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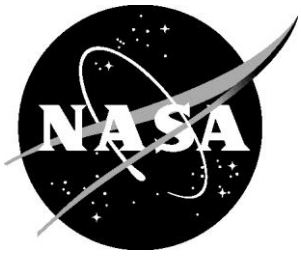

Pressure- and Temperature-Sensitive Paint at 0.3-m Transsonic Cryogenic Tunnel

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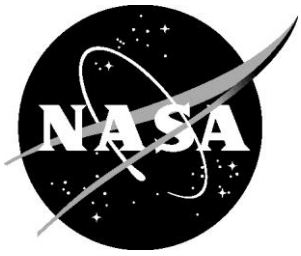

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Abstract

Recently both Pressure- and Temperature-Sensitive Paint experiments were conducted at cryogenic conditions in the 0.3-m Transonic Cryogenic Tunnel at NASA Langley Research Center. This represented a re-introduction of the techniques to the facility after more than a decade, and provided a means to upgrade the measurements using newer technology as well as demonstrate that the techniques were still viable in the facility. Temperature-Sensitive Paint was employed on a laminar airfoil for transition detection and Pressure-Sensitive Paint was employed on a supercritical airfoil. This report will detail the techniques and their unique challenges that need to be overcome in cryogenic environments. In addition, several optimization strategies will also be discussed.

1. Introduction

The accurate determination of spatially continuous pressure and temperature distributions on aerodynamic surfaces is critical for the understanding of complex flow mechanisms and for comparison with computational fluid dynamics (CFD) predictions. Conventional pressure measurements are based on pressure taps and electronically scanned pressure transducers or embedded pressure transducers, while temperature measurements are usually conducted using mounted devices such as thermocouples, RTDs, or thin film gauges. While these approaches provide accurate pressure and/or temperature information, they are limited to providing data at discrete points. Moreover, the integration of a sufficient number of these devices on a surface can be time and labor intensive and expensive.

The Pressure-Sensitive Paint (PSP) and Temperature-Sensitive Paint (TSP) techniques allow for the accurate determination of pressure and temperature distributions over an aerodynamic surface and are based on an emitted optical signal from a luminescent coating. However, when full flight Reynolds number measurements are required, it is common to use a cryogenic facility, especially if an increase in model size is not a viable option. In this case, there are several challenges to overcome using both the PSP and TSP technique.

This report will detail the results of both a TSP test and a PSP test at the 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT) conducted at NASA Langley Research Center. These tests were aimed at re-introducing the techniques into the facility after more than a decade. In addition, several areas of improvement have been identified and will be discussed.

2. PSP and TSP

Introduction to PSP

The PSP technique[1-5] exploits the oxygen (O_2) sensitivity of luminescent probe molecules suspended in gas-permeable binder materials. When a luminescent molecule absorbs a photon, it transitions to an excited singlet energy state. The molecule can then recover to the ground state by the emission of a photon of a longer wavelength, known as a radiative process. However, certain of these materials can also

interact with an O_2 molecule such that the transition back to the ground state is non-radiative in a process known as collisional quenching. The rate at which these two process (radiative vs. non-radiative) compete is dependent on the concentration of O_2 present and can be described by the Stern-Volmer relationship[6]

$$I_0 / I = 1 + K_{SV}(T) P_{O_2} \tag{1}$$

where I_0 is the luminescence intensity in the absence of O_2 (i.e. vacuum), I is the luminescence intensity at some partial pressure of oxygen P_{O2}, and K_{SV} is the Stern-Volmer constant, which is dependent on temperature (T).

There are several issues with this relationship, especially in regards to wind-tunnel applications; first, it is a practical impossibility to measure I_0 in a wind tunnel application. Second, the luminescent signal from the paint is not only a function of pressure; it also varies with factors such as illumination intensity, probe concentration, paint layer thickness, and detector sensitivity. These spatial variations typically result in a non-uniform luminescent signal from the painted surface. The spatial variations are usually eliminated by taking a ratio of the luminescent intensity of the paint at the test condition with the luminescent intensity of the paint at a known reference condition (usually wind-off). Thus Eq. 1 can be cast into a more suitable form

$$I_{REF} / I = A(T) + B(T) * (P / P_{REF}) \tag{2}$$

where I_{REF} is the recovered luminescence intensity at a reference pressure, P_{REF}. The coefficients $A(T)$ and $B(T)$ are temperature dependent constants for a given PSP formulation and are usually determined beforehand using laboratory calibration procedures.

PSP measurements are difficult to make under cryogenic conditions for two reasons. First, the test gas is typically nitrogen, refrigerant, or some other medium which typically contains little or no oxygen. Second, the diffusion of oxygen into the paint binder is highly temperature dependent, and at low temperatures, is practically nonexistent. Successful cryogenic PSP measurements have been conducted at 0.3-m TCT,[7] the National Transonic Facility at NASA Langley,[8] as well as other facilities[9,10] using a PSP binder that has a very large diffusion rate and bleeding in known amounts of oxygen into the flow stream. A typical calibration of a cryogenic PSP is shown in Fig. 1.

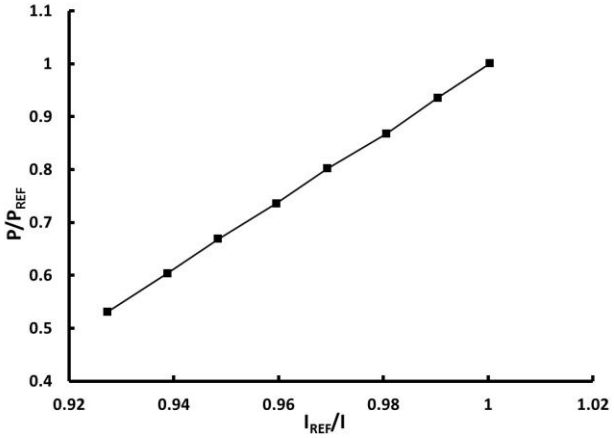

Figure 1. Typical PSP response curve to increasing gas pressure. The gas used was 3000 ppm oxygen in nitrogen and the data was collected at 137K.

Introduction to TSP

As with PSP, TSP is typically a polymer-based paint in which luminescent molecules are immobilized.[5] However, as opposed to PSP, the binder in a TSP is typically chosen so that it is impermeable to O_2. In addition, the luminescent molecules are typically chosen so that their quantum yield decreases with increasing

temperature (i.e. thermal quenching). The relationship between the luminescence of the probe molecule and the absolute temperature generally follows Arrhenius behavior over a certain range[5]

$$ln\frac{I(T)}{I(T_{REF})}=\frac{E_{NR}}{R}\left(\frac{1}{T}-\frac{1}{T_{REF}}\right) \quad (3)$$

where E_{NR} is the activation energy for the non-radiative process, R is the universal gas constant, and T_{REF} is the reference temperature. However, for some TSPs, Eq. (3) cannot fully describe the behavior, especially outside of temperature ranges where Arrenhius behavior occurs. Thus, it is also common to simply model the behavior of the TSP in a more generalized sense

$$I(T)/I(T_{REF})=f(T/T_{REF}) \quad (4)$$

where $f(T/T_{REF})$ is a function that can be linear, polynomial, exponential, etc., to fit the experimental data over a suitable temperature range. This behavior is dependent on the nature of the probe, thus it is possible to select molecules that can lead to formulations that are temperature sensitive from cryogenic to 473 K.[5,11-15] The temperature response of several ruthenium-based luminophores as a function of temperature is shown in Fig. 2.

3. Experimental

0.3-m TCT

The 0.3-m TCT is a continuous-flow, single-return, fan-driven transonic tunnel which can employ either air (ambient temperature testing) or nitrogen (cryogenic temperature testing) as the test medium. It is capable of operating at stagnation temperatures from about 100 K (-280 °F) to about 322 K (120 °F) and stagnation pressures from slightly greater than 101 kPa (1 atm) to 607 kPa (6 atm). Test section Mach number can be varied from near 0 to 0.9. The ability to operate at cryogenic temperatures and high pressure provides an extremely high Reynolds number capability at relatively low model loadings. The test section has computer-controlled angle-of-attack and traversing-wake-survey rake systems. Two inches of honeycomb and five anti-turbulence screens in the settling chamber provide flow quality suitable for natural laminar flow testing. The relevant characteristics for the 0.3-m TCT are shown in Table 1, and additional design features and characteristics regarding the cryogenic concept in general and the 0.3-m TCT in particular can be found in works by Kilgore, Adcock, and Ray[16] and Kilgore.[17]

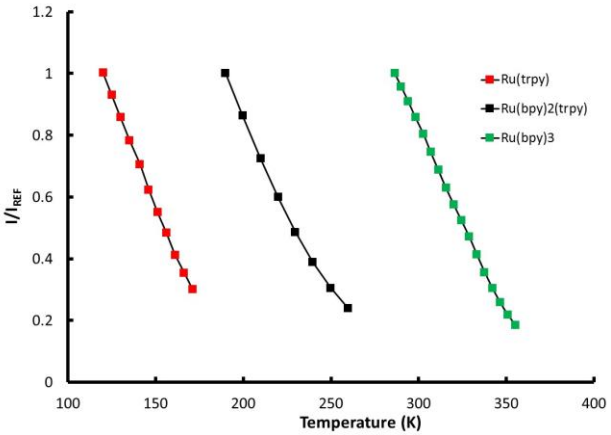

Figure 2. Typical TSP response curves for three different ruthenium complexes.

Table 1. Relevant characteristics of the 0.3-m TCT

Test section dimensions	0.33 m by 0.33 m (13 in. by 13 in.)
Speed	Mach 0.1 to 0.9
Reynolds Number	3.3 to 330 x 10^6 per m (1 to 100 x 10^6 per ft.)
Temperature	100 to 322 K (-280 to 120 ^{o}F)
Pressure	101 to 607 kPa (1 to 6 atm)
Test gas	Nitrogen or air

Models

There were two airfoil models employed in this work. For the TSP work, an airfoil that was designed for the NASA-funded Subsonic Ultra Green Aircraft Research (SUGAR) project. This project is funded by the Subsonic Fixed Wing Project in the Fundamental Aeronautics Program. The PSP test was conducted on an airfoil model designated as the NASA SC(3)-0712(B).[18] The model is a supercritical airfoil with a 0.7 design lift coefficient and 12%-percent thick. The airfoil has a chord of 15.24 cm (6.0 in) and is constructed from VascoMax C-200 steel. The airfoil also contained 74 pressure transducers on the upper surface, with approximately 40 visible in the PSP images.

Paint Formulations

This work encompasses two different wind tunnel entries. In the first entry, TSP was employed for transition detection, while PSP was employed in the second entry to measure the pressure distribution over an airfoil.

TSP: The TSP formulation used in this work was based on a formulation developed at NASA LaRC. Versions of this TSP have been used both in cryogenic conditions at the National Transonic Facility for transition detection[19] and for the measurement of heating properties at hypersonic conditions.[20] The formulation is based on a clear urethane sealant in which a ruthenium luminophore is dissolved. The urethane sealant acts as an oxygen impermeable binder, and the ruthenium-based luminophore can be easily excited using blue lights (e.g. blue LEDs) and exhibits a significant Stokes shift, emitting near 600 nm. This allows for easy discrimination of the excitation light from the camera using optical filters.

Since this tunnel entry was conducted at a nominal temperature of ~230 K (-50 ^{o}F), the ruthenium-based luminophore used in the formulation was ruthenium bis(2,2'-bipyridine)(2,2':6',2"-terpyridine)hexafluorophosphate, hereafter abbreviated $Ru(bpy)_2(trpy)$. The temperature sensitivity of $Ru(bpy)_2(trpy)$ is shown in Fig. 2, and displays excellent sensitivity in the expected temperature range. A typical synthesis of $Ru(bpy)_2(trpy)$ was accomplished by mixing 2 mmol cis-bis-(2,2'-bipyridine) ruthenium (II) chloride ($Ru(bpy)_2Cl_2$, GFS Chemicals), 4 mmol silver trifluoromethanesulfonate ($Ag(CF_3SO_3)$, GFS Chemicals), and 2 mmol 2,2',2"-terpyridine (trpy, GFS Chemicals) in 100 mL of a 3:1 v/v solution of methanol (Aldrich, reagent grade):water. This mixture is then refluxed under nitrogen for 40 hours. After reflux, the solvents are removed and the residue is re-dissolved in a minimal amount of acetone (Aldrich, reagent grade). This is then added to a 100 mL aqueous solution containing approximately 6 mmol ammonium hexafluorophosphate (NH_4PF_6, GFS Chemicals), yielding $Ru(bpy)_2(trpy)$.

Previous cryogenic PSP[7,8] and TSP[13] tests have shown that highly polished stainless steel models must first be painted with a basecoat to enhance adhesion of the PSP or TSP to the model. For this work, the model was first coated with a self-etching primer layer (GBP 988 Self-Etching Primer, Sherwin-

Williams) and allowed to cure in air. Then a white basecoat created using the Spectra-Prime system (Sherwin-Williams) was applied using a conventional spray gun or airbrush. This layer is fully cured, either in air overnight or by heating to 60 °C for 1.5 hours. This layer is then wet-sanded using 2000 grit paper to achieve the desired finish. Finally, the urethane TSP solution is applied (again using conventional spraying techniques) and allowed to fully cure. The final result should be a paint layer between 25-50 µm (0.001-0.002 in.) thick, with a roughness (Ra) usually between 0.1-0.4 µm (5-15 µin.).

PSP: The PSP used in this formulation was one that was developed independently at NASA LaRC[7] and the National Aerospace Laboratory in Japan.[9,10] This is based on using poly[1-(trimethylsilyl)-1-propyne] (PTMSP) as the binder and applying a very thin coating of platinum meso-tetra(pentafluorophenyl)porphine (Pt(TfPP)) as the PSP luminophore. PTMSP was chosen as the binder because it is a glassy polymer with a large free volume, enabling it to have a very high oxygen diffusion rate.[21] This formulation has been used previously at 0.3-m TCT,[7] NTF[8,22], and other facilities[9,10] because of its high oxygen diffusion at cryogenic temperatures as well as the fact that it can applied using traditional painting techniques. As with the TSP work, the model was initially painted with the same white basecoat.

Instrumentation

Illumination: Illumination was achieved using commercially available light emitting diode (LED) arrays. These arrays were designed specifically for PSP and TSP work, thus are capable of producing a very stable output of more than 3W with ~0.1% drift per hour after warm-up. The color of the LED arrays can also be changed depending on the experiment. For the TSP work, the LEDs were configured to emit at 460 nm (30 nm bandwidth at full width at half max (FWHM)). For the PSP work, the LEDs were configured to emit at 400 nm (20 nm FWHM). For this work, four LED arrays were used for illumination.

Image Acquisition: Images were acquired from a single camera that was placed coincident with the LEDs. The camera employed was a PCO.2000 camera from Cooke Corporation (now PCO-Tech Inc.). The PCO.2000 is a high resolution (2000 x 2000 pixel resolution) CCD camera operating with a 14-bit digital resolution. The camera is thermoelectrically cooled (to -50 °C relative to ambient) with a rated frame rate of up to 14.7 frames per second (fps) at full resolution. The camera was interfaced to the computer via Firewire (IEEE 1384) interface that was extended to the control room via fiber optic converter boxes.

Illumination and Image Acquisition Mounting: The optical access for the 0.3-m TCT consists of a "D-shaped" window that was originally designed for off-body flow visualization studies. The D-shaped window is constructed of Schlieren quality fused silica that is mounted in the upper half of the circular angle-of-attack turntables. For this work, the airfoil is centered horizontally in the test section with its center-line 1.9 cm below the lower edge of the window. As such, there is no direct optical access to the surface. A

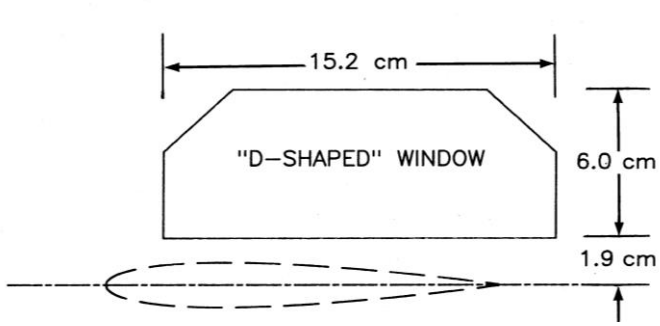

Figure 3. Geometry of the "D-shaped" window with a generic airfoil showing approximate location. From Ref. 3.

diagram of the D-shaped window with a generic airfoil is shown in Fig. 3.[23] In addition, the D-shaped window (and test section) is separated from the outside of the tunnel by a rectangular pressure plenum. To facilitate illumination and image acquisition, a pair of mirrors were deployed as a periscope to allow optical access to the upper surface of the model. This periscope was attached to the test section door and inside the plenum. A photograph of the optical setup is shown in Fig. 4.

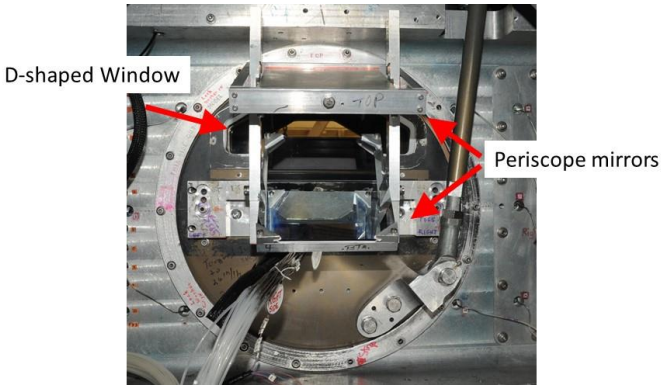

Figure 4. Optical setup showing the "D-shaped" window and the periscope assembly.

Optical access from outside of the plenum is provided by a window placed in the plenum wall. This window is also of Schlieren quality fused silica with a diameter of 22.9 cm. To keep the outer window clear of condensation (due to the large temperature difference on either side of the window), a large canister with a purge ring is connected to the plenum. The camera and the LEDs were placed in this canister. The canister mounted to the plenum is shown in Fig. 5.

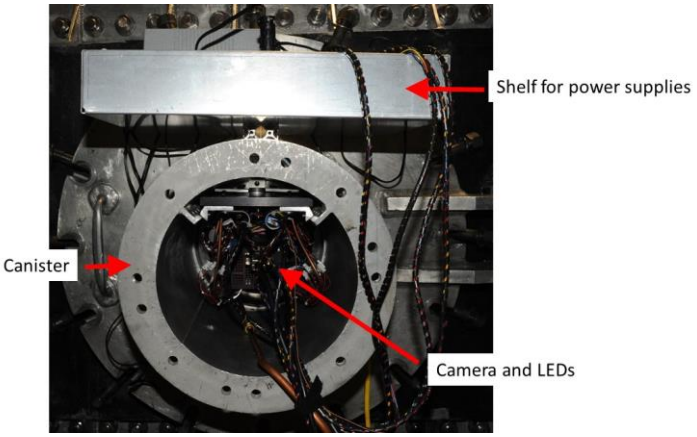

Figure 5. Canister mounted onto the side of the tunnel containing the camera and LED illumination sources.

Oxygen Monitoring: To facilitate calibration of the paint, the oxygen concentration in the flow must be measured accurately. This was done by interfacing an oxygen monitoring system into the tunnel just aft of the test section and just before the first turn in the tunnel through an existing feed-through. The oxygen sensor system (Thermox TM2000) employs a zirconium oxide sensor with a time response of less than 10 s. The system is also equipped with an in situ calibration option allowing it to maintain linearity and repeatability of less than 2% of reading or 0.5 ppm O_2 absolute. The unit is controlled by a personal computer via RS-232 protocol.

Oxygen Addition to the Tunnel: As mentioned above, PSP actually measures the partial pressure of O_2. Thus, O_2 must be present in the flow for PSP to be effective. However, in cryogenic conditions, the test medium is typically liquid nitrogen, which generally contains a very small amount of O_2 (less than 50 ppm depending on grade). Therefore, to use PSP at cryogenic conditions, some O_2 must be injected into the tunnel to increase its concentration. For this test, O_2 was introduced using cylinders of air. The air was introduced to the flow just prior to the test section (through another pre-existing feed-through). To keep the air from freezing at the feed-through, the line was heated using a heater tape. The flow was activated remotely from the control room using a solenoid valve. The air insertion equipment is shown in Fig. 6. With this configuration, the amount of O_2 in the flow could be increased from ~20 ppm (no air flow) to 500-1000 ppm, depending on tunnel conditions.

Data Acquisition

For both the TSP and PSP experiments the standard radiometric method for acquiring data was employed. In this method a reference image at a known condition is acquired followed by an image at the condition to be tested. In these cases, conversion of the ratioed data to temperature or pressure can be accomplished using Eqs. (1)-(4) as described above. However, for cryogenic testing, several minor tweaks to the data acquisition procedures need to be made and these will be described below.

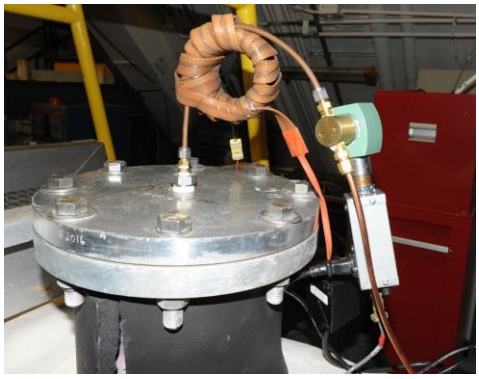

Figure 6. Air insertion line showing heating tape (to keep air from freezing upon injection) and solenoid for remote operation.

TSP: For transition detection using TSP it is generally desirable to enhance the natural transition temperature difference on the surface by introducing a step change in temperature to the flow. For cryogenic operations, this is typically dine by either temporarily increasing (to lower the temperature) or decreasing (to increase the temperature) the nitrogen injection rate into the facility. For this work, the temperature was lowered by increasing nitrogen injection. The typical data acquisition procedure generally followed the following paradigm:

1. The tunnel was cooled and the flow was established.

2. After the temperature had stabilized, a series of images was acquired to act as a reference image.

3. The nitrogen flow rate was increased to lower temperature. Meanwhile, image collection from the camera was begun.

4. Images were collected for several seconds throughout the temperature step (which generally resulted in a temperature decrease of ~10 K).

5. The image where the temperature change was greatest was generally selected as the image for ratioing with the reference image.

PSP: For the PSP work, care must be taken to ensure that the reference images are acquired under similar oxygen concentrations as the run images. To ensure that this occurs, the reference images were taken at Mach 0.2. This was done as there is very little pressure changes occurring on the surface at these speeds, but it also ensures that the oxygen that was injected will mix in the flow. In order to make more efficient use of the wind tunnel time, the general data acquisition procedure for the PSP work was as follows:

1. Flow was established in the tunnel and stabilized at the desired speed.

2. Air was injected into the tunnel and allowed to equilibrate as measured by the oxygen sensor system.

3. Wind-on images were acquired at various angles of attack. The oxygen concentration at each image was noted.

4. The speed of the tunnel was decreased to Mach 0.2, leaving the temperature constant.

5 Air was again introduced and metered to match the wind-on condition.

6. Wind-off images were taken at the same angles of attack as the wind-on condition.

4. Results and Discussion

TSP Test Results

Transition from laminar to turbulent flow over a surface is generally indicated by a small change in temperature on the surface. However, at transonic conditions, the adiabatic wall temperature difference for transition is on the order of 0.5 K,[12] which, under steady conditions, can be overwhelmed by factors such as heat conduction through the model surface. One method to amplify the temperature change is artificially increasing the temperature difference between laminar and turbulent flow by introducing a rapid step change of temperature to the flow.[24] Because the convective heat transfer coefficient of turbulent flow is much higher than that of laminar flow, the temperature change in the flow is more rapidly transferred to the surface in turbulent flow, leading to an increased change in the TSP response in a turbulent boundary layer. The transition line between laminar and turbulent flow can thus be detected as the borderline between light and dark areas in a TSP image, as shown in Fig. 7. In this work, the temperature step was introduced by increasing the injection of liquid nitrogen into the flow, thus creating a negative temperature step (temperature rapidly decreases). In Fig. 7, the light areas indicate a higher surface temperature, and thus laminar flow, as the temperature decrease in the flow is not efficiently transferred to the surface in a laminar boundary layer. Likewise, the darker areas indicate regions of turbulent flow.

Fig. 7 also shows one of the effects of the paint on the surface. There seems to be a multitude of turbulent wedges forming on the surface. One of the causes of these wedges is most certainly due to the roughness of the paint. While the TSP can be worked to improve its surface roughness, it can only partially correct for any surface roughness. In addition, the TSP coating can also act as an anchor for small bits of debris to stick to the surface. This can in turn also cause additional roughness, equivalent to small randomly placed trip dots. This effect can be implied by examining two different runs, as shown in Fig. 8. It is readily apparent that the wedges are originating from different points on the surface. If this was due simply to the inherent roughness of the

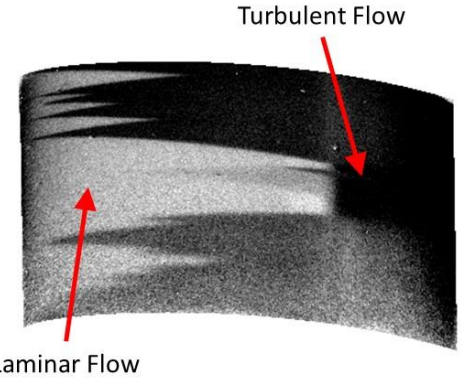

Figure 7. Representative TSP image for transition detection. The lighter areas represent laminar flow while the darker areas represent turbulent flow.

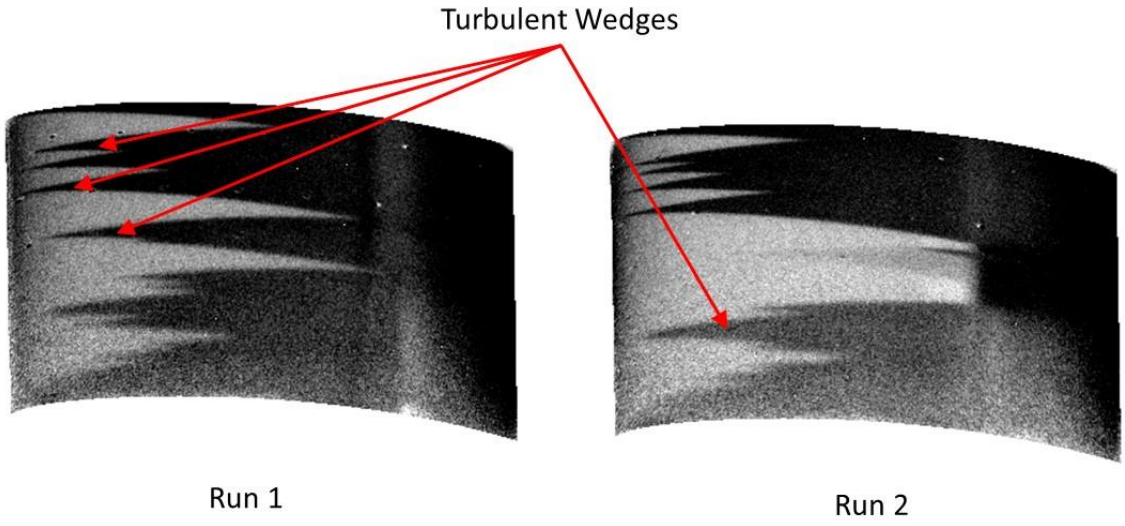

Figure 8. Comparison of two different TSP runs showing that there is variability in the turbulent wedges in both number and origination points.

TSP, then the wedges should all be originating from the same places on the surface (there is no access to the model once it is cooled down, so there was no opportunity to re-work the surface). These wedges are numerous enough that for most cases, it was difficult to determine the exact point of transition, though there are some cases where the transition point can be seen.

A sample of the TSP images collected for an entire run is shown in Fig. 9, detailing the evolution of the temperature step throughout a single run. From Fig. 9, it can be seen that once the injection rate of nitrogen is increase (corresponding to t = 0s), it takes several seconds for the temperature change to really begin. However, once it begins (in this case, at t = 7s), the visualization of the transition can be easily seen. In this data set, the temperature has begun to stabilize at t > 15s as evidenced by smaller temperature differences occurring on the model causing the visualization of the transition areas to fade. If this data set had been continued, the image would have shown similar features as seen at t = 0s. For the remainder of the report, results will be presented using the images that provided the highest contrast between laminar and turbulent flow (i.e. the point of highest temperature change in the tunnel).

The transition location on the airfoil surface was investigated as a function of both Mach number and angle of attack. The results for Mach 0.5 are shown in Fig. 10. The approximate location of the transition is depicted by the dotted line. For the lowest angle of attack (AOA = -1.75^{o}), this is difficult to identify due to the large number of turbulent wedges. However, for the other angles of attack, it is readily apparent where the transition front occurs. Furthermore, this seems to move to the leading edge as one increases the angle of attack. Unfortunately, the rest of the images did not provide as clear of a transition front, again, due to excessive turbulent wedges. The results for Mach numbers 0.67, 0.74, and 0.76 are shown in Figs. 11, 12, and 13, respectively. While the determination of the transition front is difficult to determine, there is evidence of a shock location near the trailing edge of the model. These are highlighted in Figs. 12 and 13. It is unclear whether this is a shock on the top of the model (and visualized due to refractive index changes in the air during the temperature step, similar to a shadowgraph-type of effect), or transmitted as a temperature change through the model from the underside. There was no computational results to

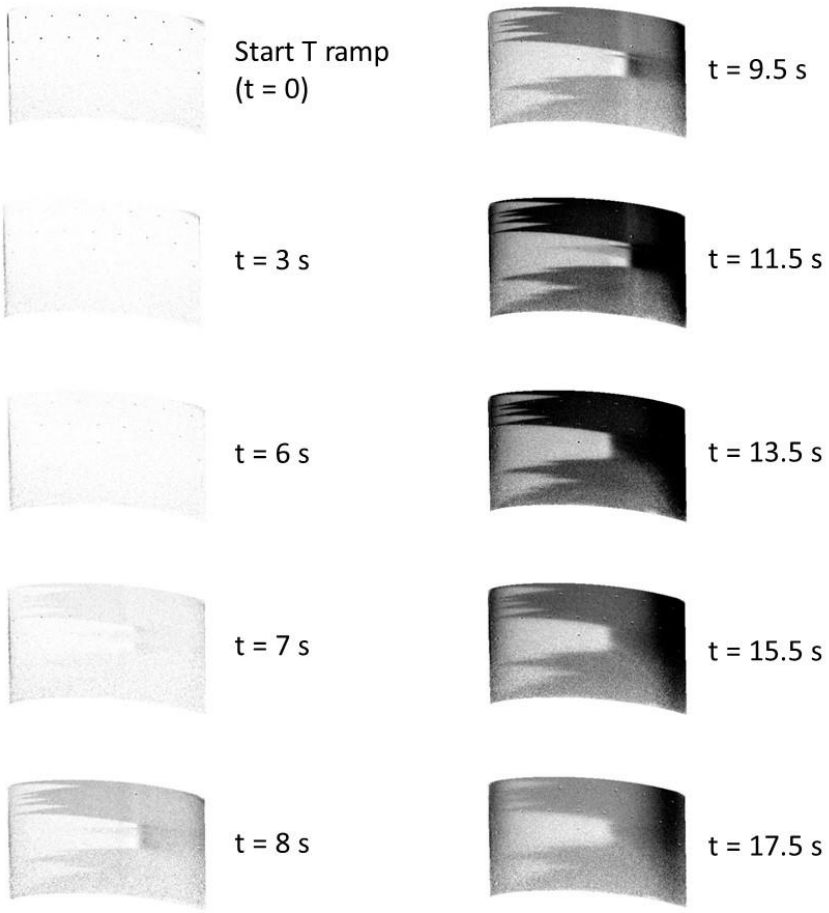

Figure 9. Series of TSP images from one run showing the evolution of the temperature step. The rate of temperature change is greatest at t = 11.5s.

compare these results to see if and where a shock occurs.

PSP Test Results

For PSP testing, data was taken at several angles of attack and Mach numbers of 0.7 or 0.5. The majority of the data was taken under full cryogenic conditions (116 K or -250 °F) though a set of data was taken at a warmer condition (250 K or -10 °F) to more closely match on of the conditions acquired in the first cryogenic PSP test conducted in the late 1990s.[7] In addition, a second cryogenic PSP formulation was also applied to the model in an attempt to demonstrate a more sensitive formulation. Unfortunately, due to an issue in the application, this formulation did not perform adequately in the tunnel. A line on the images that follow is used to demarcate the area that has the second PSP formulation. For this discussion, all data will be presented based on the Pt(TfPP) in PTMSP formulation described above.

A similar test on the same airfoil was conducted at the 0.3-m TCT in the 1990s, as mentioned above.[7] A sample of the data is shown in Fig, 14. Unfortunately, the data is currently available only as an image, so no manipulation of that data is possible. However, it does show that the PSP is capable of visualizing pressure gradients at cryogenic temperatures, with better results as the temperature is warmed (as should

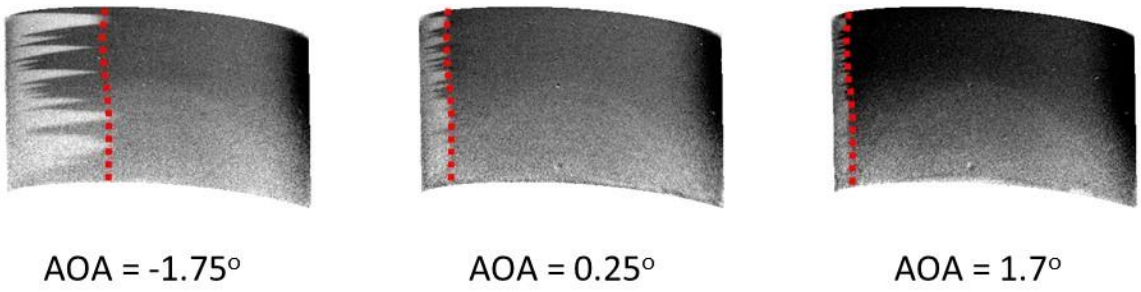

Figure 10. TSP transition images at M = 0.5. The red line demotes approximate transition location.

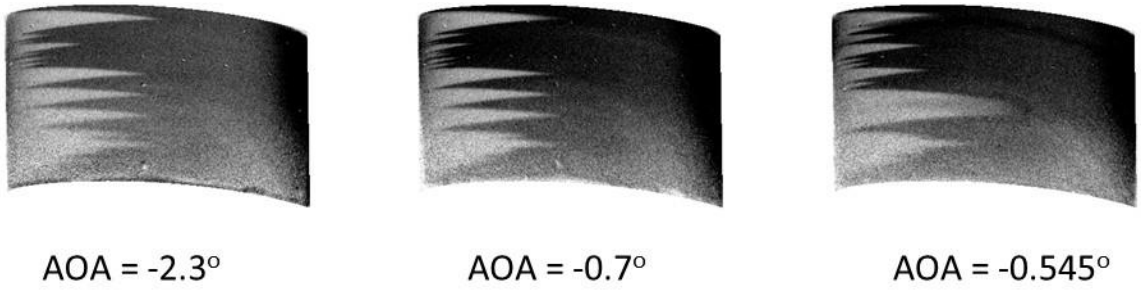

Figure 11. TSP transition images at M = 0.67.

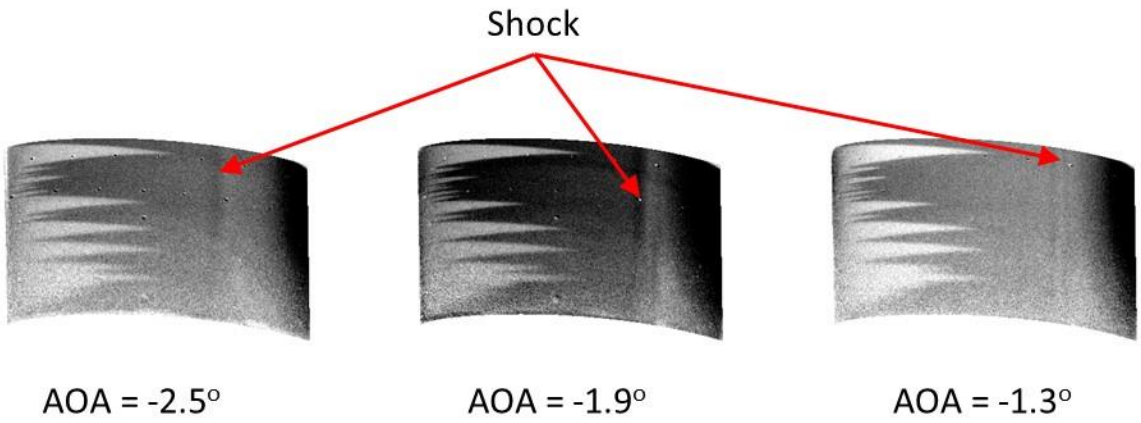

Figure 12. TSP transition images at M = 0.74. Possible shock locations are also indicated.

be expected).

Results for the case at M = 0.5 taken at a tunnel temperature of 116 K is shown in Fig. 15. For this run, the O_2 concentration could only be increased from ~18 ppm (native to the liquid N_2) to ~550 ppm using the air bottles. While the data is fairly noisy, the general trend of the PSP does qualitatively agree with the pressure tap data (as shone in the comparison plots below each image). However, there are cases where the PSP begins to significantly deviate from the pressure taps. This, as well as the increased noise in the data, is most likely due to the low concentration of O_2 in the flow. Previous testing[7] have shown that

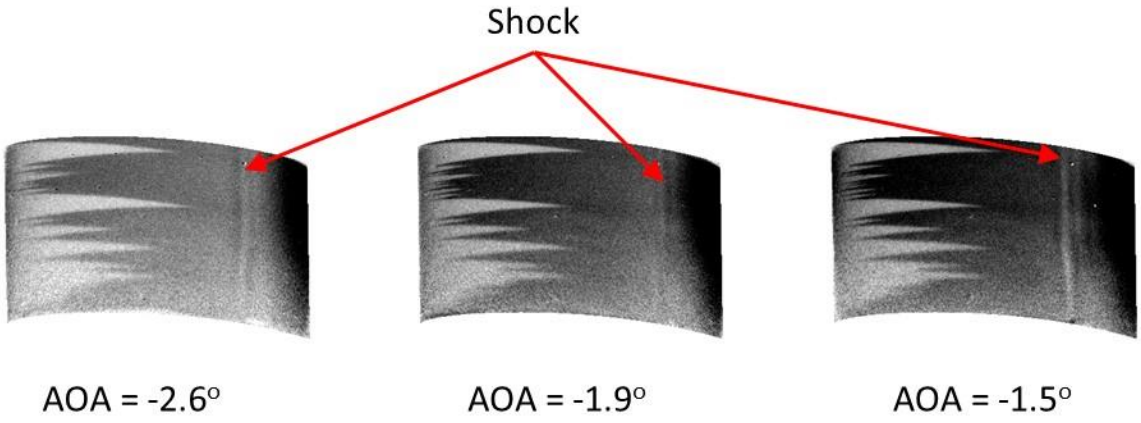

Figure 13. TSP transition images at M = 0.76. Possible shock locations are also indicated.

ideally, a concentration of more than ~1500 ppm is ideal.

When the Mach number is increased to 0.7, the results become better due to the larger pressure gradients on the model. The results are shown in Fig. 16. In these cases, the noise is approximately half that of the M = 0.5 cases and the PSP data does agree more closely with the pressure taps. The separation bubble near the leading edge of the airfoil also becomes very pronounced at the higher angles of attack.

When the temperature of the tunnel is increased to 250 K, it would be expected that the PSP would have better results. This would be mostly due to the temperature dependence of the O_2 diffusion in the

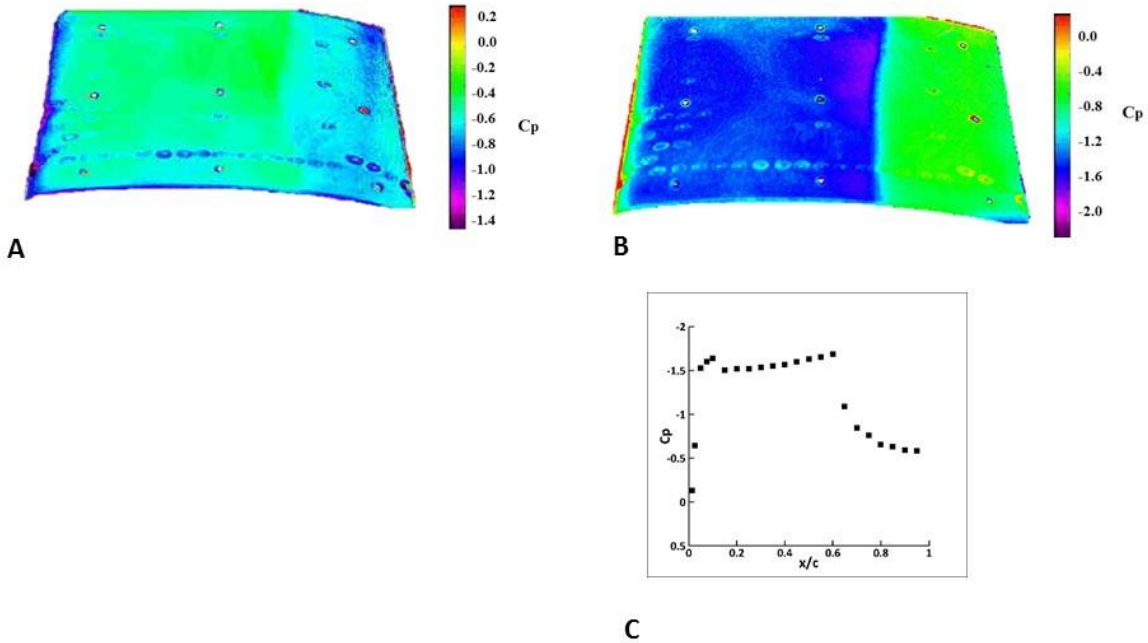

Figure 14. Representative PSP images acquired from the 0.3-m TCT from Ref. 7. (A) Data acquired at T = 168 K, M = 0.7, Re = 12.3 x 10^6/ft, AOA = 2°; (B) data acquired at T = 251 K, M = 0.7, Re = 3.78x10^6/ft, AOA = 2°; (C) pressure tap measurements from (B).

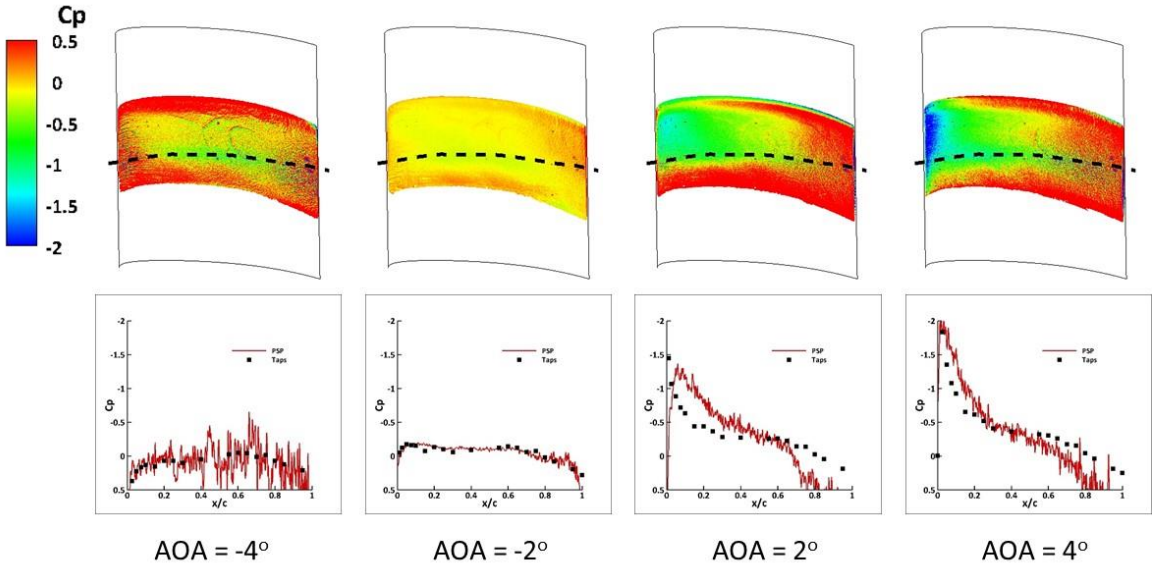

Figure 15. PSP data acquired at T = 116 K, M = 0.5, Re = 9.7 x 10^6/ft. The line in the upper regions denotes the location of a second PSP formulation which exhibited a different calibration and sensitivity.

polymer. Furthermore, with the lower nitrogen injection rates (to achieve the higher tunnel temperature), the O_2 concentration could be increased to almost twice the previous test. The results obtained at M = 0.5 are shown in Fig. 17, and it is readily apparent that the PSP is operating better than at 116 K. The noise in the images have decreased significantly, though there is still some disagreement between the PSP and the taps, especially nearer the leading edge of the model. The cause of this is still under investigation.

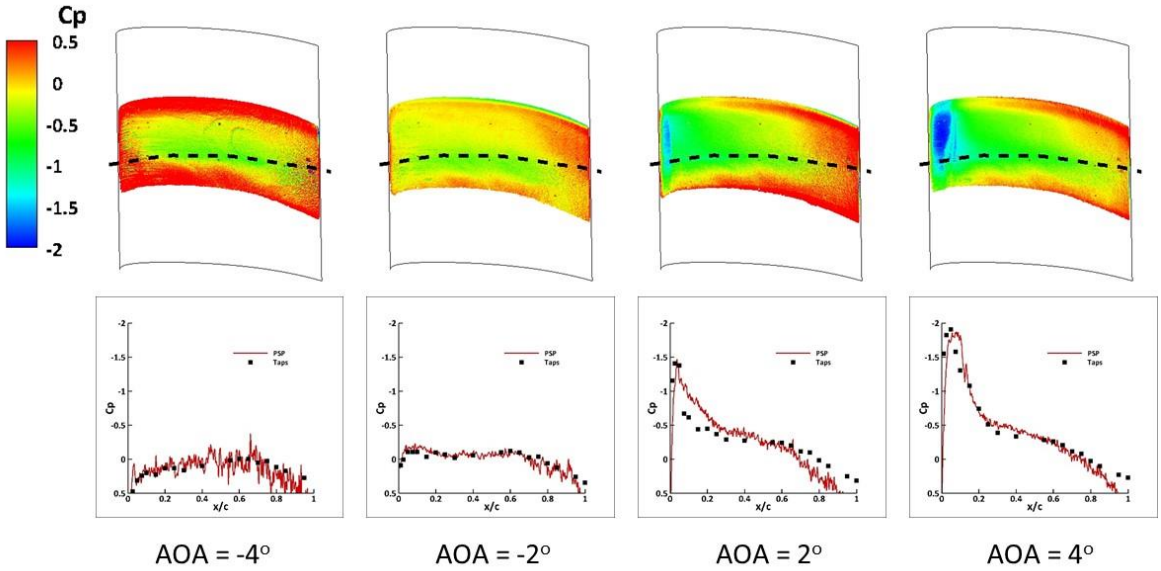

Figure 16. PSP data acquired at T = 116 K, M = 0.7, Re = 12.6 x 10^6/ft. The line in the upper regions denotes the location of a second PSP formulation which exhibited a different calibration and sensitivity.

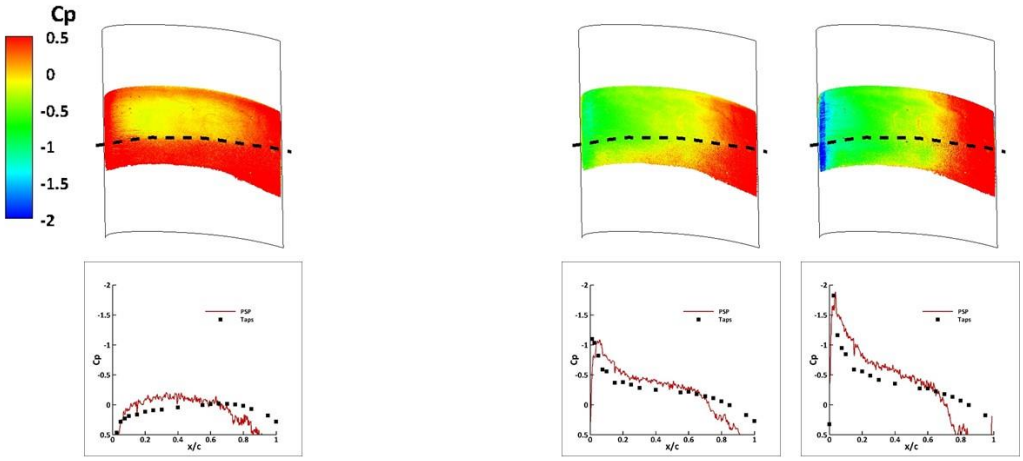

Figure 17. PSP data acquired at T = 250 K, M = 0.5, Re = 3.3 x 10^6/ft. The line in the upper regions denotes the location of a second PSP formulation which exhibited a different calibration and sensitivity.

Regardless, this does show that PSP can be used in a nitrogen tunnel at lower Mach numbers.

The results are significantly improved as the Mach is increased to 0.7, as shown in Fig. 18, with much greater agreement between the pressure taps and PSP (with one notable exception at the most negative angle of attack). The separation region is also well defined. In addition, it can be seen that the second PSP formulation is actually beginning to show response as well, though it does have a different sensitivity (accounting for the apparent differences in pressure in this region).

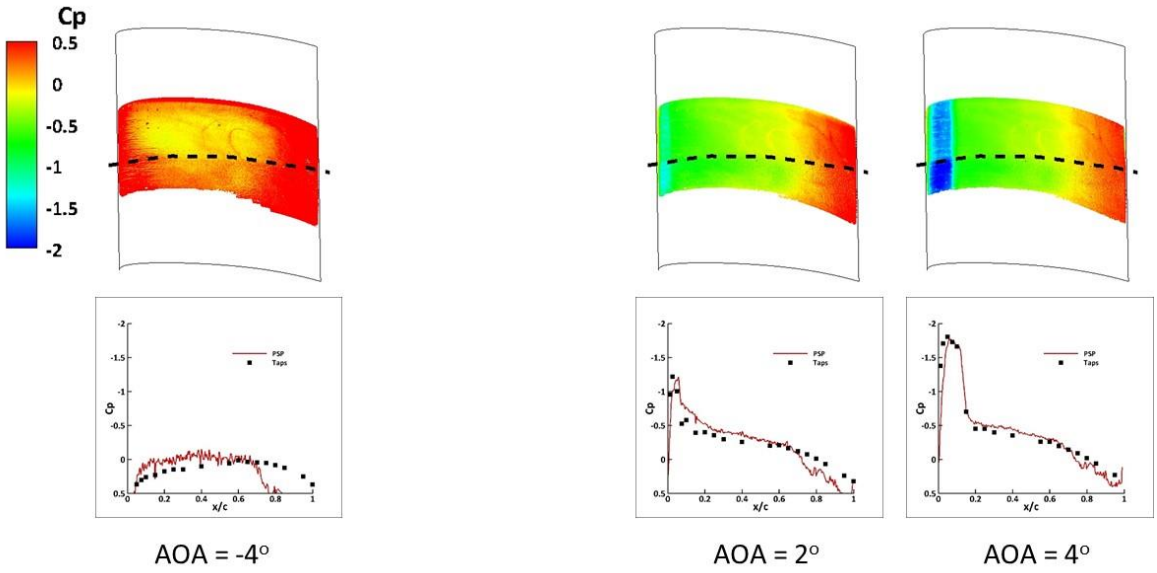

Figure 18. PSP data acquired at T = 250 K, M = 0.7, Re = 4.2 x 10^6/ft. The line in the upper regions denotes the location of a second PSP formulation which exhibited a different calibration and sensitivity.

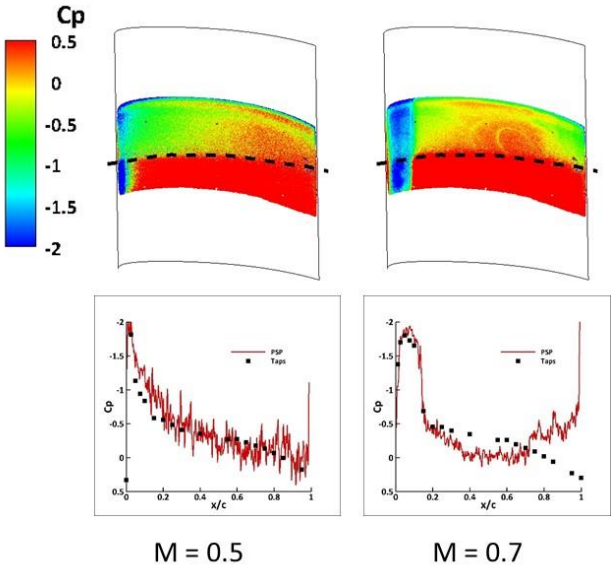

Figure 19. PSP data acquired at T = 250 K with no injection of air. The line in the upper regions denotes the location of a second PSP formulation which exhibited a different calibration and sensitivity.

The greater sensitivity of the PSP at the higher temperatures is almost completely due to the increased diffusion rate of O_2 in the PTMSP binder, with the increased O_2 concentration having a secondary effect. This can be proven as a setoff PSP runs was collected at the higher temperature without any addition of O_2 to the flow. In this case, the native O_2 concentration 35-70 ppm (some change was noticed, most likely due to the final bleed-out of the air from a previous run), and the PSP should have shown little, if any, response. However, as can be seen in Fig. 19, there is a significant PSP response. While it is higher in noise than the previous runs, the separation bubble is evident at both speeds, and the PSP data has a fair

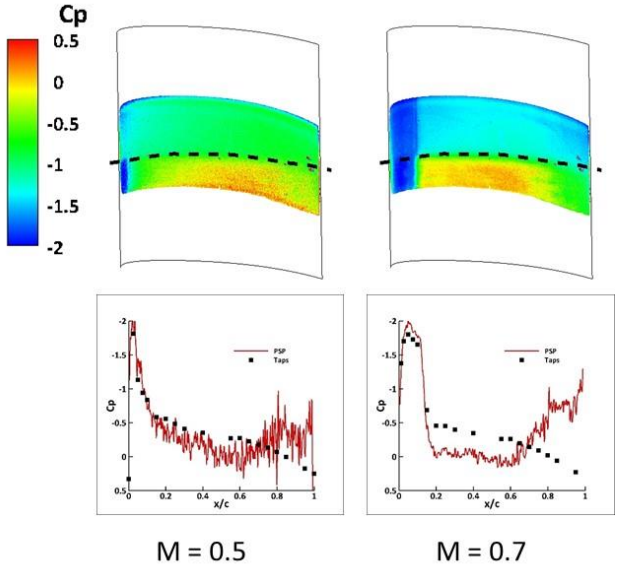

Figure 20. PSP data acquired at T = 250 K with no injection of air. This is calibrated using the second PSP formulation (below the dotted line).

qualitative agreement with the taps. One other observation to note is that the second PSP formulation seems to have a significantly different response. To investigate this, the images were calibrated with regards to the second PSP formulation, and the results are shown in Fig. 20. While noisier than the first PSP formation, the results are fairly similar.

There is one final observation that needs to be made. There is a significant difference in the airfoil performance between the 1990s and this test. This is readily apparent by simply observing the pressures measured by the taps in Fig. 14c and comparing with the pressures measured in this experiment. Therefore, a meaningful direct comparison between this data and the previous data cannot easily be made. Regardless, this work has shown that PSP has been successfully reintroduced to the 0.3-m TCT.

5. Conclusions and Future Work

This report has presented results from two recent tests at the 0.3-m TCT in order to re-introduce the optical paint techniques back into the facility. This required essentially re-learning the techniques due to several factors, including the loss of experience and the need to implement newer technologies. These factors were overcome and the results of the tests were both successful. Hopefully, this report will serve as a means to convey the knowledge and experience gained in these tests for possible future work conducted in this facility.

For the TSP test, the detection of transition points had some success but also had several issues. These issues involved the generation of an excessive number of transitional wedges on the surface which made the accurate determination of the transition point difficult to accurately determine. Transitional wedges are usually formed by surface roughness, and this could very well be one of the causes of their formation, even though the surface of the TSP was worked to as smooth a finish as possible. There were no edges on the leading edge, as the TSP was applied around the leading edge to a point ~20% of the chord on the underside of the airfoil. Another possibility could be debris from the tunnel flow, and there is evidence that this indeed caused a significant amount of the wedges, mostly from the fact that the wedge origination points are not consistent from one run to another. If this was truly due solely to the finish of the paint, then it could be assumed that the vast majority of the wedge origination points would be consistently in the same place, especially given the fact that there was no access to the model between runs. Regardless, this test showed that the mounting strategy for the lights and camera was viable, the methodology to produce the temperature steps was correct, and the overall performance of the TSP for capturing the temperature changes was sufficient to easily visualize the flow phenomena on this surface.

Extension of this testing to PSP was then done using a supercritical airfoil shape. For the PSP, the addition of a suitable means to introduce O_2 to the flow as well as measure the concentration was required. This was done using existing plumbing connections in the tunnel (i.e. no physical modification of the facility was needed), and seemed to provide an adequate solution to the problem. One issue that was encountered was that using the air injection system designed for this experiment, the overall concentration of O_2 that could be introduced was significantly less than ideal (at most about half of what was used in previous testing in the 1990s.[7] This resulted in some added noise to the images (especially in the Mach 0.5 cases), but there was a generally good agreement between the pressure taps and PSP. For the faster speeds, the PSP data was less noisy (due to the larger pressure gradients on the model). When the temperature was increased from 116 K to 250 K, the results were much better due to the increased rate of diffusion of O_2 in the PTMSP binder. This was proven as a set of data was acquired at 250 K that had less than 100 ppm O_2 in the flow, and adequate results could still be obtained.

Even with these results, there are several areas that can be further optimized for improved results. These include the need to improve the final TSP coating, investigate some new lighting techniques, trying to increase the O_2 concentration in the tunnel, and the development of newer, more sensitive cryogenic PSP formulations. Some ideas for each of these areas will be briefly discussed below.

Further development of the TSP application and treatment of the final coating will continue to obtain as smooth a coating as possible. However, this will most likely not completely alleviate the transitional wedge problem if there is debris or contamination from the tunnel flow. The TSP formulations that are currently available have good sensitivity throughout the possible temperature ranges of the 0.3-m TCT, so no further development of these needs to be done.

One of the issues that needs to be addressed is the illumination of the model. While the LED-based lighting that was used in these tests is significantly better in terms of brightness, stability, and energy consumption than the quartz-halogen lamps used in the previous tests, the quartz-halogen lamps had a significant advantage in that they could be placed in tunnel plenum and able to illuminate the airfoil surface from the top. This allowed for a much brighter illumination field on the model surface compared with this testing, which had the LEDs imaging the surface through the periscope assembly. In their current configuration, the LED lights cannot be placed in the cryogenic environment inside the plenum for several reasons. First, mechanically, they are not designed for this environment, and several components that are epoxied will most likely delaminate. Second, LEDs do not operate natively in cryogenic environments. Light generation by an LED is accomplished through the interaction of electrons with electron-holes that are generated in a semiconducting material with impurities. As the temperature is lowered, the current required to generate the photons (through these electron and electron-hole interactions) is generally increased to overcome the increasing band gap. Eventually, this band gap becomes too large and no photons are generated. This issue was solved in the NTF using specially designed LED arrays, as shown in Fig. 21.[8,25] Briefly, these arrays consist of 80 individual LED elements arranged on a 12.7 cm diameter 4.5 m thick aluminum substrate. The aluminum substrate is also equipped with an RTD sensor to monitor temperature as well as resistive heaters on the back for cryogenic operation. Employing these above the test section should allow a better illumination field as well as provide more freedom to position the camera to conceivable image more of the surface.

If the current generation of cryogenic PSP formulations are employed, the O_2 concentration in the tunnel will need to be increased to improve results. There are several possible solutions to this. First, the tube connecting the air bottle to the injection point could be increased to increase the flow rate. This would necessarily increase the O_2 concentration (by a factor of ~4 if the tube diameter is doubled), though the air bottles would be used at a much faster rate (by the same factor of ~4). Another alternative would be to replace the air cylinders with cylinders of O_2 gas. This would increase the concentration of O_2 be a factor of ~5 without any other modifications. However, this does introduce potential safety issues that will

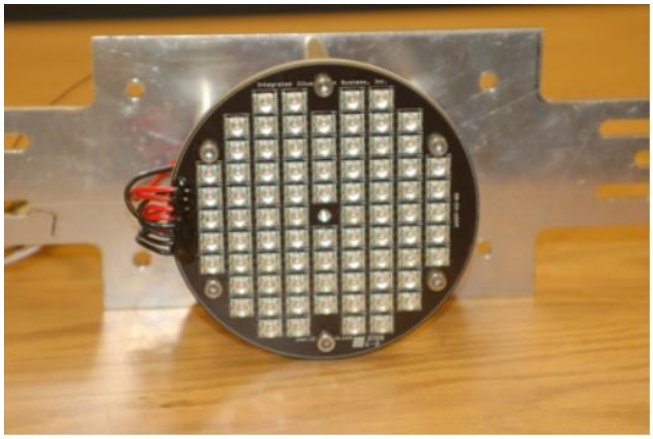

Figure 21. LED-based arrays custom designed for use in the National Transonic Facility. From Ref. 8.

need to be addressed at both the injection point as well as the storage location for the cylinders. Finally, instead of using gas cylinders, the injection could be tied directly to the air line from the NASA steam plant. This method was recently used at the National Transonic Facilit[8] without any direct evidence of frost generation (from water introduced with the air).

Finally, while the current generation of cryogenic PSP formulations can provide suitable data, formulations that have a higher sensitivity to O_2 will probably need to be developed. This could involve optimization of two components of the PSP. First, the development of a binder that has an even greater permeability to O_2 can be realized to enhance sensitivity. However, the PTMSP has been shown to have one of the highest O_2 permeability currently, so this could be a difficult task to accomplish. Alternately, the Pt(TfPP) dye could be replaced with another dye that would show greater sensitivity. This would most likely require the new dye to have a significantly longer lifetime than Pt(TfPP). Several candidate luminophores have been identified and testing of these is currently underway.

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14. ABSTRACT

Recently both Pressure- and Temperature-Sensitive Paint experiments were conducted at cryogenic conditions in the 0.3-m Transonic Cryogenic Tunnel at NASA Langley Research Center. This represented a re-introduction of the techniques to the facility after more than a decade, and provided a means to upgrade the measurements using newer technology as well as demonstrate that the techniques were still viable in the facility. Temperature-Sensitive Paint was employed on a laminar airfoil for transition detection and Pressure-Sensitive Paint was employed on a supercritical airfoil. This report will detail the techniques and their unique challenges that need to be overcome in cryogenic environments. In addition, several optimization strategies will also be discussed.

15. SUBJECT TERMS

Cryogenic testing; Global surface measurements; Pressure sensitive paint; Temperature sensitive paint

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