior at Mach number 1.3? To solve this question, the followed study cases (4, 5 and 6 from Table 2) can give some insight.

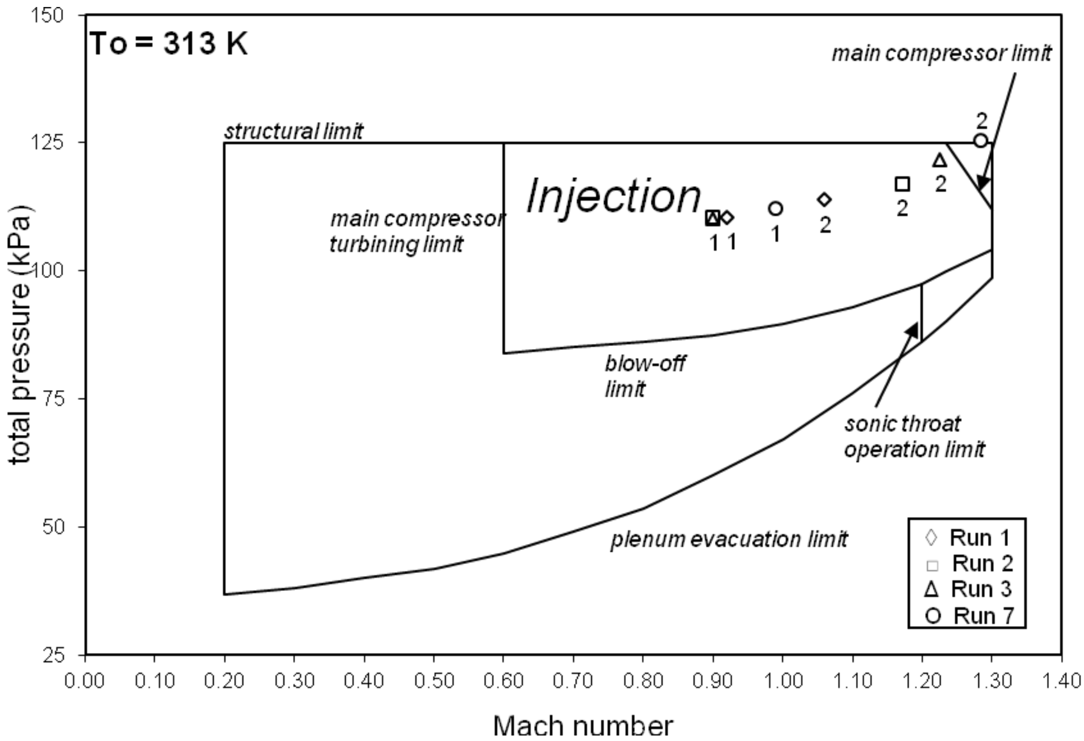


Figure 4. TTP's operational envelope with the runs 1, 2, 3 and 7, relating to Table 2.

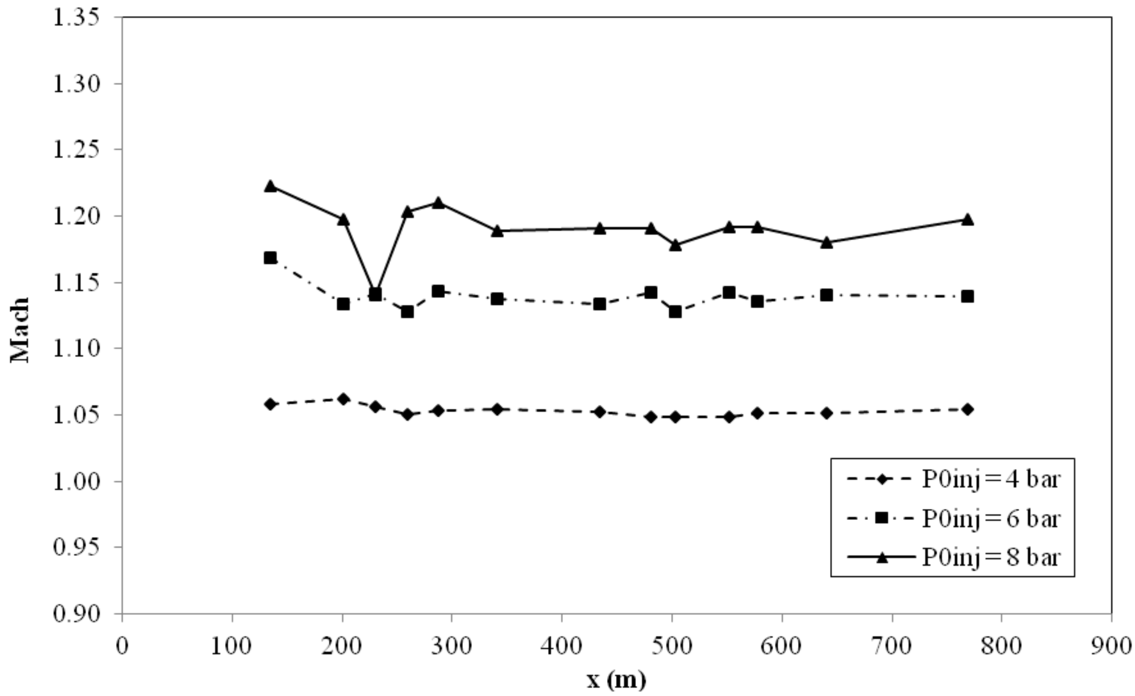


Figure 5. Mach number distribution along the upper test section wall, with the pressure probe installed for the first three study cases of Table 2.

Figure 6 shows results from the Mach number distribution along the upper test section wall for the study cases 4, 5 and 6 from Table 2, without the pressure probe and with the use of PES system – the PES helped to increase the final Mach number. The Mach numbers with the standard deviation were 1.075 ± 0.006, 1.175 ± 0.016 and 1.291 ± 0.014 and the same observation can be said here: the Mach number deviation increases much with increasing the Mach number. Surprisingly, the results show that the pressure probe was not responsible for the high deviation at Mach number 1.3, and the overall behavior was a little worse than the last case (Fig. 5) with the pressure probe installed.

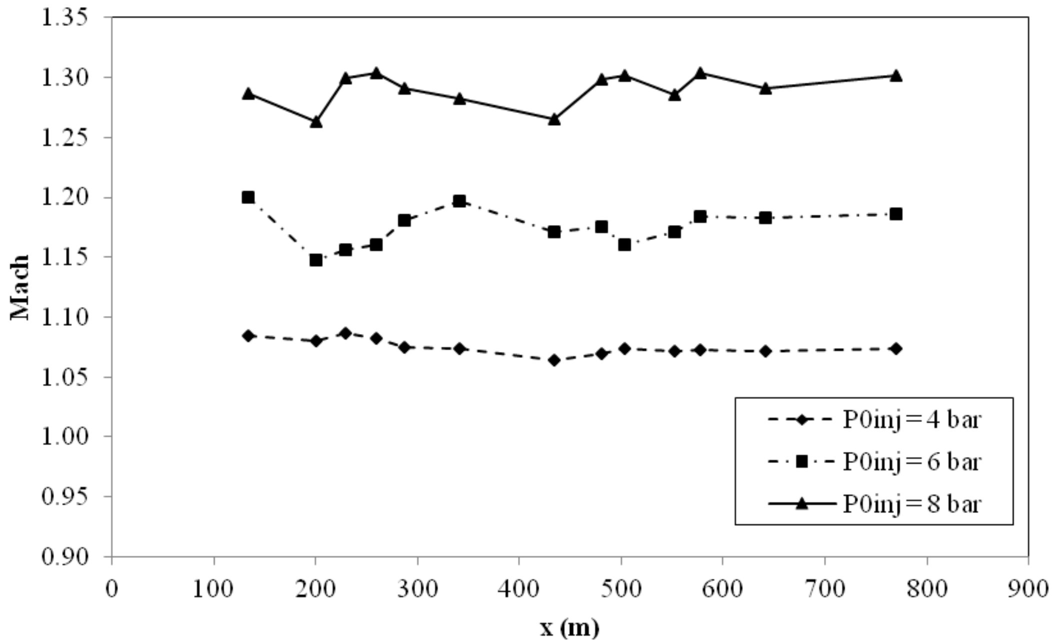


Figure 6. Mach number distribution along the upper test section wall without the pressure probe for the study cases 4, 5 and 6 of Table 2.

A new verification was undertaken, by extracting mass flow from the plenum chamber, with the pressure probe installed and starting with a higher initial Mach number at continuous condition. Figure 7 shows now the results obtained with the pressure probe compared with an Euler equations two-dimensional numerical simulation. The Mach number of the numerical simulation in the whole test section region was 1.3009 ± 0.0015 and the Mach number with the pressure probe 1.284 ± 0.017. However, considering the nominal test section region, where the model will be installed, Mach number read with the pressure probe was 1.286 ± 0.011. It is important to note that the temporal Mach number maximum deviation observed during the experiments was relatively low (about 0.001), indicating that the resulted Mach number distribution with relatively strong variations in the test section comes from possible expansion and compression waves.

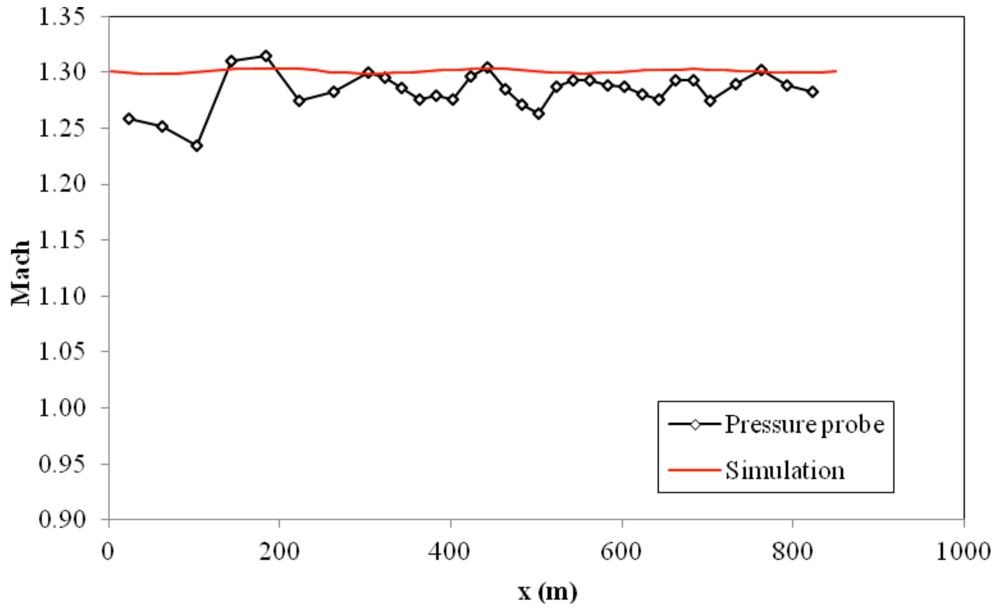


Figure 7. Mach number distribution along the pressure probe for the study cases 7 of Table 2.

But a more detailed analysis showed that this behavior is not so different from those found in the literature concerning notable industrial transonic facilities. Haines and Jones (1960) reports data from experiments with the ARA

9-ft x 8-ft Transonic Wind Tunnel with perforated walls over the range of Mach numbers from 0.6 to 1.4. At subsonic speeds up to sonic speed, the deviation was $\Delta M = \pm\ 0.002$; up to Mach number 1.1 the deviation was $\Delta M = \pm\ 0.002$, however at higher Mach numbers the quality of the flow deteriorates somewhat and the values were: $\Delta M = \pm\ 0.012$ for Mach number 1.25, $\Delta M = \pm\ 0.016$ for Mach number 1.35 and $\Delta M = \pm\ 0.016$ for Mach number 1.4. Brooks *et al.* (1994) report data from calibration experiments undertaken in Langley 8-ft Transonic Pressure Wind Tunnel with slotted walls. For Mach number up to near sonic the observed deviation was about $\Delta M = \pm\ 0.002$, while for higher Mach number values it reached about $\Delta M = \pm\ 0.019$. Considering these preliminary tests carried out in TTP much can be still investigated and improved, indicating that the tunnel will have a similar or superior flow quality compared with other outstanding transonic installations.

4. CONCLUSIONS

It was concluded the first experiments with Mach number 1.3 using the supersonic first-throat and some very interesting conclusions could be made.

A pressure probe at the center line of the test section was used to determine the Mach number longitudinal distribution for various injection system conditions and the results showed that at Mach number level up to 1.05 the spatial deviation was very good, however for increasing Mach number values the Mach number deviation increased much. However, a look in the transonic wind tunnel literature indicated that the present preliminary results are very promising.

5. ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the National Council for Scientific and Technological Development (CNPq) for supporting this research, MCT/CNPq/AEB n° 33/2010, Project 560200/2010-2, "Análise Numérica/Experimental do Veículo de Sondagem SONDA III com Detalhe da Interferência Empenagem/Fuselagem para Número de Mach 1.3", and the individual support nº 384464/2010-6 and nº 381448/2011-8.

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