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PRESSURE PROBE DEVELOPMENT AND TESTS IN A TRANSONIC WIND TUNNEL CALIBRATION

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Abstract. *The TTP (Pilot Transonic Wind Tunnel of IAE – Institute of Aeronautics and Space) is a modern wind tunnel capable of aerodynamic tests in Mach number range from 0.2 to 1.3 with automatic controls of pressure (from 0.5 bar to 1.2 bar), temperature and humidity. A stable and uniform flow in the test section is necessary to achieve a high quality of testing. In a transonic wind tunnel design the test section walls are semi-open to allow mass flow extraction, which is important to prevent aerodynamic chocking phenomenon, minimize shock/expansion wave reflections from walls, and also to help on diminishing wall effects. To set the mass flow ratio through the walls, the test section is enveloped by a plenum chamber, in which the pressure is controlled by means of a dedicated compressor. What determines how much of the flow will pass through the walls are mainly the plenum chamber pressure and the reentry flaps positioning, located at the end of the test section. Increasing the mass flow through the test section walls will increase the blockage ratio limit for articles to be tested, but an excessive extraction causes longitudinal non-uniformity. It is important to assure a stable and uniform flow distribution in the test section in order to obtain valid test results certified by the accuracy achieved. The most significant parameter to be verified is the streamwise Mach number distribution in test section. For most modern transonic wind tunnel, temporal and spatial Mach number deviation must be attained lower than 0.001. In order to comply with frequent check requests before and during test campaigns a special pressure probe was developed to measure the static pressure distribution at the test section centerline. With one total pressure at its extremity and thirty three static pressure stations along its length, the pressure probe permits determining the Mach number distribution in all the test section length, with more points in the usable test section region. This work describes the main criteria considered during the design of the pressure probe, and some practical results from tests conducted in TTP. Important details about the data acquisition system utilized during the tests and some procedures applied to demonstrate the usefulness of the device for attaining the Mach number criteria in the test section are presented.*

***Keywords**: Pressure Probe, Transonic Wind Tunnel, Experimental Data.*

1. INTRODUCTION

Transonic Wind Tunnel testing represents a significant challenge since the intrinsic characteristics of each facility must be known in depth for a full understanding of the results. There are many works in the scientific literature describing the main concepts employed in the facilities projects and the devices that are designed to a secure evaluation of the tunnel calibration and, mainly, the flow quality in its test section (Reed *et al.*, 1977, Parker, 1975, Pope and Goin, 1978, Goethert, 1961). 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 over the region of the model installed (Eq. 1), *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 installation.

$$|2\sigma_M| \leq 0.001. \tag{1}$$

Although this requirement is too demanding it is possible to observe practical values less rigid in important transonic facilities. Luchuk *et al.* (1982) report values from 0.0005 to 0.004, depending on Mach number during the calibration procedure of the AEDC-PWT-4T transonic wind tunnel with test section 4-ft x 4-ft. Haines *et al.* (1958) report standard deviation of ± 0.002 for Mach numbers up to 1.0 in the ARA 9-ft x 8-ft Transonic Wind Tunnel, and even greater values for higher Mach numbers. Parker (1974) reports many results in the Propulsion Wind Tunnel Facility (PWT) Aerodynamic Wind Tunnel (1T) with test section 1-ft x 1-ft, in which some different wall designs were tested at Mach numbers from 0.6 to 1.3: the best results of the Mach number standard deviation were about 0.001 but in some cases it reached 0.07. Brooks *et al.* (1994) present the Mach number deviation in Langley 8-Foot Transonic Pressure Tunnel which varied from below 0.001 to 0.004 depending on Mach number and the re-entry flaps positioning.

This requirement is a permanent concern for the Pilot Transonic Wind Tunnel (TTP) technical team in order to keep up to dated the tunnel's test capability. Located in the Aerodynamic Division (ALA) of the Institute of Aeronautics and

Space (IAE), the tunnel has been utilized in many aeronautical applications for the Institute and for many universities in basic research (Falcão Filho *et al.*, 2009, 2011). The tunnel is a 1/8th scaled down from an industrial project intended to support two decades ago the aeronautical activities in the country, but, because of budget restrictions at that time, the project of the industrial facility was not completed. The pilot facility was designed to study the innovative features of the industrial facility, specifically concerned with the injection system operation in combination with the conventional main compressor operation, and also to instruct technical team in high speed tests, basic and academic research assessment, to perform tests in developing new aerodynamic transonic profiles, tests with simple geometry vehicles, qualitative tests of airplane basic configuration, anemometric tests, and others.

The tunnel was installed with a long pressure probe starting at the beginning of the contraction section to the end of the test section with 96 measurement station distributed longitudinally, having a blockage ratio of 0.68% related to the test section. This device was used during the systems integration and calibration phases of the tunnel and some important works were presented to assess the contraction section and first throat designs, reporting the Mach number uniformity in the test section, with the tunnel in open circuit and in closed circuit (Escosteguy, 2000, Zanin *et al.*, 2008). This pressure probe had to be permanently removed from the tunnel circuit for new test campaigns to be held in the facility and a new idea was considered to allow a periodical verification of the Mach number longitudinal distribution in the test section. This work presents the new probe conception definition, some designs particularities and the first test results obtained with the new device.

2. PRESSURE PROBE DESIGN

Basically the new static pressure probe design is an ogive tipped 17.2 mm outer diameter cylinder with 1.24 m of length. It has thirty three static pressure orifices stations with four orifices connected to a single pressure measurement at each station. The wall thickness is 2.1 mm to ensure a sufficient rigidity not to bend the probe. Reed *et al.* (1977) recommends that pressure probe blockage ratio should be less than 0.01% to minimize wall interference effects at the tunnel centerline, but this is a very restrict design requirement for small wind tunnels, like TTP, in which some mechanical assemblies would be too tiny. The first pressure probe designed for TTP had a blockage ratio of 0.68% and it was a challenge to be fabricated. The new probe was idealized with an outer diameter of 17.2 mm, with a blockage ratio of 0.31%, requiring much expertise during the manufacturing process, but still being large compared with what was recommended by Reed *et al.* for pressure probes. Because of this, it is possible the occurrence of wall proximity effects.

However, the normal practice used in the design of long pressure probes is less demanding. Table 1 shows some pressure probe design characteristics (developed for transonic wind tunnel installations) compared with TTP, which has the lowest blockage area ratio. The closest to TTP installation – the AWT 1T wind tunnel – has a pressure probe with a blockage area ratio 25.81% bigger than TTP's pressure probe.

Table 1. Pressure Probe design characteristics used in some transonic wind tunnels.

Transonic Wind Tunnel	Test Section Area (m)	Pressure Probe Diameter (m)	Blockage Area Ratio
TTP	0.25 x 0.30	0.0172	0.31%
Langley 8-Foot TPT	2.16 x 2.16	0.0762	0.39%
ARA 9-ft x 8-ft TWT	2.44 x 2.74	0.1111	0.58%
AEDC-PWT AWT 4T	1.22 x 1.22	0.0730	1.13%
AEDC-PWT AWT 1T	0.30 x 0.30	0.0254	2.18%

Figure 1 shows a diagram of the inner parts of the TTP plenum chamber, used to control and equalize the pressure in the surroundings of the semi-open test section. It is of fundamental importance in a transonic wind tunnel test section to have semi-open walls, allowing mass extraction through them to avoid chocking phenomenon, and to diminish wave reflections and wall effects (Pope and Goin, 1978, Goethert, 1961). The contraction section promotes the flow acceleration by area variation from a large circumferential to a relatively small rectangular geometry. In the first throat the flow still accelerates up to the test section inlet condition, where it has to be very uniform. The TTP's first throat has fixed and parallel top and bottom walls and fixed with specific wall contours in both sides to adapt the flow to the test section entrance. One set of converging-only side walls is used for Mach number tests up to 1.0, and specific sets of converging-diverging side walls is used for particular supersonic Mach number condition. In the test section the flow must be as parallel and uniform as possible. That is why the pressure probe is so important in verifying this characteristic. In the flap section the flow exited through the test section walls is spontaneously re-admitted in the main stream by *Venturi* effect, and the amount can be modified by the flap panels opening angle. The second throat is used whenever a supersonic flow condition is established in test section, to slow down the flow to near sonic condition avoiding shocks at high supersonic condition. The injectors section held ten supersonic beaks which works chocked at

Mach number 1.9. The injection system is used to enlarge the operational envelope of the tunnel at a determined power condition in the main compressor.

The pressure probe design is 1.24 m long, including the support end, and it is installed with 33 independent internal reels and an ogive at its tip. Each reel has a circumferential chamber which is limited by two O-rings seals, to feel the average pressure created by four circumferentially equally spaced holes drilled over the pressure probe surface (see detail in Fig. 1). A capillary steel tube is soldered in each reel and it goes through the probe up to pressure sensor. During the probe assembly, initially one capillary tube is connected to the probe tip orifice, to measure the total pressure at the front of the ogive, followed by the 33 reels which are introduced sequentially into the main tube having all capillary tubes passing through the remaining reels, to measure average static pressure at longitudinal stations. A total of 34 capillary tubes go out from the probe end to be connected to pressure sensors.

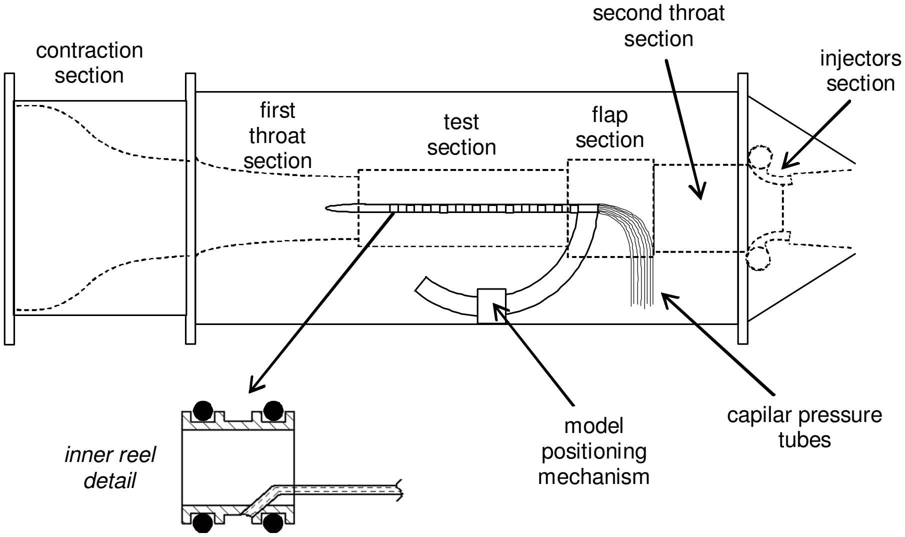

Figure 1. Plenum chamber internals with the pressure probe installed in the model positioning mechanism.

Figure 2 shows a perspective view of the pressure probe with the support end and details of the ogive design, with the total pressure tap in its front. The ogive nose has length 2.7 times the probe outer diameter, a half shorter than that suggested by SAE (1990) and it is expected a low performance in high subsonic regime.

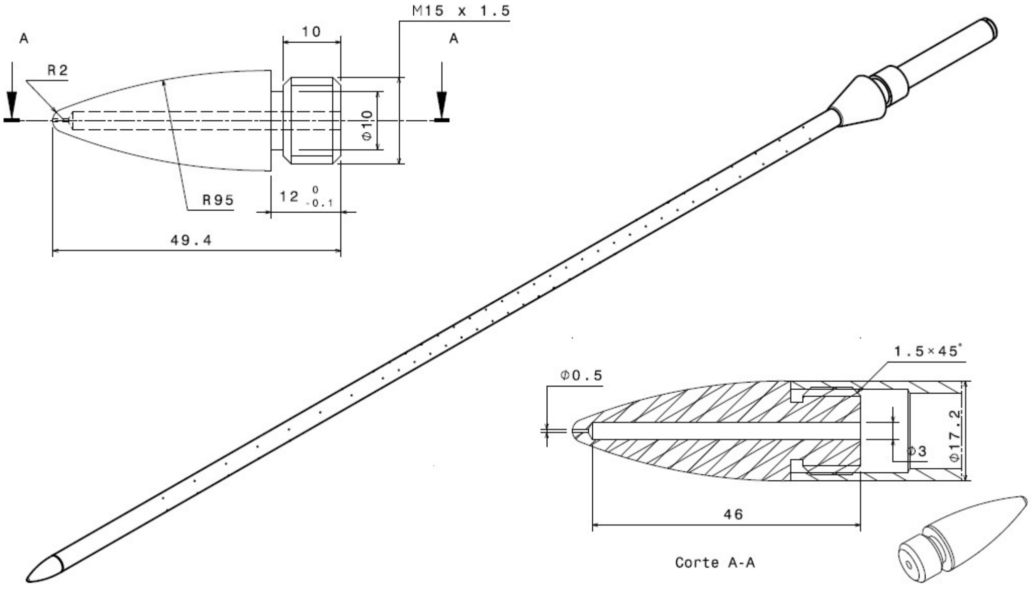

Figure 2. Perspective view of the pressure probe and ogive details.

Observe how the static pressure taps are distributed over the cylinder surface. There are more measuring points in the region corresponding to the called nominal test section, with 20 mm of distance between measuring stations, in which the Mach number distribution must be determined with more accuracy; in the upstream region of the probe the distance observed between measuring stations is 40 mm and in the downstream region 30 mm. Spacers were installed between the reels to guarantee their perfect positioning regarding the holes over the cylinder surface. Note also that the static pressure taps sets over the cylinder surface were spirally distributed to prevent that one pressure tap could interfere in the measurement of the next pressure tap in probe axial direction.

All pressure taps have 0.5 mm of diameter, following recommendation of SAE (1990), to increase the measurement precision (error about 0.1 %). The first measuring section is located about 10 diameters from the probe tip – longer than the 8 diameters suggested by SAE.

A conical aerodynamic fairing of 15° degrees at the end of the cylinder adapts the flow to minimize interference with the support structure. The glove attachment at the end of the probe allows a perfect fitting to the TTP's model support.

Figures 3 (a) and (b) show the pressure probe installed in the TTP test section. Thanks to the rigidity imposed by the design, it was observed a total bending in the tip of only 0.5 mm, practically not noticed in the nominal test section region.

It is interesting to observe the flap panel completely open (20 degrees from streamwise direction) with the so called finger flaps at its end. This structural detail, like channels dug in the panel surface at the exact location of the wall slots, permits that, even with the flaps completely closed, there will occur some mass flow being extracted through the test section slotted walls returning spontaneously to the flaps section main stream. Thus, in the TTP operation, the flaps effect will be always present at any run condition and mass flow through the slotted walls may always occur.


(a) (b)

Figure 3. The pressure probe installed in the TTP test section: (a) support at the rear, (b) front part.

3. FLOW STABLISHMENT IN TEST SECTION

Mass extraction through semi-open walls of a transonic wind tunnel directly affects the flow distribution in the test section and represents the technological solution for attaining transonic tests. Goethert (1961) is an important reference in transonic testing and has reported a huge data collection from transonic wind tunnels tests experiences together with theoretical analysis of the main existing physical phenomena. Experiments in transonic wind tunnel have indicated that, in general, the boundary layer along partially open test-section walls has to be thinned artificially in order to provide favorable conditions for shock cancellation. This effect can be accomplished by means of lowering the plenum chamber pressure, removing part of the boundary layer by means of suction. That is why a capable measuring instrument like a pressure probe is so important during transonic range test investigations conducted during the tunnel calibration phase.

Goethert (1961) presented succession of tests conducted in the transonic model tunnel of the AEDC "Arnold Engineering Development Center" (Allen, 1955) with a slotted test section and with auxiliary suction source for plenum chamber suction. Figure 4 shows some of these test results. Without plenum chamber suction, the Mach number at the downstream end increased greatly as a result of the boundary layer development along the test section walls. The results from 5% of mass flow removal indicate that too much air was removed through the slots and that, consequently, the Mach number in the downstream region was drastically reduced. A proper amount of suction, approximately 2.8%, resulted in uniform Mach number distribution through practically the entire test section. Goethert shows that in slotted test sections plenum chamber suction affects only the flow in the downstream end of the test section. This fact proves the great importance of controlling the flaps allowing them to modify the mass flow through the walls in order to obtain the best condition for each particular test and article installed in the test section. The problem is well discussed by Goethert (1955) in a theoretical investigation conducted in order to analyze the flow conditions in perforated test sections with plenum-chamber suction and various wall settings. The results were also compared with experimental data obtained in the Transonic Model Tunnel (TMT) of the Propulsion Wind Tunnel Facility.

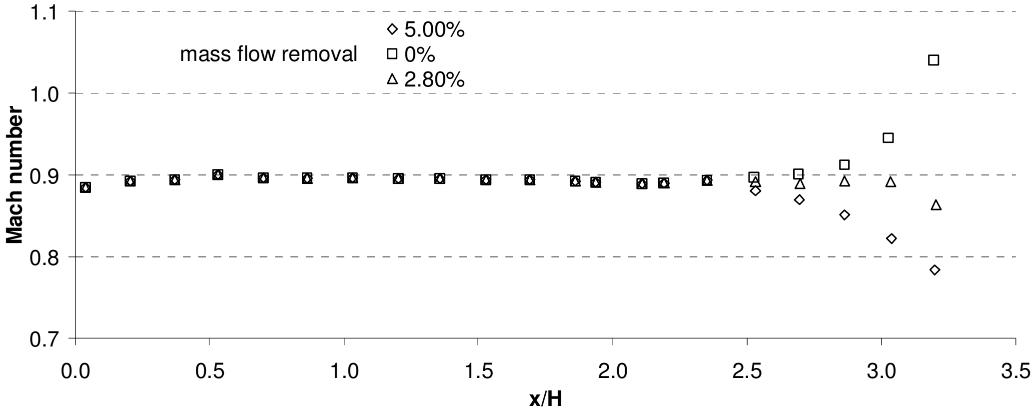

Figure 4. Influence of plenum chamber suction on Mach number distribution at centerline of slotted test section (solid diffuser walls, sixteen slots with 11 % open-area, parallel walls) (Goethert, 1961).

4. RESULTS

Figure 5 shows the Mach number distribution along tunnel central line by the static pressure probe with flaps closed and without plenum mass extraction. Shadowed region marks the nominal test section region and the dashed vertical line marks the test section end and the beginning of the flap region.

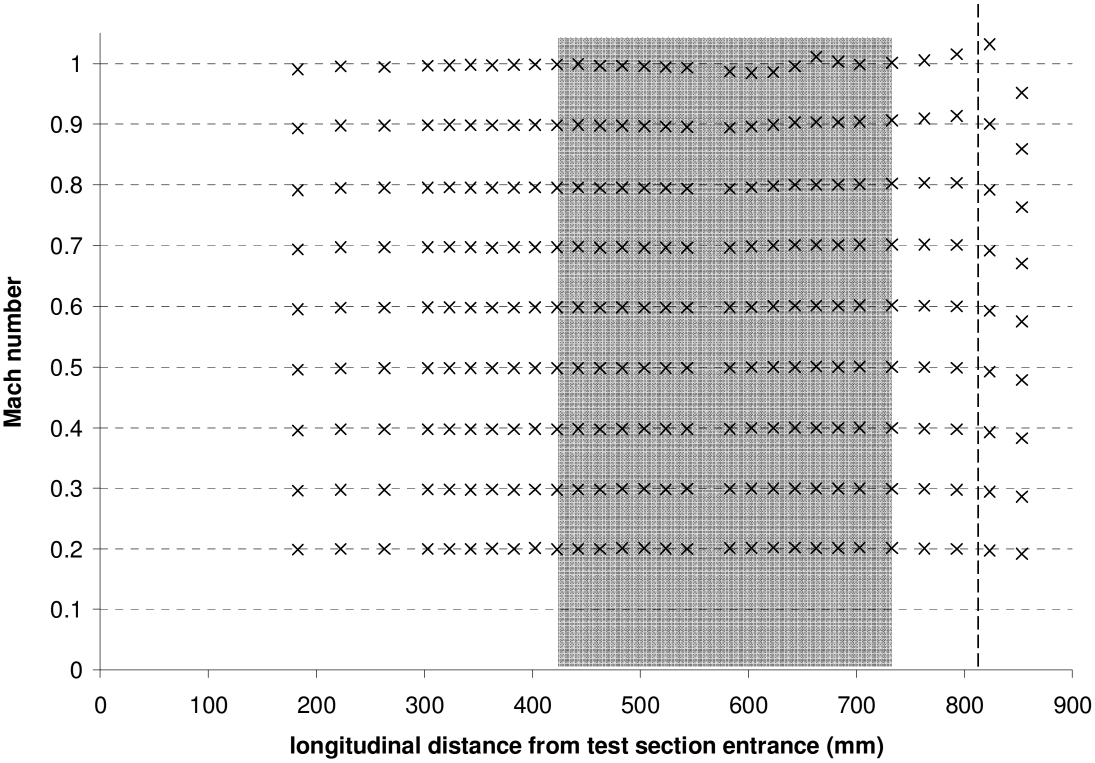

Figure 5. Mach number centerline distribution in pressure probe measuring stations.

Two measuring stations are located into the flap region (see Figs. 3 and 5). One can also observe an apparent missing measuring point near the central of the nominal test section. For some reason this measuring point is clogged and it was simply ignored. Mach number values in figure were obtained taking an average value from the read data during about 60 seconds of test runs. In Figure 5 it is interesting to observe the effect of the finger flaps at high Mach numbers, distorting a little the longitudinal distribution. Into the flap section the Mach number suffers a decrease due to the area expansion. But at the end of the test section, for example at Mach number 1.0, the Mach number increased, indicating a deficient mass flow removal through the walls, according to Fig. 4. For a better Mach number adjustment at Mach number 1.0 a flap opening will certainly help.

Table 2 shows the averaged Mach number and the standard deviation for the nominal test section region measuring points. Observe that the standard deviation is higher than the recommended values given by Davis *et al.* (1986) in Eq. (1). The worst results were observed at low and at high Mach numbers.

Table 2. Determined average Mach number with standard deviation from the measured stations located in the nominal test section.

Nominal Mach number	Calculated Mach number
0.2	0.2009 ± 0.0040
0.3	0.2988 ± 0.0020
0.4	0.3983 ± 0.0017
0.5	0.4990 ± 0.0021
0.6	0.5993 ± 0.0022
0.7	0.6987 ± 0.0025
0.8	0.7971 ± 0.0024
0.9	0.8994 ± 0.0028
1	0.9960 ± 0.0031

One possible reason to explain the high Mach number deviation observed might be the tunnel control system adjustments during the runs, since the parameter's time deviations directly affect the flow establishment into the test section. Figure 6 shows the evolution of the stagnation pressure (p_0), static pressure (p) and the Mach number (M) calculated for the whole experience. Mach number was determined by the isentropic pressure relation, given by

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

where γ is the specific heat ratio for the air as a perfect gas.

In Figure 6 it is possible to observe the Mach number variation during all the acquisition periods, in plateaus-like regions – the same is also observed during the static pressure progress. After some time spent to stabilize the control parameters, the acquisition data system is started for about 60 seconds to collect the pressure data by differential pressure scanner modules ESP-16BP from PSI™ (PSI, 2000) with a pressure range from -10 to +10 psi. The plateaus are much longer at some Mach numbers setting because it was necessary more time to obtain stable control system conditions to proceed with the data acquisition routine.

Figure 7 shows the evolution of the stagnation temperature control system. The system was adjusted initially to 30 degrees Celsius, however, at higher Mach number conditions it was not possible to maintain good control characteristics and the adjusted temperature was increased. Although the stagnation temperature is not directly used for Mach number determination, its control affects the other control systems behavior. Particularly, all the tests were performed during hot days. Better control behavior certainly will be attained in the winter.

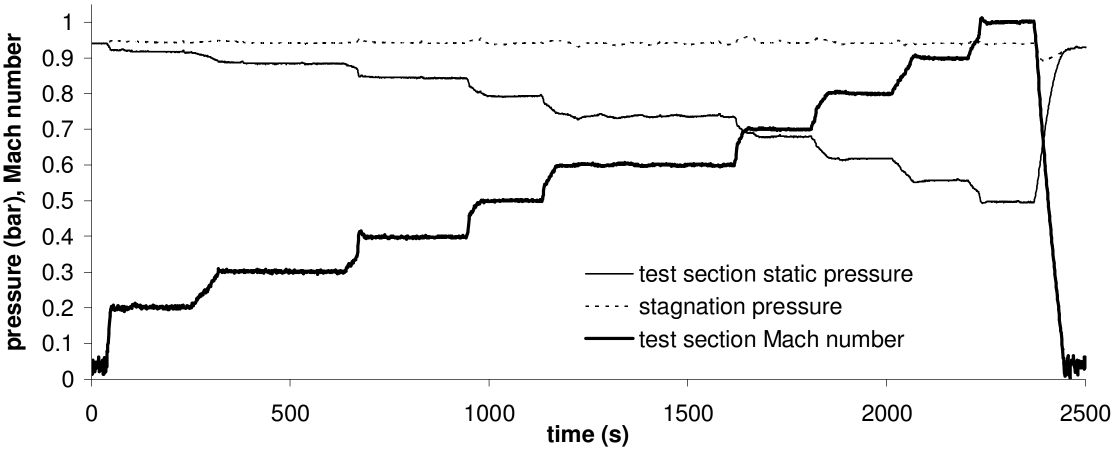

Figure 6. Stagnation and static pressure, and Mach number evolution during the whole experience.

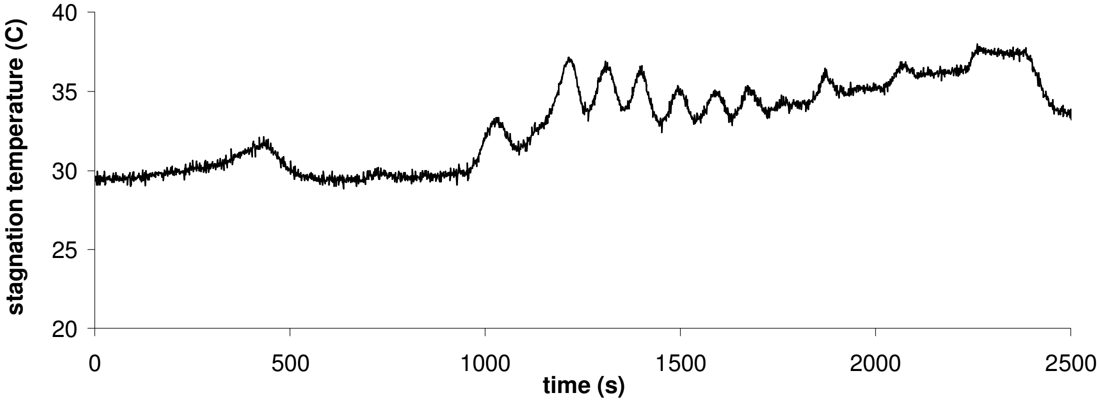

Figure 7. Control systems stagnation temperature evolution during the experience.

For each acquisition time period, stagnation temperature and pressure, static pressure and determined Mach number standard deviation were determined and are presented in Table 3. The values concerning Mach number appear to be a little high. The current pressure control system works with a resolution of 0.001 bar.

Table 3. Standard deviations of the tunnel control system parameters during each run.

Nominal Mach number	Standard Deviation T_0 (K)	p_0 (bar)	p (bar)	Mach number
0.2	0.1655	0.0011	0.0012	0.0031
0.3	0.1869	0.0005	0.0007	0.0024
0.4	0.2050	0.0005	0.0005	0.0015
0.5	0.3242	0.0007	0.0006	0.0016
0.6	0.6521	0.0013	0.0016	0.0012
0.7	0.2215	0.0005	0.0006	0.0009
0.8	0.1258	0.0005	0.0005	0.0010
0.9	0.1495	0.0010	0.0017	0.0010
1	0.1690	0.0012	0.0014	0.0015

According to these results, it is being considered to improve the accuracy of the control system pressure sensors to keep the standard deviation below 0.0002 bar, guaranteeing a better pressure control in the test section. As the Mach number is determined directly from pressures ratio (Eq. (2)) the Mach number standard deviation observed in Table 3 will not have better results into the test section. It is interesting to observe that the worst values of Mach number standard deviation were at lower Mach numbers and this can be explained by the worst values verified in pressure from Table 2.

Other possible causes, like the longitudinal non-uniformity itself into the test section, flow angularity, etc., will only be precisely assessed with improvements in the control system readings, to decrease the standard deviation in the Mach number control.

5. CONCLUSIONS

The main criteria considered during the design of the pressure probe are presented and how it can be useful in determining the Mach number deviation to comply with the requirements applied to modern transonic wind tunnels.

The Mach number results with its standard deviation in the test section centerline were determined for Mach numbers from 0.2 to 1.0 with re-entry flaps in closed position. The tests results proved that the TTP has characteristics considered reasonable, slightly worse than the requirement for high quality modern tunnels. But two important conclusions are raised. First, some important transonic installations have results even poor than those found in TTP. Second, there were observed that the TTP control system can still have improvements to increase the accuracy of the total pressure sensor. Consequently the system will have a more precise Mach number adjustment.

6. ACKNOWLEDGEMENTS

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