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SURFACE PRESSURE MEASUREMENTS ON A SPACE LAUNCH VEHICLE IN THE TRANSONIC REGIME

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Abstract. *Wind tunnel surface pressure measurements are important for understanding the aerodynamics of flight vehicles, as well as to identify specific phenomena, such as shock waves occurrences. The most commonly used method for pressure measurements is through pressure taps, in which small orifices are installed in several positions on the model surface, and these small holes are connected by flexible tubes to pressure transducers. Despite its many advantages, this method is costly and demands high installation time. In addition, the pressure taps can not be installed in some areas of the models due to physical limitations. Alternatively, there is the relatively new technique of Pressure Sensitive Paint (PSP), which is based on the deactivation of the luminescence due to the presence of oxygen. This method has high spatial resolution and is a non-intrusive measurement. In the present study, results obtained from pressure measurements performed in a transonic wind tunnel with a sounding vehicle model using PSP and pressure taps will be presented and discussed. Flow features around the model obtained using the Schlieren technique will also be discussed. The measurements were performed for values of Mach number between 0.5 and 1.1 for zero angle of attack. A good agreement between the results obtained with PSP and pressure taps were obtained. Complex flow phenomena as shock and expansion waves as well as flow separation regions were clearly identified.*

Keywords: *VS-40, Pressure Sensitive Paint, Pressure measurements, Transonic Wind Tunnel.*

1. INTRODUCTION

Surface pressure measurements in wind tunnels are of great importance for the understanding of the aerodynamic performance of flight vehicles as well as to provide critical information about complex flow phenomena (Liu and Sullivan, 2005). This is specially true in the transonic regime, which is associated with several important flow features, as expansion and shock waves occurances, flow separation and shock wave boundary layer interaction, among others.

The most traditional method for surface pressure measurements is the technique of pressure taps, which consists of installing arrays of small orifices on a model surface and connecting them throught small flexible tubes to pressure transducers. This technique, relatively simple, provides good results, but has also some drawbacks. It is costly in price and time to manufacture and to prepare a model with the hundreds of pressure taps necessary to provide a reasonable resolution. In addition it is not possible to install pressure taps in very thin areas of the model. An option for pressure measurements, that brings a solution for measurements in thin areas is the technique of Pressure Sensitive Paint (PSP) that has been used for several years in wind tunnel around the world as a standard technique for obtaining quantitative global pressure measurement on model surfaces (Liu and Sullivan, 2005; Vardaki, *et al*. 2012). The advantages of PSP in comparison with the conventional methods are its high resolution and the possibility to access any area of interest on the model surface in a non-intrusive way, with a relatively low cost. In addition, PSP is an important tool for validation of CFD codes. The PSP technique requires a special paint in which the luminescence is inversely dependent to air local pressure. This paint is applied upon the surface of a wind tunnel model and the pressure field is obtained from images produced by proper illumination.

The PSP technique working principle is based on an oxygen-quenching process in which excited molecules are deactivated by oxygen, this phenomenon produces different degrees of luminosity on the model surface. The final pressure map is obtained using complex image processing techniques (Engler, *et al*., 2000). The PSP paint consists of an oxygen-permeable polymer binder containing luminnescent oxygen-sensitive molecules. When illuminated with light at an appropriate wavelength, the luminescent molecules become excited electronically to an elevated energy state, Fig. 1. These molecules can decay to the ground state through a radiative process, luminescence, or nonradiatively

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through the release of heat. In some materials, oxygen can interact with the luminescent molecules such that the transition to the ground state can be non-radiative, and takes place by colliding with an oxygen molecule, a process known as "oxygen quenching." (Bell, *et al*., 2001). Conceptually a PSP system, Fig. 2, is composed of a PSP, an illumination source, a detector, and a long-pass filter. The PSP is distributed over the model surface and the surface is then illuminated by the excitation source causing the PSP to luminesce. The luminescent intensity from the PSP is recorded by the detector and converted to pressure using a previously determined calibration. Conceptually a PSP system, Fig. 2, is composed of a PSP, an illumination source, a detector, and a long-pass filter. The PSP paint is distributed over the model surface, which is then illuminated by the excitation source causing the PSP to luminesce. The luminescent intensity from the PSP is recorded by the detector and converted to pressure using a previously determined calibration.

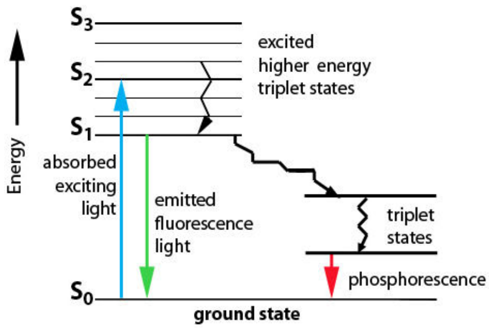

Figure 1. Jablonski diagram and the process of luminescence deactivation.

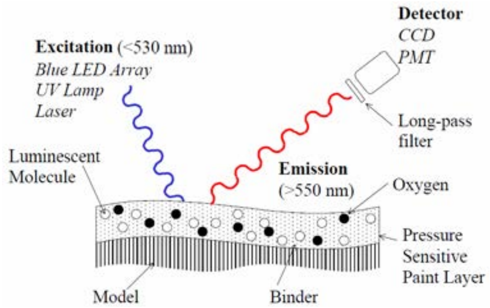

Figure 2. Basic Pressure-Sensitive.

The rate of quenching is proportional to the local oxygen partial pressure, which is in turn proportional to absolute pressure. Therefore, the luminescence of the PSP coating is inversely proportional to the local surface pressure. Since this is an absolute measurement technique, it works more effectively for the high speed flows (transonic and higher), where the pressure gradientes are high. Regrettably, the luminescent intensity distribution does not depend only on the partial pressure of oxygen. Actually, it varies with illumination intensity, paint layer thickness, temperature and uniformity. Theses variations can origin a non-uniform signal from the painted surface and can be eliminated or minimized taking the ratio of the luminescence intensity, wind-on and wind-off. With this procedure, the response of the system can be modeled using a modification of the Stern-Volmer equation, Eq. (1), (Liu and Sulivan, 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 wind tunnel test section (wind-off).

$$\frac{I_{ref}}{I} = A + B\frac{p}{p_{ref}} \tag{1}$$

The lifetime based PSP measurement, used in the present study, includes phase-sensitive detection and multi-gate integration techniques. A schematic representation of theses gates is shown in Fig. 3. 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 obtained through 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 a signal of pressure (www.innssi.com).

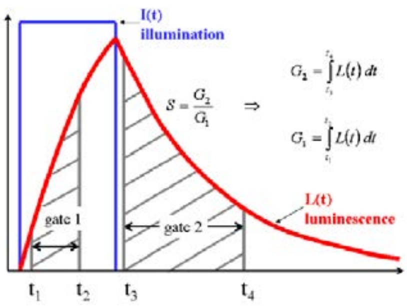

Figure 3. Schematic representation of Life-time method working principle (extracted from Vardaki *et al*. (2010)).

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In the present study, the PSP technique and pressure taps were simultaneously used, and the Schlieren visualization were conducted for investigating the flow pattern in the fore body of a sounding vehicle, VS-40, shown in Fig. 4, for Mach numbers ranging from 0.5 to 1.1. The Schlieren Technique is an optical method that allows the visualization of the density variation in flows and consequently important phenomena typical of compressible flow. A Schlieren system consists, basically, of a light system installed behind the object to be tested, as a background, which are distorted by the refraction caused by the gradient of the fluid density. A good description of this technique is given by Tropea *et al.*, (2007).

The VS-40 is a Brazilian vehicle developed in the *Instituto de Aeronáutica e Espaço*, IAE. It is a non controlled, unmanned and high performance space vehicle. It is a bi-stage vehicle and can provide a wide exposure to the microgravity environment, which is characterized by a condition where an object is subjected to a g-force less than 10 µg (La Neve and Corrêa Jr, 2001).

The measurements were carried out in the Pilot Transonic Wind Tunnel (*Tunel Transônico Piloto* - TTP), located in the IAE Aerodynamics Division (ALA). For the PSP measurements, most of the obtained results are still being processed and will be published further. From the preliminary results, a good agreement between the PSP and pressure taps results were observed and the identification of important flow phenomena as shock and expansion waves as well as flow separation was allowed.

Figure 4. VS-40 sounding vehicle.

2. EXPERIMENTAL METHODOLOGY

The Transonic Wind Tunnel, Fig. 5, was built in the 90s with a conventional closed circuit, continuously driven by a main compressor of 830kW 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, 25 cm high and 80 cm length, with slotted walls. TTP has automatic pressure controls from 0.5 bar to 1.25 bar, with Mach number varying between 0.2 and 1.3 as well as control of temperature and humidity in its test section. The tunnel operational envelop is shown in Fig. 6. A detailed description of TTP wind tunnel can be found in Falcão Filho and Mello (2002).

Figure 5. Pilot Transonic Wind Tunnel (TTP).

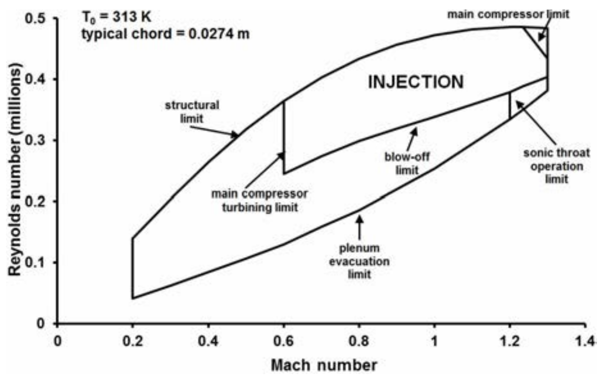

Figure 6. Operating envelope (injection system).

The experiments were carried out on a model in scale 1:34 of the sounding rocket VS-40. The model was built with 15 embeded pressure taps and it was fixed in the TTP test section as shown in Fig. 7, by means of a sting. Just the region of the nose fairing was investigated.

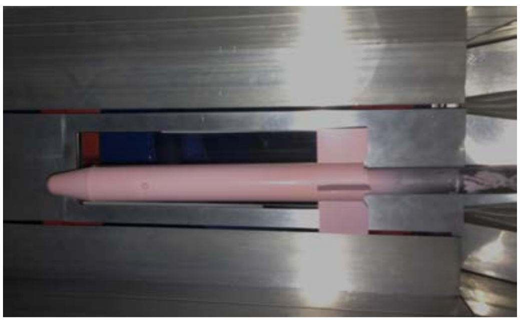

Figure 7. The VS-40 model painted with PSP paint inside the TTP test section.

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The PSP paint used is a commercial UniFIB paint, purchased from Innovative Scientific Solutions, Inc. (ISSI). Regarding the painting process, initially the model was carefully cleaned with acetone. Then a basecoat layer was sprayed onto the model surface to fill in voids and imperfections, providing a clean, smooth surface to the FIB-based paint to adhere to. Finally, a layer of the UniFIB paint was applied to the model surface, Fig. 8. An airbrush gun was used in the painting process.

A serious concern when painting the model was to avoid the obstruction of the 0.5 mm diameter pressure taps. With this purpose, air was gently blown through the holes during the painting procedure using compressed air connected to the flexible tubes. Because of safety concerns, since in general PSP products are toxic, the painting procedure was carried out under an air exhauster and gloves were worn by the painter.

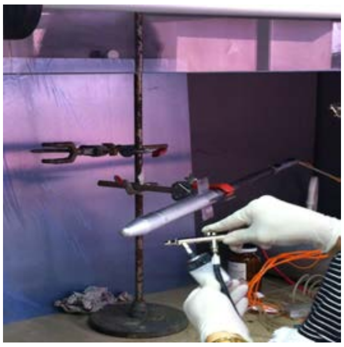

Figure 8. The VS-40 model being painted.

Once painted, the model was dried up in an oven at 60ºC for 90 min. Finally, it was installed in the wind tunnel test section. For the PSP measurements, the model was illuminated using a 400nm frequency LED (Light mission Diode) LM2X-DM-400. The images were acquired by using a PCO 1600 14 bit cooled CCD camera with 1600 x 1200 pixels of resolution fitted with a Nikkon lens f# 2.8 with focal length of 55mm. A Quantum Composer 9600+ pulsed generator was used for the synchronism between the camera, illumination system and the computer, and a commercial system from ISSI was used for data acquisition and analysis. The CCD camera and the illumination system are shown in Fig. 9.

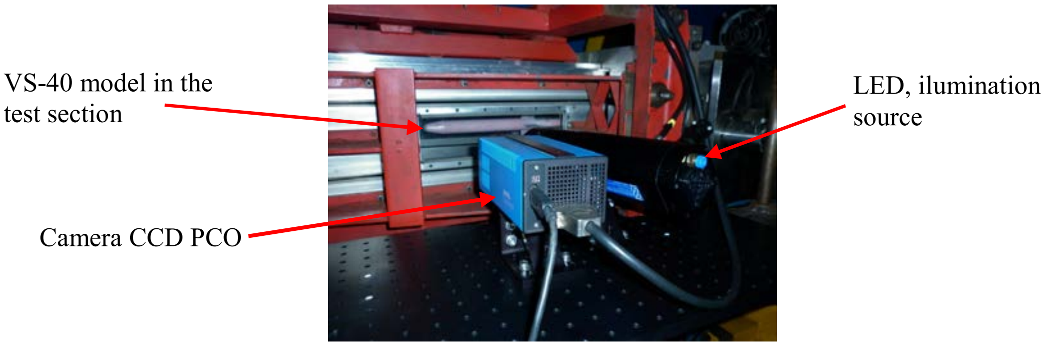

Figure 9. The VS-40 model installed in the TTP test section, the CCD Camera and the illumination device.

Flow visualization using the Schlieren technique around the VS-40 was conducted after the PSP measurements, not in the same day, which means that is not possible to guarantee exactly the same test conditions, although this was tried.

The main components of Schlieren system used in the present study are two parabolic mirrors, 6" diameter, two flat mirrors, 8" diameter, one knife edge, and of one CCD camera, PCO 1600, the same used in the PSP measurements and one light source. The light source consists essentially of a point source of white light having a diverging beam. This light source has basics adjustments, which allow the center of the beam to be directed to the first of two parabolic mirrors and a linear adjustment, to allow the source to be located at the focal point of the first parabolic mirror, Fig. 10a. This Parabolic mirror focuses the light beam into parallel rays, which are directed toward the first flat mirror, Fig. 10b, positioned at an angle of 45^{o} to these rays, and which directs them to the TTP test section and chamber window, making them the parallel light beam to pass through these windows. The second flat mirror, Fig. 10d, is positioned on the opposite side of the tunnel and directs the parallel light beam toward the second parabolic mirror, which collects and directs the light beam toward the knife-edge, where they are focused to a point, and continues through the CCD camera.

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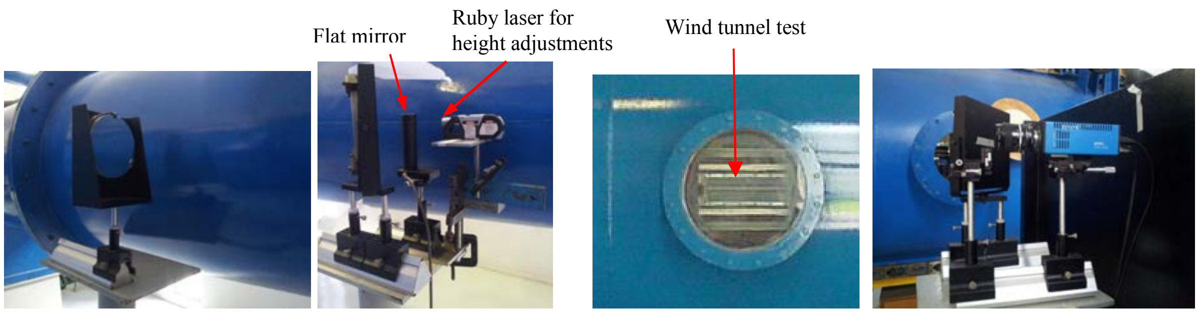


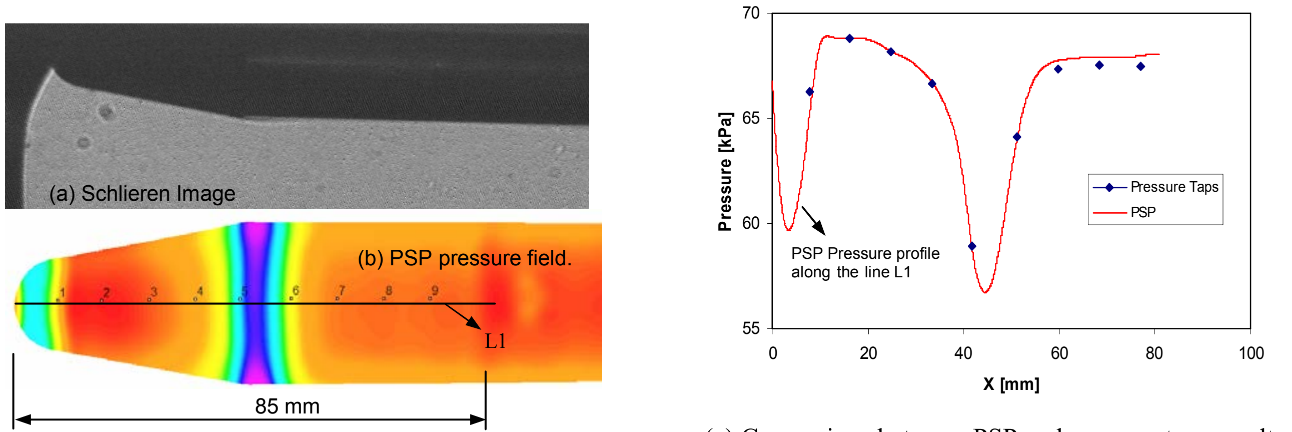
(a) 1th parabollic Mirror (b) 1th flat Mirror and light adjustment system (c) TTP Window. (d) 2nd flat plane and CCD camera.

Figura 10. Schlieren /shadowgraph set-up.

Basic adjustments of the parabolic mirrors include vertical tilt, horizontal rotation and height. The same adjustments, except horizontal rotation can be applied also to the flat mirror.

3. RESULTS AND DISCUSSIONS

In this section some preliminary results obtained with the techniques PSP, pressure taps and Schlieren are presented. Observing from Fig. 11 the results of PSP and pressure taps for Mach number of 0.7, strong pressure gradients can be identified in the transition region between the vehicle nose and the beginning of its fuselage, as well as the occurrence of an expansion wave. A good agreement between PSP and pressure taps results can be observed, being the highest difference between PSP and pressure taps results around 500 Pa.



(c) Comparison between PSP and pressure taps results.

Figure 11. Schlieren and PSP results for Mach number equal to 0.7.

Based on the lowest pressure level observed just after the nose cone, it is possible to determine the local Mach number of 0.88. Since the flow is all subsonic in the Schlieren image little can be seen because of the inexistence of shock waves. However it is possible to observe the boundary layer detachment caused by a small back step just after the cone nose.

From Fig. 12, the occurrence of two shock waves can be clearly identified by observing the Schlieren and PSP images. The first one, a weak shock wave took place in nose region of the vehicle, and the second one, a normal shock wave occurred after the beginning of the fuselage cylindrical region. Based on the two lowest pressure levels observed, it is possible to determine the local Mach number of 1.04 in the nose and 1.17 after the cone nose.

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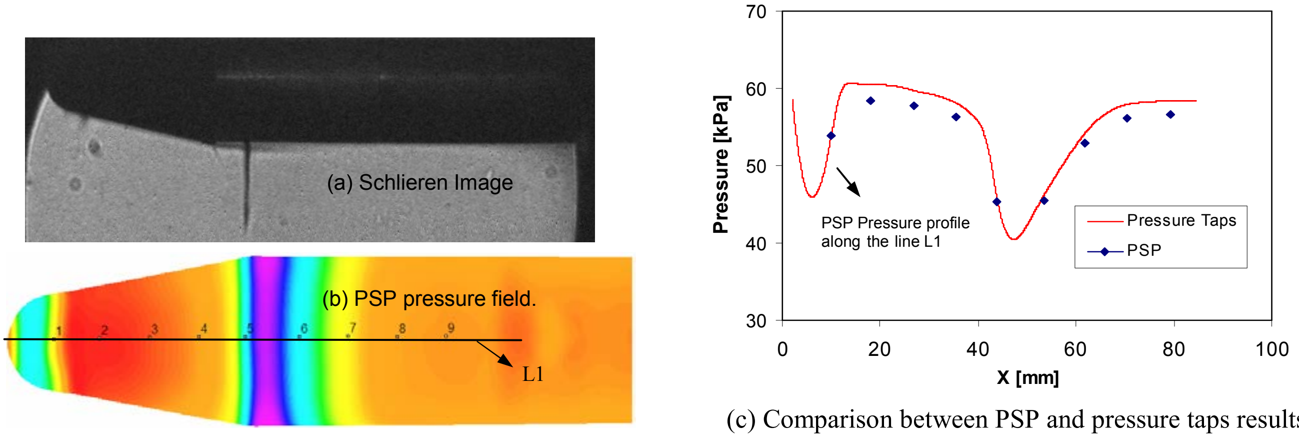
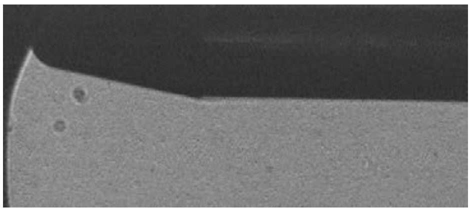
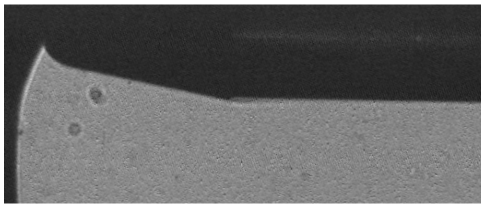
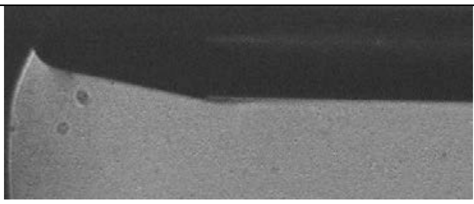
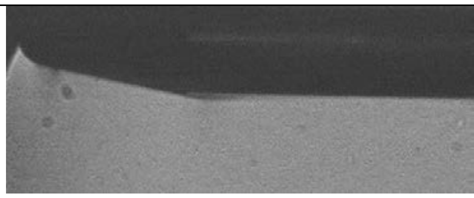
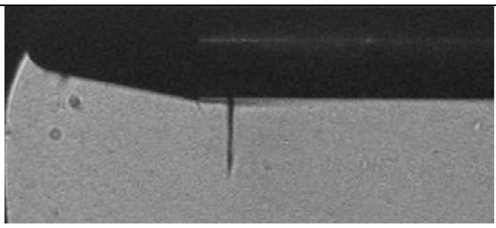
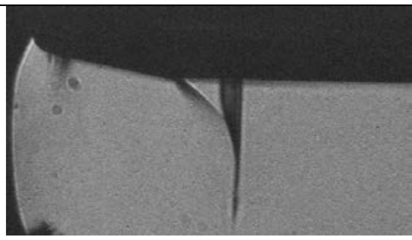
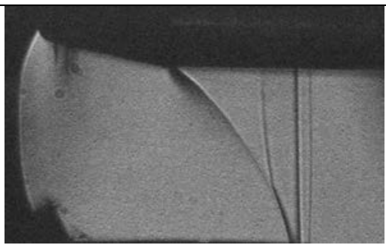
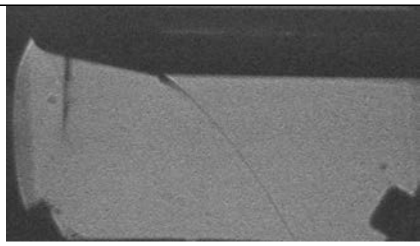


(c) Comparison between PSP and pressure taps results.

Figure 12. Schlieren and PSP results for Mach number equal to 0.9.

Schlieren images for Mach number varying from 0.5 to 1.1 are shown in Tab. 1. A separation region just after the step formed between the end of the conical region and vehicle fuselage can be identified for Mach numbers of 0.5 to 0.9. For Mach number 0.9 the occurrence of a shock wave is clearly verified in the cylindrical part of the model as well as a weak shock wave in vehicle nose. As the undisturbed Mach number increases, starting at 0.8, the expansion regions, in the initial part of the nose and in the beginning of the cylindrical part, increases with higher supersonic Mach number and stronger shock waves. For Mach number equal to 1.1, a bow shock occurs in front of the nose.

Table 1. Schlieren images for Mach number varying from 0.5 to 1.1.

 Mach 0.5	 Mach 0.6
 Mach 0.7	 Mach 0.8
 Mach 0.90	 Mach 0.95
 Mach 1.0	 Mach 1.1

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4. CONCLUSIONS

Experimental procedures to analyse the flow patterns around the VS-40 sounding vehicle were described, and preliminares results obtained with the three techniques used: Schlieren, PSP an pressure taps, were presented. The obtained results allowed the identification of several important flow features, as shock waves, expansion waves and flow separation. In general, a good agreement between the results obtained with PSP and pressure taps were observed. The technique Schlieren combined with the quantitative techniques of PSP and pressure taps constitute a powerful tool for indentification and analyses of complex phenomena.

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