Proceedings of ENCIT 2010
13th Brazilian Congress of Thermal Sciences and Engineering
December 05-10, 2010, Uberlandia, MG, Brazil

PRESSURE MEASUREMENTS OVER A NACA 0012 PROFILE IN A TRANSONIC WIND TUNNEL USING PRESSURE SENSITIVE PAINT(PSP)

Rafael Silva Costa, rafaels.costa@hotmail.com
Universidade do Vale do Paraíba, São José dos Campos – Brazil

Ana Cristina Avelar, anacristina@iae.cta.br
João Batista P. Falcão Filho, jb.falcao@ig.com.br
CTA/IAE/ALA, São José dos Campos – Brazil

Henrique de Oliveira da Mata, henriquemata@aluno.ita.br
CTA/ITA, *São José dos Campos – Brazil*

Abstract. *In the present paper, preliminary results of global pressure measurements on a NACA 0012 profile, obtained with pressure sensitive paint (PSP) will be presented. The lifetime method was used. The measurements were conducted in the Pilot Transonic Wind Tunnel (PTT) of Institute of Aeronautic and Space (IAE) for Mach number ranging from 0.2 to 0.7 and angle of attack of 4 degrees. For comparison with PSP results the model has been instrumented with pressure taps. Good agreement between the results obtained with both methods has been observed. However, in this initial test the influence of dust in the wind tunnel was noticed.*

Keywords: *Transonic Wind Tunnel, Pressure Sensitive Paint (PSP), NACA 0012 profile*

1. INTRODUCTION

The study of flow characteristics and the analyses of their effects on aircrafts, rockets or any specific part of them are essential in the development of an aerospace project. A very important task is to acquire the surface pressure distribution on a model for structural analysis and for optimizing the aerodynamics coefficients. In general, pressure information is obtained through pressure taps measurements. Pressure taps are little holes located at discrete points on the model surface that are connected to a pressure transducer. This technique, although efficient owns drawbacks as: the physical limitations to create holes on a thin model, intrusiveness, geometry deformation of the model due several holes and a high cost in the model manufacturing. Pressure-sensitive paint (PSP) is a relatively new measurement technique for global surface pressure measurements in aerodynamic testing (Gregory *et al*., 2007). The ability to determine instantaneous two-dimensional pressure distributions on the surface of a model in test facilities like wind tunnels or turbomachines by the application of a pressure-sensitive paint (PSP) is a major advance in the non-contact measurement techniques in aerodynamics. The method allows one to obtain not only qualitative pressure images, but also quantitative absolute pressure values at the desired locations on the model, without introducing flow-disturbing probes or affecting the surface of the model (Engler *et al*., 2000). The main advantage of PSP is the high spatial resolution, so that a complete pressure mapping of the entire surface of the model can be obtained (Basu *et al*., 2009). Another great advantage of the PSP is the possibility of obtaining data pressure on locations where it would be almost impossible with conventional methods (Kurita *et al*., 2006). This technique can also be used for predicting aerodynamic loads and validating computational fluid dynamics (CFD).

The beginning of the PSP technique development occurred when the oxygen quenching phenomenon was discovered by H. Kautsy and Hirsch (1935). Pioneering studies of applying oxygen sensors to aerodynamic experiments were initiated independently by scientists at the Central Aero-Hydrodynamic Institute (TsAGI) in Russia and the University of Washington in collaboration with the Boeing Company and the NASA Ames Research Center in the United States. The conceptual transformation from oxygen concentration measurement to surface pressure measurement was really a critical step for aerodynamic applications of PSP, signifying a paradigm shift from conventional point-based pressure measurement to global pressure mapping (Liu and Sullivan, 2005). The first PSP measurements at TsAGI were in reasonable agreement with the known theoretical solution and pressure tap data (Ardasheva *et al*., 1982, 1985) and, in the late 1980s, independently of the Russian, researchers of the chemical group at the University of Washington understood the important implication of oxygen sensors in aerodynamic testing and started to develop a luminescent coating applied to surface for pressure measurements and their first data obtained had a very favorable agreement with the pressure taps data, clearly indicating the formation of a shock on the upper surface of the model (Kavandi *et al*., 1990; McLachlan *et al*., 1993). More information about the historical development of PSP can be obtained in Liu and Sullivan (2005).

The experiment described in this paper has been carried out in the Pilot Transonic Wind Tunnel of the institute of Aeronautics and Space (IAE), and it has been conducted as a task of a VLS Associated Tecnology project sponsered by the Brazilian Space Agency (AEB). The aim of this project is the implantation of the PSP tecnique in PTT for tests in sounding vehicles models. The present paper describes experimental measurements performed to obtain the surface pressure distribution on NACA 0012 profile using the life-time method for Mach number values of 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7 and angle of attack of four degrees using the PSP technique. Pressured taps measurements were also conducted for comparison with the PSP data. Good agreement between the results obtained with both methods has been observed. However, in these preliminary tests, the influence of dust in the wind tunnel was noticed for the highest values of Mach number. The PTT has been cleaned and further results are expected to be closer to the pressure taps measurements in cases of high Mach number.

2. PSP Working Principles

The PSP technique requires a special paint in which its luminescence is inversely dependent to air local pressure. This paint is applied upon surface of a wind tunnel model and the pressure distribution is obtained from images produced by proper illumination. The PSP technique is based on an oxygen-quenching process in which excited molecules are deactivated with oxygen, this phenomenon produces different degrees of luminosity on the surface of the model. The final pressure map is obtained using complex image processing techniques (Engler *et al*., 2000).

As showed in Fig. 1, generally pressure sensitive paint is composed of two main parts, an oxygen permeable binder, and an oxygen-sensitive luminophore. When a luminescent molecule absorbs energy through a specific light, the molecule raises to energy excited state. Then, in the most times recovers to the ground state by the emission of a photon of a longer wavelength.

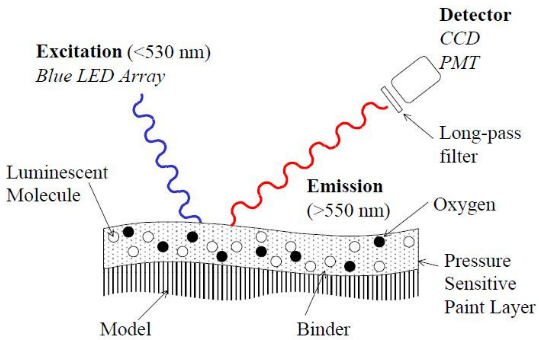


Figure 1 – Basic PSP system (extracted from ISSI website).

The intensity of the luminescence gives a measure of the partial pressure of oxygen and hence the local pressure of air. If the paint receives a pulse of light, the luminescence will decay exponentially to the ground state characterizing the Lifetime method and that it is also quenched by oxygen. Unfortunately, the luminescent intensity distribution is not only a function of the partial pressure of oxygen. In fact the luminescence from the painted surface varies with illumination intensity, paint layer thickness, and uniformity. Theses variations result in a non-uniform signal from the painted surface and can be eliminated or minimized taking the ratio of the luminescence intensity. Through this wind-on and wind-off ratio, the response of the system can be modeled using a modification of the Stern-Volmer Eq. (1). Liu and Sullivan (2005), where, I, is the luminescence at an unknown test condition (wind-on) and I_{ref}, is the luminescence at a reference test condition at the test section (wind-off).

$$\frac{I_{ref}}{I} = A + B\frac{p}{p_{ref}} \quad (1)$$

Lifetime based pressure sensitive paint measurement includes phase-sensitive detection and multi-gate integration techniques. A schematic of theses gates is shown in Fig. 2. In the first phase, the paint receives a short illumination pulse and its molecules are excited to the maximum point of energy, so after, the luminescence is emitted and decay exponentially to the ground state, characterizing the second phase. The Lifetime method is obtain the integration of the gate one ($t_1 – t_2$), and gate two ($t_3 – t_4$) ratio. The signal from the first phase is sensitive to the intensity from the illumination pulse and relatively insensitive to pressure and the second phase is also sensitive to the intensity from the illumination pulse, but very sensitive to pressure, then, by taking the ratio of the two gates is possible to remove the signal of illumination, resulting in signal of pressure.

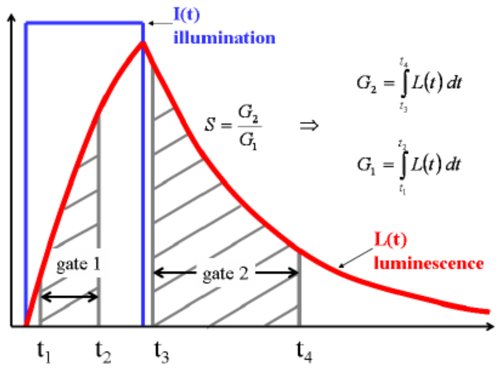


Figure 2 – Two-gate Lifetime method (extracted from ISSI website).

Typically the PSP system consists of illumination devices, CCD cameras or photomultiplier, a wheel filter, that separates the illumination from the red shifted emission of the luminescent molecule, data acquisition and reduction systems, PSP paint, and in the case of Lifetime method, a synchronism device between camera, illumination system and the PC, as represented in Fig. 3. The luminescent intensity distribution is recorded and stored for conversion to pressure using an *a priori* or *in situ* calibration.

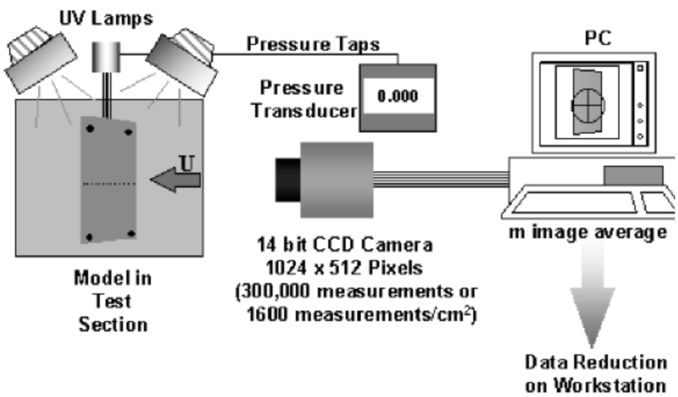


Figure 3 **-** A typical pressure-sensitive paint measurement system (extracted from Bell *et al*., 2001).

3. Descripition of the experiments

The PSP measurements has been conducted in the PTT (Pilot Transonic Tunnel), located at the Institute of Aeronautics and Space (IAE), which is a modern installation, with a conventional closed circuit, continuously driven by a main compressor of 830 kW of power, and with an intermittent injection system which operates in a combined mode, for at least 30 seconds. Its test section is 30 cm wide and 25cm high, with slotted walls. The tunnel has automatic control of pressure (from 0.5 bar to 1.25 bar), Mach number (from 0.2 to 1.3), temperature and humidity, in test section (Falcao *et al*., 2009). Figure 4 shows a partial view of the PTT and a schematic representation of the wind tunnel circuit.

Figure 4 - The partial view of the PTT.

A NACA 0012 profile with twelve pressure taps, 0.5mm of diameter, distributed along the model chord of 125 mm has been used in this experiment, Fig. 5.

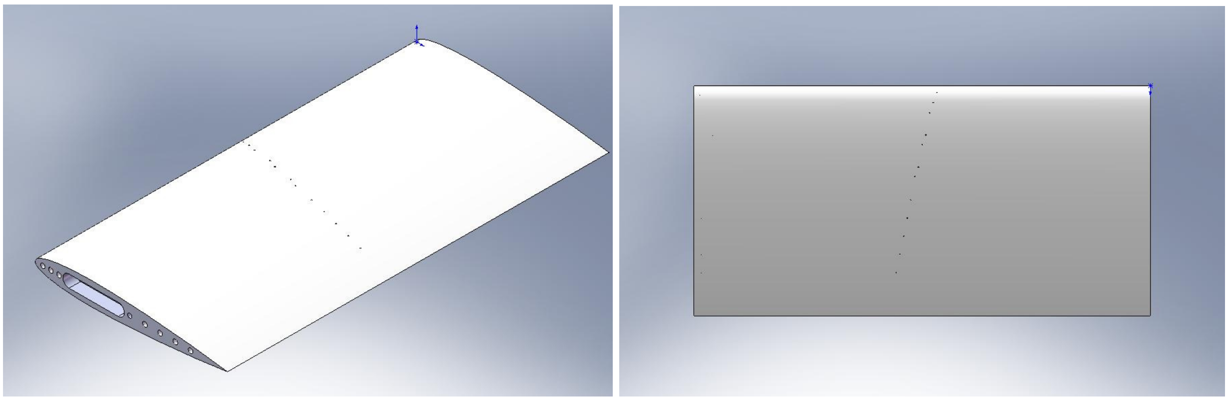
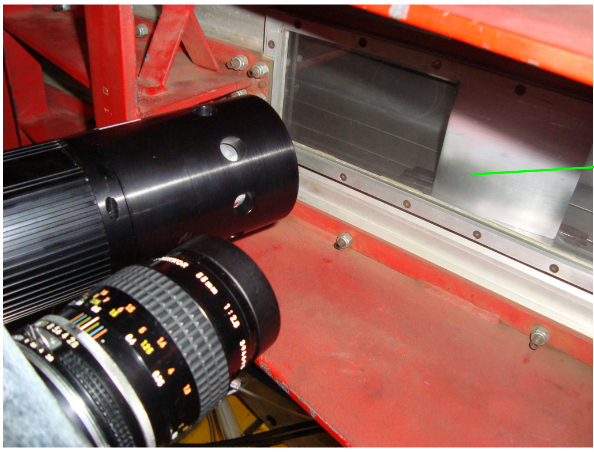


Figure 5 - Schematic NACA 0012 profile in superior view.

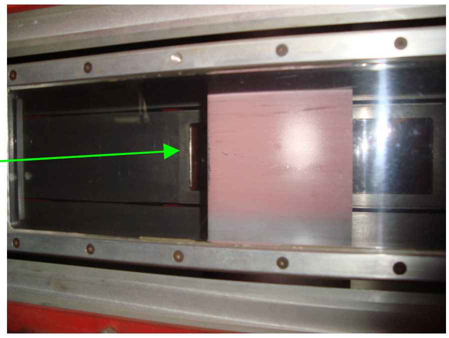
The model and PSP system components have been installed in PTT test section as showed in Fig. 6. The model of NACA 0012 profile was vertically installed with 4 degrees of angle of attack in all tests.

A commercial UniFIB paint purchased from Innovative Scientific Solutions, Inc. (ISSI) has been used. The UniFIB has low temperature sensitivity and good sensitivity to pressure. Before being fixed in the test section, the model was cleaned and painted. The PSP paint was applied by using a professional airbrush. The painting has been conducted in the Materials Division (AMR) of IAE, at the Laboratory for composites processing. For personal protection gloves were used and the painting process conducted in an exhauster. A tiny layer of FIB basecoat (Issi FB-200) was sprayed on the model surface followed by the application of the top coat (Issi UF-400). Finally the model was dried up in an oven to 60 ºC for one and a half hour.

For the PSP measurements the model was illuminated using a 400nm frequency LED (Light Emission Diode) LM2X-DM-400. The images were acquired by using a PCO 1600 14 bit cooled CCD camera with 1600 x 1200 pixel of resolution, low noise and the available exposure time range from 5μs to 49 days. A Nikkon lens f# 2.8 with 55 mm of focal length lens was used. A Quantum Composer 9600+ pulsed generator was used for the synchronism between the camera, the illumination system and computer. The ISSI OMS v.3.1 software was used for images acquisition and analyses.



(a)



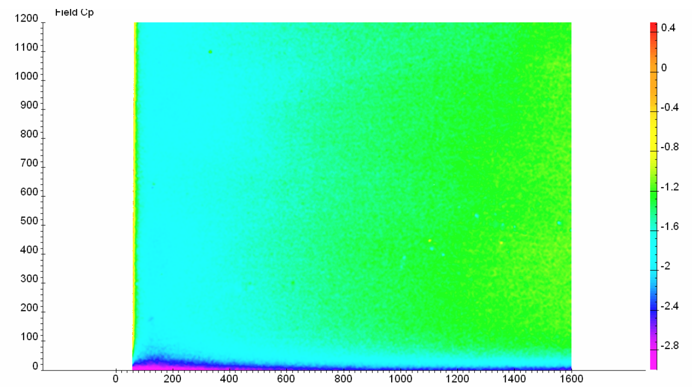
(b)

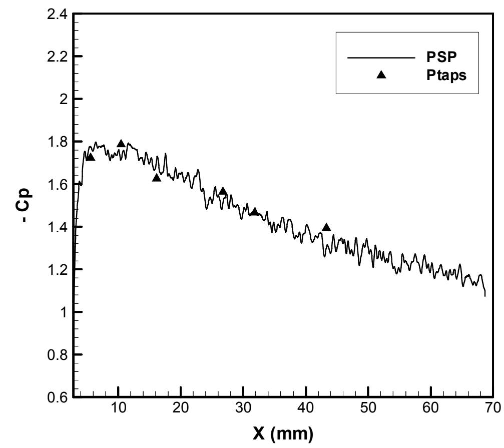
Figure 6 – (a) The PSP set-up in PTT test section with NACA 0012, (b) NACA0012 painted with PSP.

4. Results and discussion

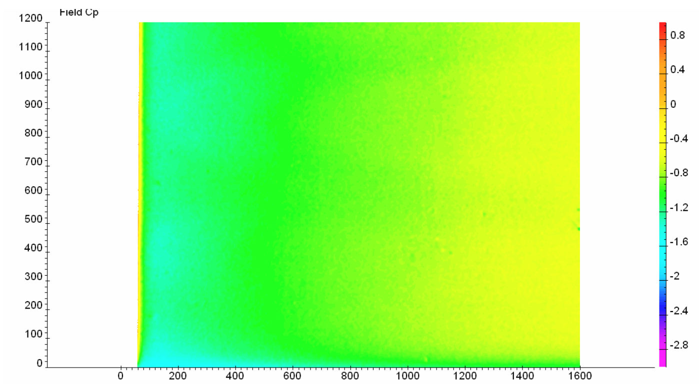
Some preliminary results of pressure field and comparisons between PSP and pressure tap data, obtained from the experiments, are presented in Fig. 7. These results were obtained for pressure and temperature stagnation conditions at the test section of 94000 Pa and 300 K. For some flow configuration the pressure fields are represented in images by Cp (Pressure Coefficient) that is a dimensionless number which represents the value pressures. For the Mach number 0.3 the results present a great difference between PSP and Taps value, apparently there is no reason for that, but this subject has been investigated. It was also observed in Mach number 0.6 the pressure taps captured a weak shock wave, but the PSP didn't follow due to the dust influence.

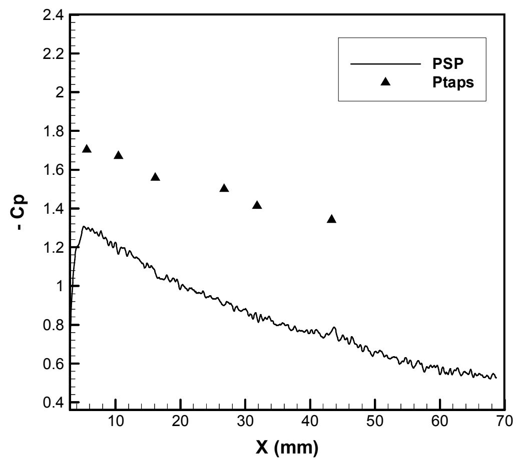
Mach number 0.2; 4º angle of attack



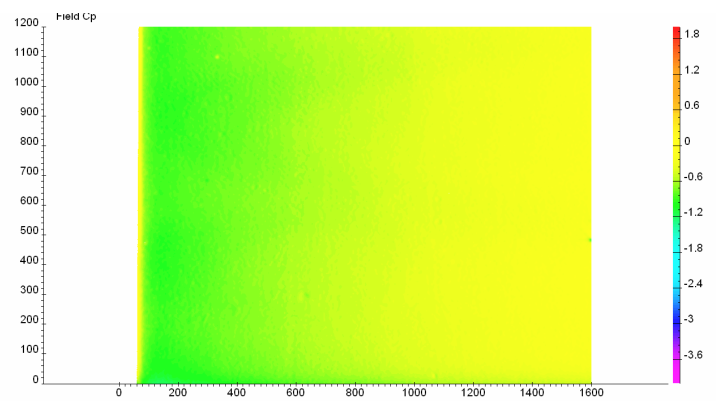


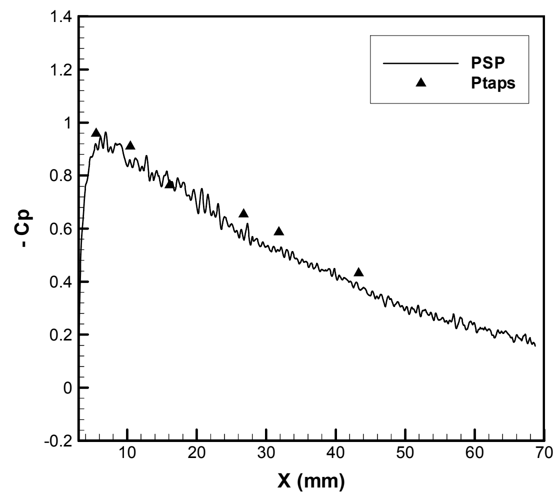
Mach number 0.3; 4º angle of attack



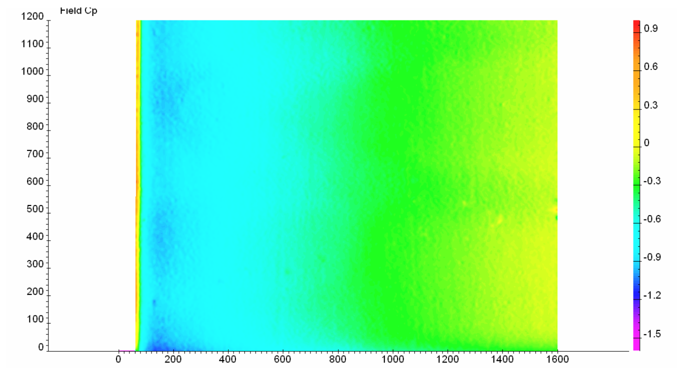


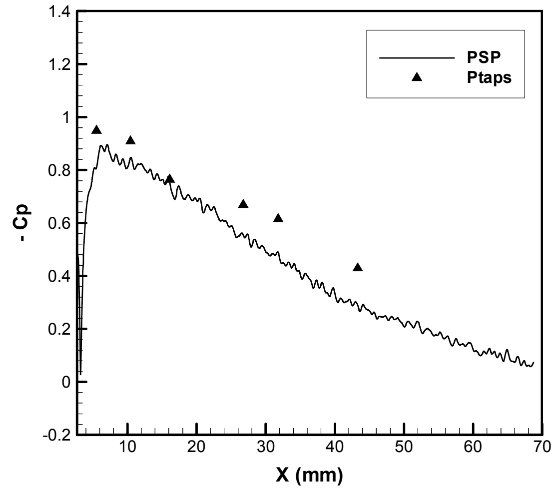
Mach number 0.4; 4º angle of attack



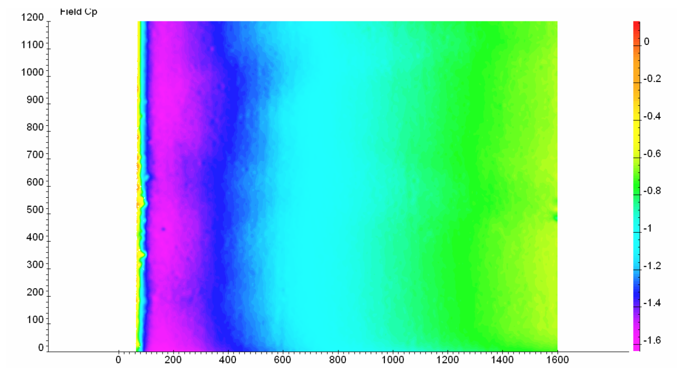


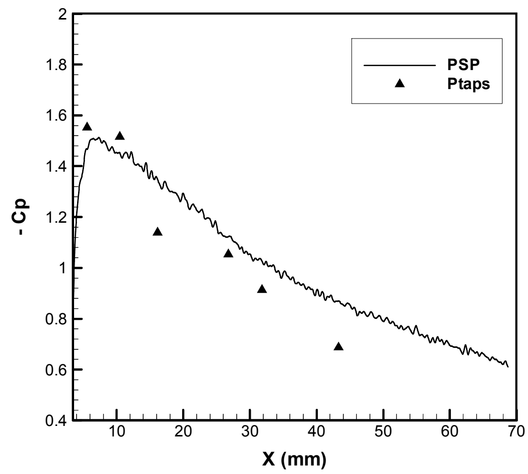
Mach number 0.5; 4º angle of attack



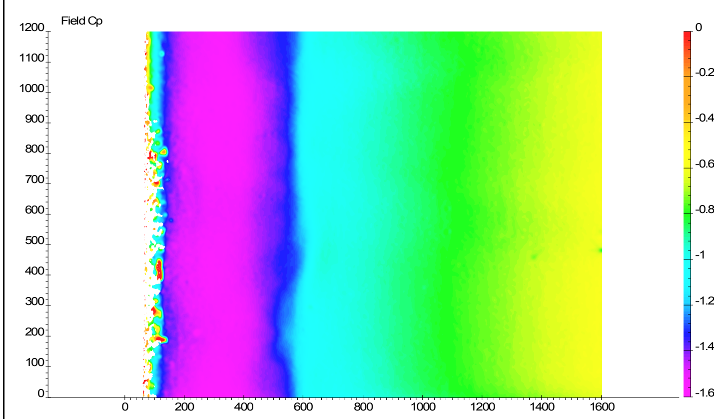


Mach number 0.6; 4º angle of attack





Mach number 0.7; 4º angle of attack



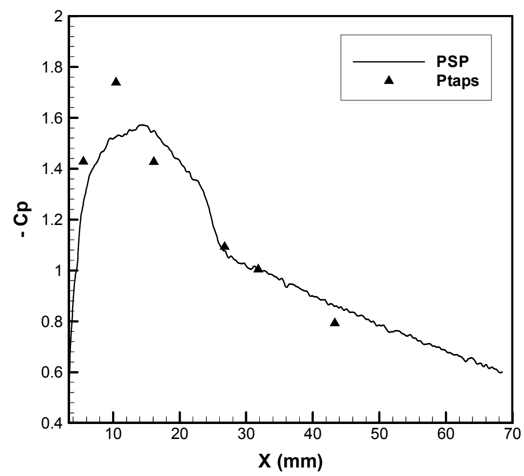


Figure 7 - Results of surface pressure distribution on NACA 0012 with angle of attack of 4º, for Mach numbers 0.2, 0.3, 0.4; 0.5; 0.6 and 0.7, using PSP and pressure taps data.

The Cp values obtained from PSP and with pressure taps were compared. Due the flow compressibility the Prandtl-Glauert for Mach 0.4 and 0.5 using Eq. 2, Karman-Tsien for Mach 0.6 using Eq.3 and Laitone for Mach 0.7 using Eq. 4 were used to small correction effects.

$$C_p = \frac{C_{p0}}{\sqrt{1 - M_\infty^{\ 2}}}, \tag{2}$$

$$C_p = \frac{C_{p0}}{\sqrt{1 - M_\infty^{\ 2}} + \left[M_\infty^{\ 2} / \left(1 + \sqrt{1 - M_\infty^{\ 2}} \right) \right] C_{p0} / 2}, \tag{3}$$

$$C_p = \frac{C_{p0}}{\sqrt{1 - M_\infty^{\ 2}} + \left\{ M_\infty^{\ 2} \left[1 + \left(\frac{\gamma - 1}{2} \right) M_\infty^{\ 2} \right] / 2\sqrt{1 - M_\infty^{\ 2}} \right\} C_{p0}} \ . \tag{4}$$

Although some problems presents along of tests, as: Uncertainty in pressure taps values, caused by obstruction of the taps when it was applied the painting on model and the dust influence in the wind tunnel that caused paint loss on leading-edge to high Mach numbers like showed in Figure 8. The results have been satisfactory and present the good agreement with between PSP and pressure taps data. In image of Mach 0.7 is possible to see the initial formation of a shock-wave through the pressure sudden rises present in Figure 8, where the graph show the step of pressure.

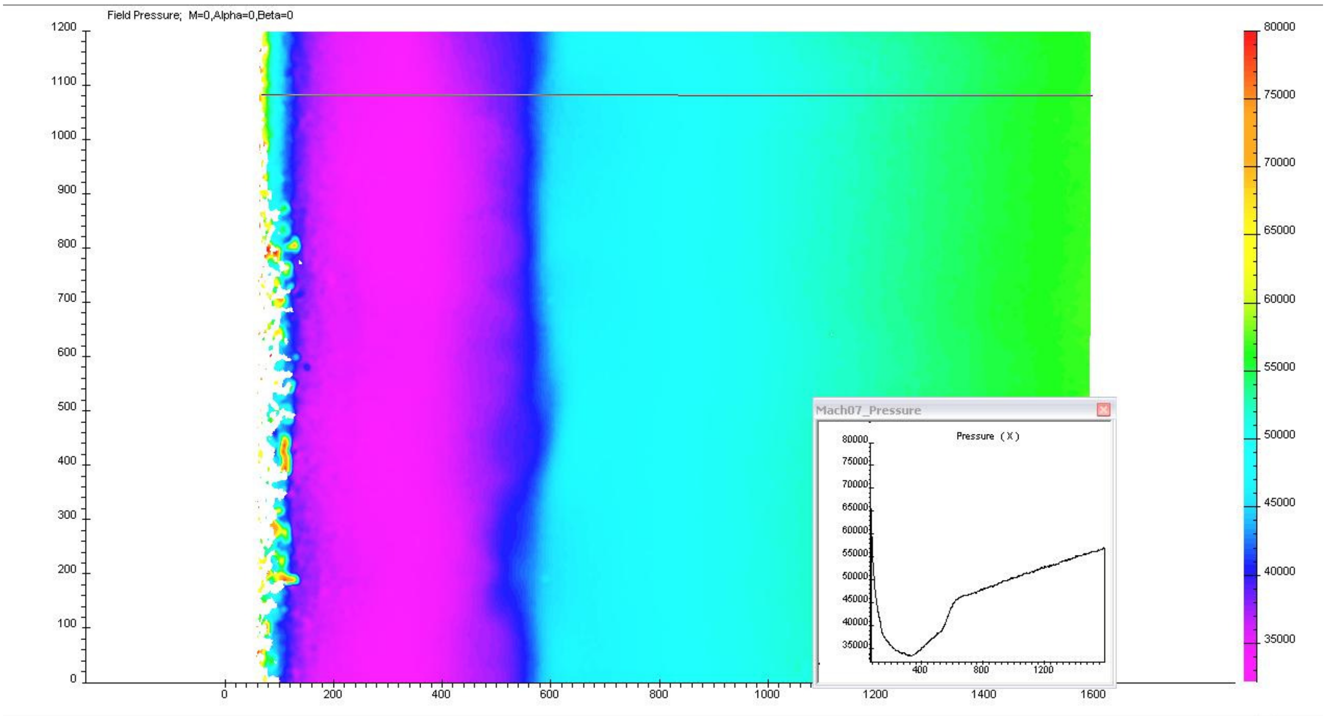


Figure 8 – Pressure Field with values in Pascal. Initial formation of shock-wave.

3. CONCLUSIONS

PSP measurements have been performed at the TTP using NACA 0012 and other models. This technique has demonstrated a great tool to obtain pressure field and analysis of aerodynamics phenomena. Although of the test problems the PSP technique has been well established at TTP and the next works are intended to optimize and to e diminish the errors sources that decreases the accuracy of the results.

4. ACKNOWLEDGEMENTS

The authors would like to express their gratitude to CNPq, The Brazilian National Council of Research and Development, for the partial funding of this research, under Grant nº 106254/2008-1. Thanks also to to the the Brazilian Space Agency for the financial support and the Aerodynamics Division (ALA), technicians José Rogério Banhara, José Ricardo Carvalho da Silva and Wellington Rodrigues dos Santos for their valuable help in the experimental apparatus assemble.

5. REFERENCES

Ardasheva, M.M., Nevsky, L.B. and Pervushin, G.E., 1982, “Method of pressure distributionVisualization with the organic luminophores”, III the USSR School on the Methods of Aerophysical Investigations, Novosibirsk, Russia, pp. 103-10.

Ardasheva, M.M., Nevsky, L.B. and Pervushin, G.E., 1985, “Measurement of pressure distribution by means of indicator coatings”, Journal of Applied Mechanics and Technical Physics, Vol.4. pp. 24-33.

Bell, J. H., Schairer, E. T., Hand, L. A. and Mehta, R. D., 2001, “Surface Pressure Measurements Using Luminescent Coatings”, Annu. Rev. Fluid Mech., Vol.33, pp. 55-206.

Gouterman, M., Callis, J., Burns, D., Kavandi, J., Gallery, J., Khalil, G., Green E., McLachlan B. and Crowder, J., 1990, “Luminescence imaging for aerodynamic testing”, In: Sullivan J.P., Holmes B. (eds) Proc. of the ONR/NASA Workshop on Quantitative Flow Visualization, Purdue University, IN, USA.

J. H. Bell, E. T. Schairer, L. A. Hand, R. D. Mehta, 2001 “Surface Pressure Measurements Using Luminescent Coatings”, Experimental Physics Branch, National Aeronautics and Space Administration, Ames Research Center, Moffett Field, California,Vol.33, pp. 155-206.

J. W. Gregory, K. Asai, M. Kameda, T. Liu and J. P. Sullivan, 2007, “A Review of pressure-sensitive paint for high-speed and unsteady aerodynamics”, Department of Aerospace Engineering, The Ohio State University, Ohio, USA.

Kautsky, H. and Hirsch, H., 1935, “Detection of minutest amounts of oxygen by extinction ofPhosphorescence”, Z. Anorg Allg, Germany, Chem, pp. 222-216.

Kavandi, J., Callis, J.B., Gouterman, M.P., Khalil, G., Wright D., Green E., Burns D. and McLachlan B., 1990, “Luminescent barometry in wind tunnels”.

Liu, T. and Sullivan, J. P., 2005, “Pressure and Temperature Sensitive paints”, Springer, Berlin.

McLachlan, B.G., Kavandi, J.L., Callis J.B., Gouterman, M., Green, E. and Khalil G., 1993, “Surface pressure field mapping using luminescent coatings”, Experiments in Fluids, Vol.14, pp. 33-41.

Pervushin, G.E. and Nevsky, L.B., 1981, “Composition for indicating coating”, Patent of USSR-SU, Russia.