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PRESSURE DISTRIBUTIONS ON AN AGARD MODEL IN A TRANSONIC WIND TUNNEL USING PSP TECHNIQUE

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Abstract. *The TTP (Pilot Transonic Wind Tunnel) of the IAE (Institute of Aeronautics and Space) is a modern installation and completely operational but, since it is a relatively new installation, new technologies and procedures are being aggregated and special tests are needed to verify its reliability in comparison with other wind tunnel installations. Among many testing devices used to assess the flow behavior in the test section of a transonic wind tunnel, standard models are very useful because they provide a more complete test assessment for the verification of final aerodynamic parameters. The AGARD association (Advisory Group for Aerospace Research and Development) has created useful standard models which are now widely used because of the great amount of compiled data in the scientific literature. The models are used as an inter-laboratorial tool to compare wind tunnel performances. Standard Model C was used in the tests undertaken in the TTP because it has good transonic behavior. In this approach, the pressure distribution over the model was found by the PSP (Pressure Sensitive Paint) technique that allowed determination of the surface pressure field in front region of the model to be compared with the experimental data from a reliable transonic industrial installations, the NAA 7' TWT wind tunnel. Thus, experimental data obtained in TTP with a standard AGARD Model C available in the Aerodynamic Division (ALA) was compared with data obtained from the literature showing a good agreement in the pressure coefficient distribution over the model, attesting the tunnel reliability in aeronautical experiments.*

Keywords: *AGARD standard model C, transonic testing, PSP*

1. INTRODUCTION

The Pilot Transonic Wind Tunnel (TTP) of the Institute of Aeronautics and Space (IAE) is a modern installation suitable to perform aerodynamic tests in a wide range of Mach and Reynolds numbers. It is continuously driven by a two-stage main compressor of 830 kW, but can also operate in an intermittent mode using a combined injection system. Their control subsystems (pressure, temperature, speed and humidity) work in an integrated manner to settle stable flow condition in its 0.25 m high and 0.30 m wide test section, and guarantee Mach and Reynolds values to better represent the real scale vehicle flight conditions (Falcão Filho and Mello, 2002).

Now, the tunnel is completely operational but, since it is a relatively new installation, new technologies and procedures are being integrated and some special tests are needed to assess its reliability when compared with other wind tunnel installations. Some very basic devices used to verify the flow quality in the test section region are: (1) the center line pressure probe to determine longitudinal Mach number variation; (2) five-holes probe to measure the flow angularity; (3) pressure rakes to verify spatial flow variation; (4) hot-wire anemometry to capture the turbulence level.

Other classes of wind tunnel calibration tests are performed with standard models, whose aerodynamic behaviors are well documented in scientific literature, like some very common airfoil profiles, e.g., NACA 0012, cone-cylinder and AGARD models. In these cases the results represent a more complete test assessment as the final aerodynamic parameters are addressed.

TTP has undertaken many calibration tests to assess its reliability and this particular test campaign is of great importance for demonstrating the tunnel capability for performing aeronautical model tests (Falcão Filho *et al.*, 2009, 2011). Figure 1 shows part of the TTP aerodynamic circuit, with its plenum chamber open.

This work will present the experimental results of pressure distribution over the AGARD C model installed in TTP using the PSP (Pressure Sensitive Paint) technique. This quite modern optical technique is now very common in modern wind tunnel installations and gives a complete surface pressure distribution over the model through a non-intrusive experimental procedure.

The experimental data collected during the campaign is compared with data, from the scientific literature (Fromm and Leef, 1961), of tests conducted in two very important industrial transonic facilities: AEDC 16' PWT (16 Feet Propulsion Wind Tunnel from Arnold Engineering Development Center) and NAA 7' TWT (7 Feet Trisonic Wind Tunnel from North American Aviation).

Figure 1. Pilot Transonic Wind Tunnel installation – plenum chamber door open.

Hereafter, presentation of data will be expressed in terms of a dimensionless parameter *Cp* (pressure coefficient). Data acquired from the software which does the data reduction were also described in terms of *Cp*. The calculation method for both data is shown below:

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho_\infty V_\infty^2} \tag{1}$$

where ρ_∞, V_∞ and p_∞ are, respectively, density, velocity and pressure away from the model, in the non-perturbed region of the flow, and p is the local static pressure.

2. EXPERIMENTAL METHODOLOGY

TTP has automatic control systems to settle Mach number, stagnation pressure, stagnation temperature and humidity in the test section. Its slotted test section walls are adequate to obtain excellent results in high subsonic regime and many tests undertaken with other models has proved to have good precision for models with blockage ratio lower than 1% as it is predicted in specialized literature (Goethert, 2007). Even though, it is noted that vented walls do not completely solve the problems of wall interference in transonic tunnels.

The tests described in the present work were carried out with a model of small size (0.8% of the test sections cross sectional area) and it is assumed in data reduction that wall effects could not be observed. In all tests up to Mach number 0.95 the tunnel will be continuously operated by the main compressor. For better comparison to the data from literature, the tests will be conducted at Mach number 0.6, 0.8, 0.9, 0,95 and at zero angle of attack.

Among the most common standard models the AGARD (Advisory Group for Aerospace Research and Development) model is ostensibly used as an inter-laboratorial tool to compare wind tunnel performances (AGARD, 1955). During technical meetings of the AGARD Wind Tunnel and Model Testing Panel four aeronautical models were defined for use in supersonic and transonic wind tunnels in order to provide an opportunity to exchange test data and compare results on the same model configurations tested in different wind tunnels for specific speed regimes. Figure 2 shows model C which is particularly adequate for transonic tests.

AGARD geometry is best represented by means of its diameter instead of its length in order to be compared scientifically. The TTP model has a diameter of 28 mm representing a cross sectional area of 0.8% of the test section area compared to 0.4% for the NAA model test prepared by Fromm and Leef (1961). It was chosen the smallest blockage ratio model for comparisons in order to avoid wall effects.

Figure 3 (a) shows the AGARD-C model available in the TTP and installed in its test section with a blockage ratio of 0.8%. Figure 3 (b) shows the ogive definition whose ratio is given by

$$R = \frac{x}{3}\left[1 - \frac{1}{9}\left(\frac{x}{D}\right)^2 + \frac{1}{54}\left(\frac{x}{D}\right)^3\right] \tag{2}$$

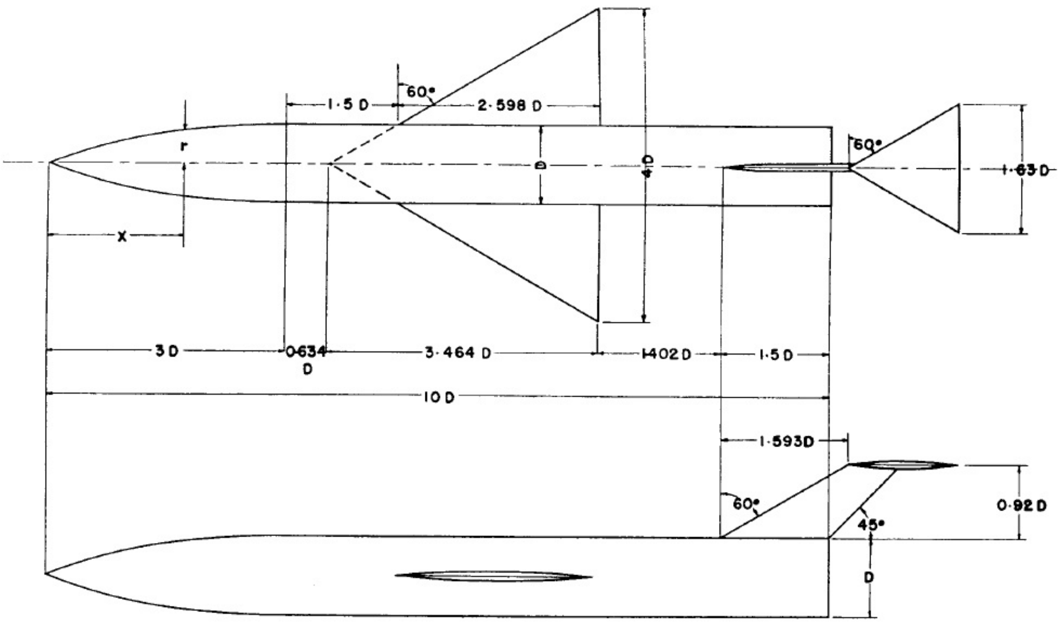
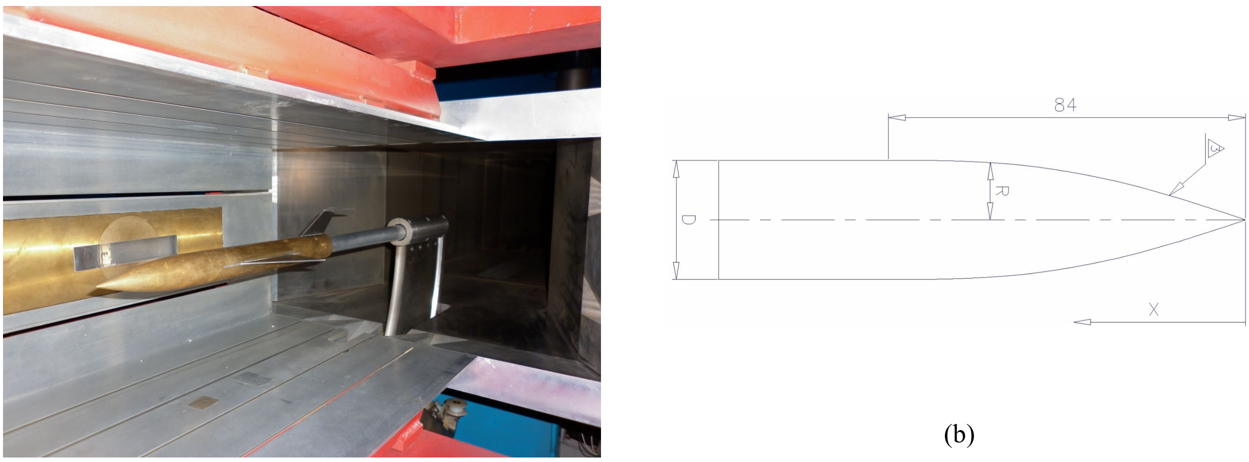


Figure 2. AGARD-C model definition.



(a)

(b)

Figure 3. (a) AGARD-C model installed in the TTP test section, (b) ogive definition.

3. METHODOLOGY

In wind tunnel experiments pressure measurements performed on the model surface are of fundamental importance to identify and study specific phenomena like boundary layer separation and shock wave recognition (Bell *et al.*, 2001).

Pressure measurements are typically based on conventional pressure taps and electronically scanned pressure transducers connected to remote pressure sensors distributed in such way to obtain pressure values for some points on the model. However, this technique presents some spatial limitations when very thin wings or models with sharp corners are the object of investigation (Watkins *et al.*, 2011). While these approaches provide information on the exact pressure at a point on the model, pressure taps are limited to providing data at any other points, thereby making it difficult to measure the surface pressures between these sites. In fact, the pressure between data points can only be interpolated to provide a better spatial resolution, but we must take into account that the interpolation can result in pressure values that are fairly precise on the interpolated site. Furthermore, the integration of a sufficient number of pressure taps on a surface can be time consuming and expensive. The accurate determination of the spatially continuous pressure distributions on aerodynamic surfaces is a central key in understanding mechanisms of complex flow and on the determination of global aerodynamic coefficients, as well as the behavior of boundary layer growth and detachment and shock discontinuities. Also, this information is essential for comparison with computational fluid dynamics (CFD) predictions and analyses. This is especially true in transonic to hypersonic regimes for testing new concepts for vehicles such as reentry capsules, where complex phenomena such as the interaction between shock waves and boundary layers, vortex generation and shock reflections often occur.

Fortunately, during the 1980 decade a new technique was developed, based on a special paint sensitive to partial oxygen local pressure providing good spatial resolution. This technique known as PSP (Pressure Sensitive Paint) utilizes special paint whose electrons are capable of absorbing photons with wavelength near ultraviolet. After absorbing this ultraviolet energy the electrons are excited and have a probability to decay through photoemission or electronic quenching that depends on the partial pressure of oxygen in the flow, which is directly associated with expansions and compressions of the gas as it flows over a given geometry.

Applying pressure sensitive paint offers an alternative to the acquisition of these critical global surface properties. PSP is therefore a non-intrusive measurement device to obtain pressure distributions over the surface of test models.

The technique, as explained above, exploits oxygen-sensitive luminescent molecules that are dispersed in polymeric binders or paints. This process denominated luminescence can be quenched by the local oxygen concentration (oxygen quenching) embedded in the paint during the test. Due to the proportionality between the luminescence generated and the local pressure, high precision equipment as scientific cameras CCD (Charge Couple Device) can map digitally the pressure field on the surface under test (Pedrassi, 2009, Bell *et al.*, 2001) so that a software, as the ProImage software, developed by ISSI, can compute the provided data. The emission intensity is inversely proportional to the partial pressure of oxygen on the surface of the model, e.g., more emissions produce regions of low oxygen concentrations relative to painting areas producing less emission. Considering the fact that the gas used in the TTP is air, the emission intensity of the paint can be correlated to the total pressure on the surface of model since oxygen is a fixed element in the air. Figure 4 describes the physical principle of the technique.

PSP was applied to the model by conventional spray painting. Light sources consisting of an array of light emitting diodes (LEDs) were mounted external to the test section to illuminate the painted model.

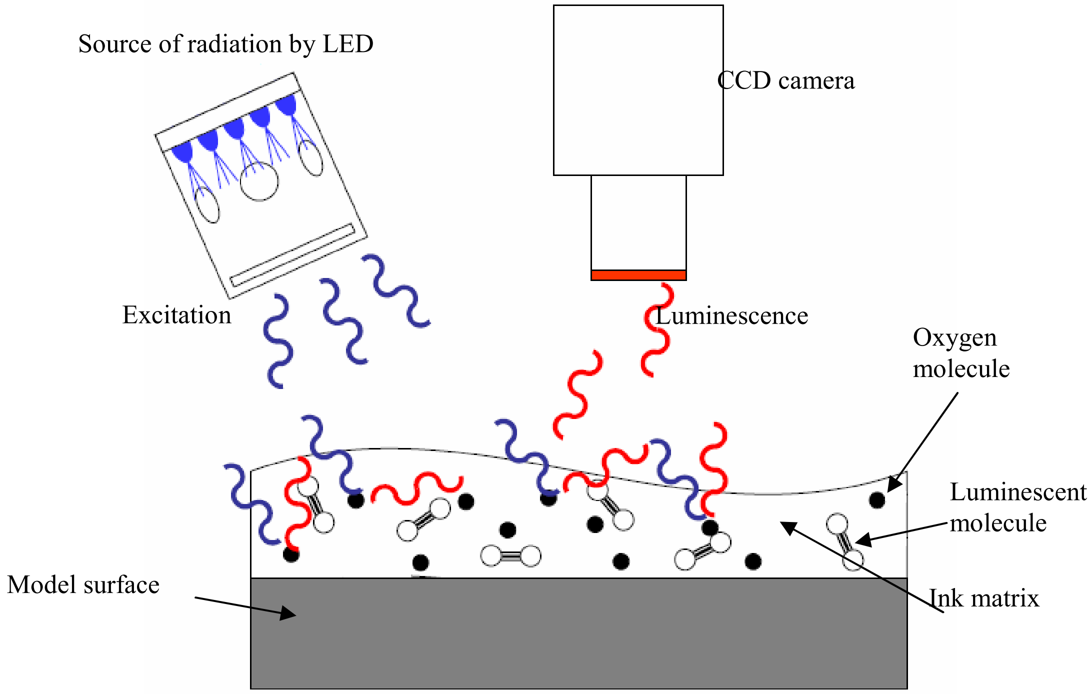


Figure 4. Physical principle of the PSP technique.

4.TEST CONDITIONS

The TTP has automatic controls of Mach number, pressure, and temperature inside the test section providing a really good precision with over thousands of measurements per run. Table 1 gives the control parameters averaged values during the performed tests. The overall deviation observed during the tests for the control systems parameters were: for pressure ± 0.01 kPa, for temperature ± 0.06 K and for Mach number ± 0.001.

Table 1. Test conditions during the tests.

Mach Number	Total Pressure (kPa)	Ambient Pressure (kPa)	Temperature (K)	Reynolds Number($\times 10^5$)	Blockage Ratio
0.6	94.00	94.21	308.0	2.9	0.8%
0.8	94.00	94.21	308.0	3.4	
0.9	94.00	94.21	308.0	3.6	
0.95	94.00	94.21	308.0	3.7	

5. RESULTS

Data obtained from TTP experiments with standard model AGARD C to be compared with other wind tunnels data are presented in this section.

The results are shown using non dimensional pressure coefficient *Cp*, for an adequate comparison with literature data. For the sake of brevity only two very distinguished cases will be discussed: a subsonic case at Mach number 0.6 where it is expected a very well flow behavior with smooth pressure variation, and a full transonic case at Mach number 0.95, where expansion and compression waves may appear. Figures 5 and 6 show the non-dimensional pressure coefficient fields for both cases. In part (a) of the figures it is shown a picture obtained by the PSP technique, after adequate data reduction by specific software with distances made non-dimensional by the fuselage diameter, and in part (b) it is shown the data acquired from the experiment in terms of pressure distribution with PSP technique over the model compared with the experimental data from Fromm and Leef (1961). In this case, in order to allow comparison from the available date with different model lengths the longitudinal dimension was made dimensionless first by converting its length to number of diameters and then dividing the horizontal axis by the size of the largest model length.

The main objective of the work was to produce a comparative analysis of the experimental results in TTP with a reliable literature in order to assign confidence for future tests with PSP technique in the tunnel. Besides the great spatial resolution obtained from images, data from PSP suited both qualitatively and quantitatively the results from other tunnel data such as those from Fromm and Leef (1961). The PSP software available provided images which can be a simple method to visualize some important characteristics of the flow.

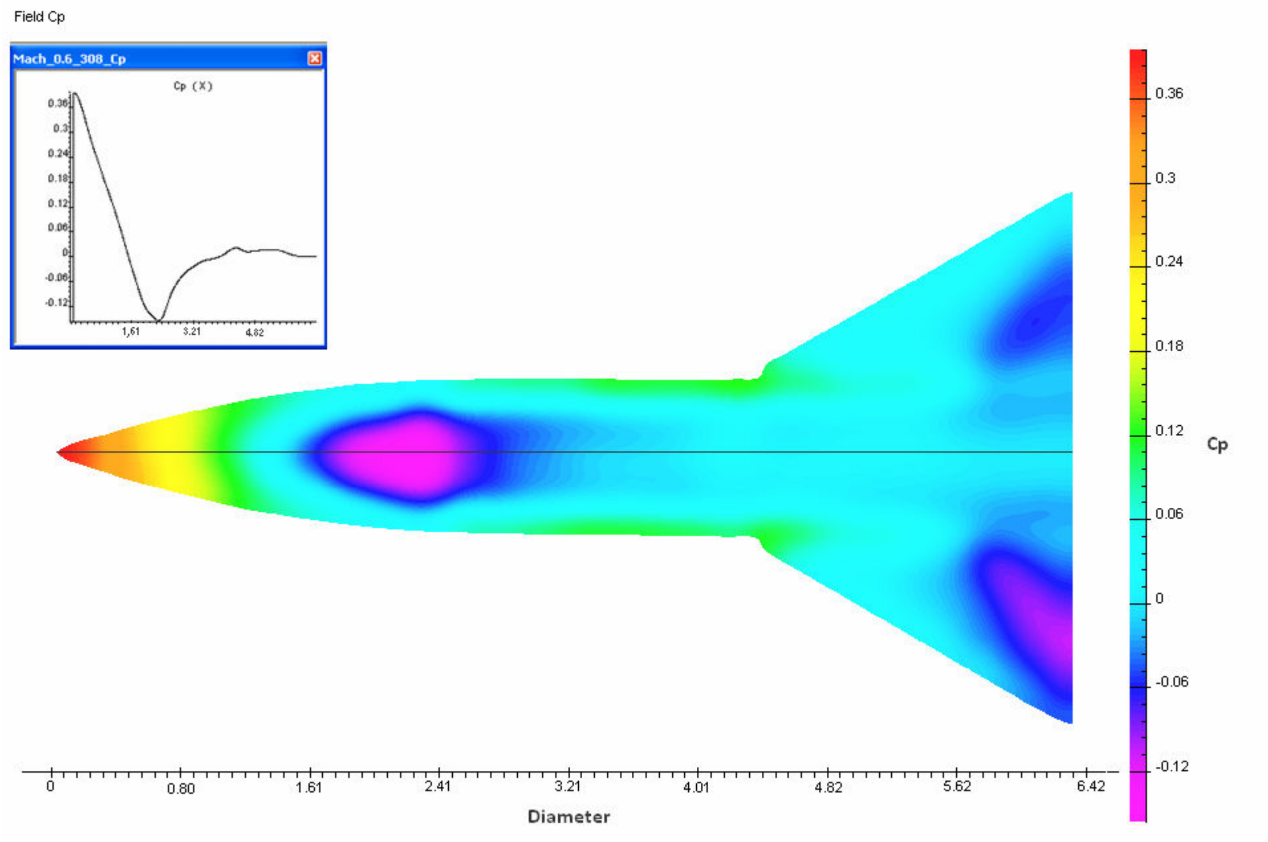
For the subsonic case, Fig. 5 (a) shows a very coherent pressure coefficient distribution which is demonstrated by the graphic of distribution along the fuselage, starting at the tip of the model. Figure 5 (b) compares the experimental results from PSP with the experimental results from Fromm and Leef (1961), which shows good agreement, except in some waving in PSP curve which is motive for a future investigation.

For the full transonic case one can easily observe in Fig. 6 (a) the expansion wave induced by the shoulder of the ogive depicted by the sudden transition from the light region to the dark one, where the flow is noticeably locally supersonic. Also, from this situation, it can be noticed a slight baseline at the end of flow acceleration, where the ogive ends. This effect could barely be seen with discrete measurements. Figure 6 (b) shows a reasonable comparison which can be explained by the difficulty of the speed regime.

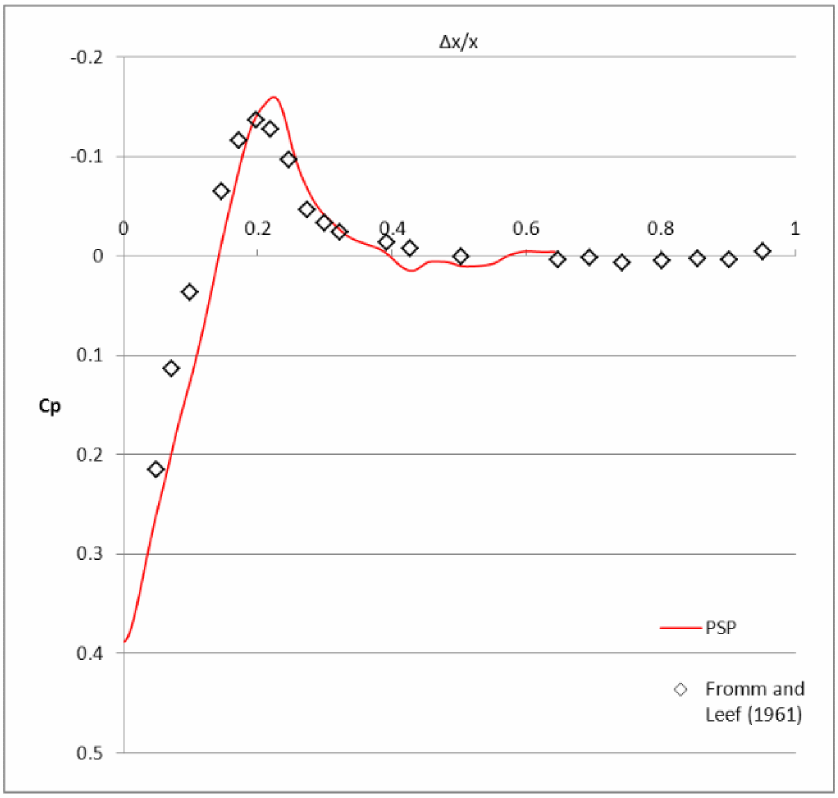
It is also noticed that for higher Mach number, both data from TTP and literature experience a slight loss of pressure. This phenomenon can be associated with two different effects:

- although not the most significant in this situation, there is an edge effect due to lightning reflection so that the corners of the model do not represent a trustful spatial distribution. This statement can be noticed in any image produced since the model is axisymmetric and, therefore, should present a symmetric vertical distribution, which is not observed. The software ProImage provides a simple non automatic method of obtaining data just by delineating along the picture of the model. Thus, collecting results from a centered line in data is strongly recommended.
- secondly and most relevant can be the effect of the expansion corner on the diamond wing reducing the pressure due to generation of expansion waves.

Apparently the vented walls rather than solid walls, as expected, worked really well avoiding undesirable wall effects over the model surface such as unexpected shock waves due to compression of transonic flow. The blockage ratio was also chosen wisely so that the wall effects could be lessened.

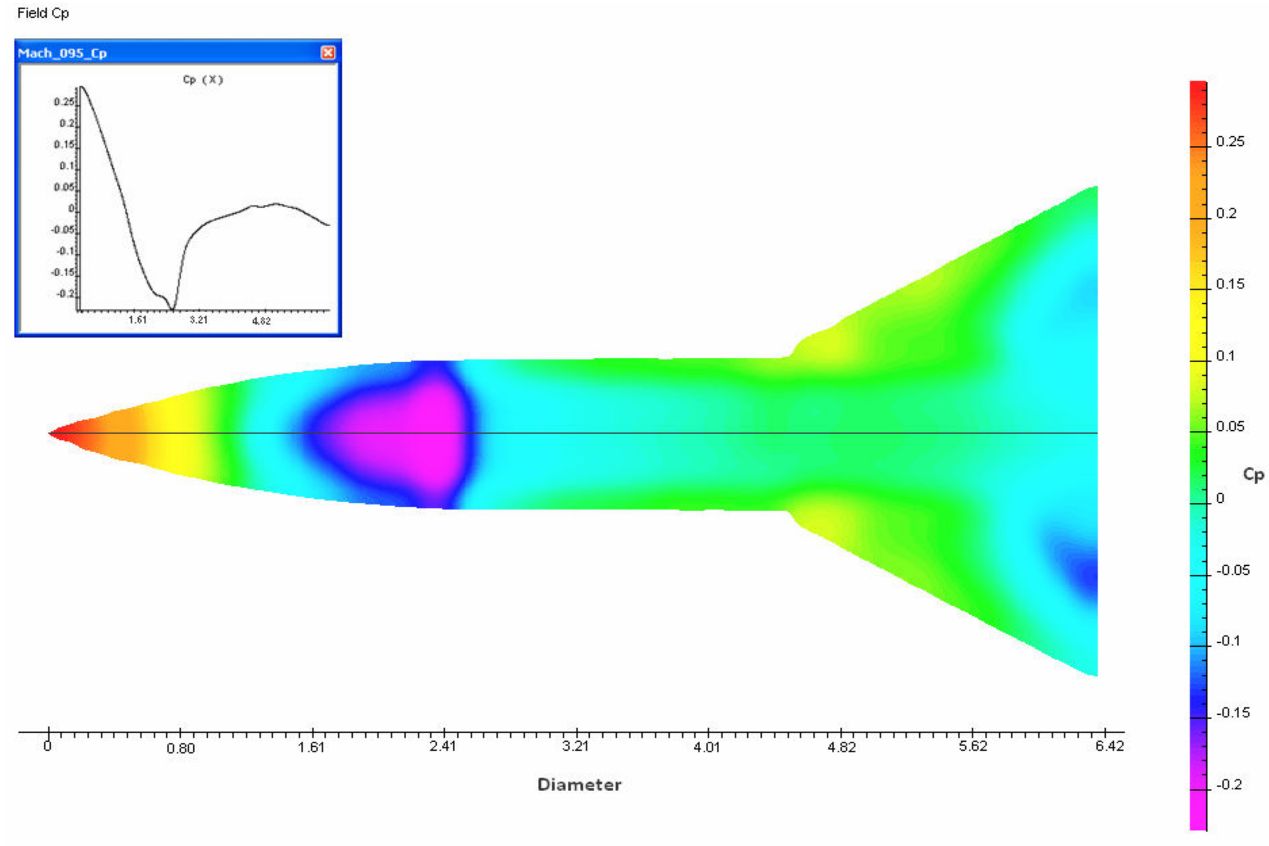


(a)

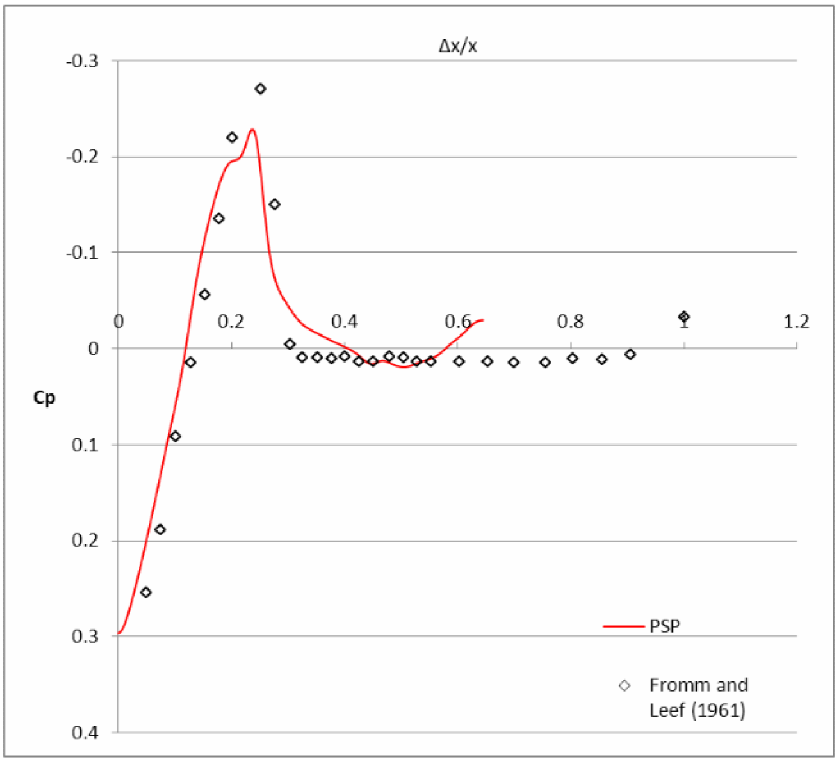


(b)

Figure 5. Dimensionless pressure coefficient distribution along surface of AGARD-C test model obtained with PSP technique, freestream Mach number 0.6, and blockage ratio of 0.8% compared to model from calibrated tunnel, measured with pressure taps and 0.4% of blockage.



(a)



(b)

Figure 6. Dimensionless pressure coefficient distribution along surface of AGARD-C test model obtained with PSP technique, freestream Mach number 0.95, and blockage ratio of 0.8% compared to model from calibrated tunnel, measured with pressure taps and 0.4% of blockage.

6. CONCLUSIONS

From the results presented in this paper, it was noticed that the tests performed in TTP can be used to help to improving the knowledge about the relatively new PSP technique in the transonic regime, however some oscillation occurred in the pressure coefficient line needs to be investigated more accurately.

Correlations between data were expressed in terms of *Cp* and final results suited properly with Fromm and Leef article (1961). This test suggests, therefore, that TTP becomes a reliable tool for scientific research.

The images acquired from the software brought some meaningful results revealing to be a powerful tool if associated with PSI technique. Detecting expansion and shock waves with pressure taps requires a huge number of pressure taps, however, it could be easily perceived through PSP results. PSP technique has much to improve but it can already be used as a complementary tool for better physical understanding of problems.

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