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Results From a Pressure Sensitive Paint Test Conducted at the National Transonic Facility on Test 197: The Common Research Model

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Abstract

This report will serve to present results of a test of the pressure sensitive paint (PSP) technique on the Common Research Model (CRM). This test was conducted at the National Transonic Facility (NTF) at NASA Langley Research Center. PSP data was collected on several surfaces with the tunnel operating in both cryogenic mode and standard air mode. This report will also outline lessons learned from the test as well as possible approaches to challenges faced in the test that can be applied to later entries.

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 the comparison with computational fluid dynamics (CFD) predictions. Conventional pressure measurements are based on pressure taps and electronically scanned pressure transducers. While these approaches provide accurate pressure information, pressure taps are limited to providing data at discrete points. Moreover, the integration of a sufficient number of pressure taps on a surface can be time and labor intensive and add significant expense to the model.

Using pressure sensitive paint (PSP) allows for the accurate determination of pressure distributions over an aerodynamic surface and is based on an emitted optical signal from a luminescent coating. As originally developed,¹⁻³ this technique was primarily useful for mean pressure measurements at transonic and higher flows, but has since been adapted to lower speed flows⁴⁻⁶ as well as measurements of fluctuating pressures.^{7,8} A number of review articles cover the topic in detail.⁹⁻¹¹ PSP measurements exploit the oxygen (O₂) sensitivity of luminescent probe molecules suspended in gas-permeable binder

materials. In wind tunnel applications, the PSP is applied to the model by conventional paint spraying techniques. Light sources such as UV LED arrays are mounted external to the test section to illuminate the painted model and effect luminescence emission from the entrapped oxygen-sensitive molecules. For the majority of pressure paints, PSP emission occurs in the red or orange region of the visible spectrum (~580 - 650 nm). The intensity is inversely proportional to the amount of oxygen present such that brighter regions in the paint emission indicate lower concentration of oxygen (and thus lower pressure) relative to the darker regions. Scientific-grade CCD cameras with spectral band-pass filters to discriminate between the excitation (blue) and emission (orange) signals, capture the intensity image of the PSP-coated model surface, providing a means to recover global surface pressure distributions on test articles of interest. PSP measurement systems all employ a ratio of image pairs to compensate for intensity non-uniformity due to sources other than oxygen concentration, the most significant of which are paint application and illumination heterogeneity. In the conventional approach, PSP images acquired either prior to or immediately following tunnel operation (wind-off) are ratioed with images acquired at each tunnel condition (wind-on). A companion technique, temperature sensitive paint (TSP), uses probe molecules whose brightness varies with temperature, but which are insensitive to oxygen concentration.

If the test surface under study is immersed in an atmosphere containing O₂ (e.g. air), the recovered luminescence intensity can be described by the Stern-Volmer relationship¹²

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

where I_0 is the luminescence intensity in the absence of O₂ (i.e. vacuum), I is the luminescence intensity at some partial pressure of oxygen P_{O_2} , and K_{SV} is the Stern-Volmer rate constant. The value of K_{SV} depends on the properties of both the luminescent molecules and the binder, and is generally temperature dependent. Since it is a practical impossibility to measure I_0 in a wind tunnel application, a modified form of the Stern-Volmer equation is typically used. This form replaces the vacuum calibration (I_0) with a reference standard

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

where I_{REF} is the recovered luminescence intensity at a reference pressure, P_{REF} . A and B are temperature dependent constants for a given PSP formulation and are usually determined *a priori* using laboratory calibration procedures. The calibration and interpretation of TSP data follows a similar procedure, using the TSP luminescence intensity recovered at a reference temperature.

PSP measurements are difficult to make under cryogenic conditions for two reasons. First, the test gas is typically nitrogen, refrigerant, or some other medium that usually 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. As such, it is not surprising that initial cryogenic testing with luminescent paints used TSP.¹³ Indeed; probe molecules can be found which respond strongly to temperature even under cryogenic conditions.

For PSP, researchers developed two distinct methods to overcome the challenges caused by the low diffusion of oxygen into the paint binder. Initial cryogenic PSP tests were conducted using anodized aluminum.¹⁴ In these tests, the model was constructed from aluminum and anodized to coat the surface with a monolayer of aluminum oxide. Then the model was coated with an oxygen luminophore that chemically bonds with the aluminum oxide. This produces a coating that is essentially a few molecules thick, thus alleviating the issues with paint binders and oxygen diffusion. The disadvantages to this

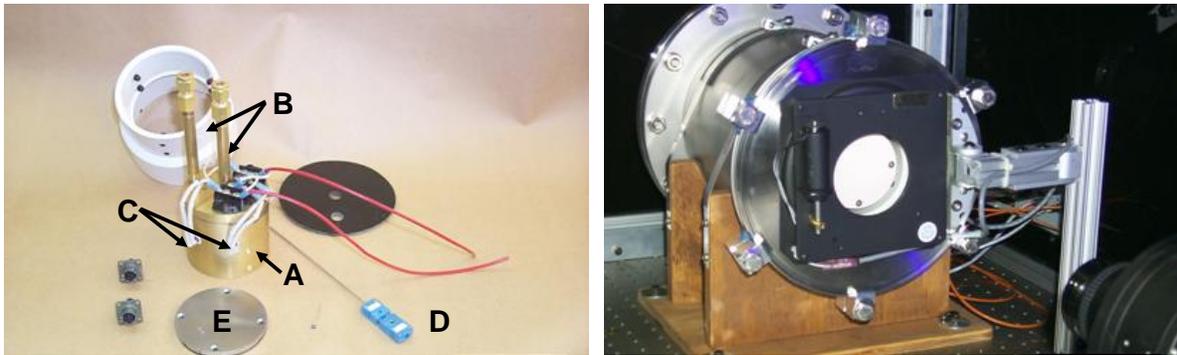


Figure 1. Calibration chamber for cryogenic PSP and TSP formulations. The left picture depicts the interior of the chamber including the brass block (A), the inlet and outlet for liquid nitrogen flow (B), the resistive heaters (C), the thermocouple for temperature monitoring and control (D), and an unpainted coupon (E). The right picture shows the complete calibration chamber with a coupon and the external shutter open.

technique are that the anodizing requirement makes it difficult to use with large and complex models, and it cannot be used with the stainless steel models that are typically employed in large-scale cryogenic testing. For this testing, a PSP formulation consisting of a binder that has a very large diffusion rate and can be applied with standard airbrush techniques and capable of adhering to many different types of surfaces was developed.^{15,16} These formulations have been used successfully at the NASA Langley 0.3-Meter Transonic Cryogenic Tunnel¹⁵ as well as other facilities.¹⁶ A variation of the PSP technique has been performed at the NTF with this formulation to visualize surface flow patterns on a blended wing body model,¹⁷ and preliminary testing of cryogenic PSP at the European Transonic Windtunnel has also been reported.¹⁸ Recently, a full cryogenic PSP test has also been reported at the NTF on a traditional commercial transport wing.¹⁹

Experimental

Paint Formulations

Two separate PSP formulations were used for this test depending on the operating conditions of the tunnel. In both formulations, the oxygen sensitive luminophore platinum meso-tetra(pentafluorophenyl)porphine, or Pt(TfPP), was dissolved in an appropriate oxygen-permeable binder. In the cryogenic testing phase, this binder was polytrimethylsilylpropine, PTMSP,^{15,16,20} chosen because it is a glassy polymer with a large free volume, enabling it to have a high oxygen diffusion rate. This leads to high oxygen permeability even at cryogenic conditions. For the air mode operation of the tunnel, the binder is made from a co-polymer of trifluoroethylmethacrylate and isobutylmethacrylate (FEM).²¹

Paint Calibration

All paint calibrations were performed separate from the wind tunnel in a laboratory calibration chamber. The chamber cell, shown in Figure 1, consists of a brass block (A). Temperature control of the block is accomplished by flowing liquid nitrogen into the block through milled channels internal to

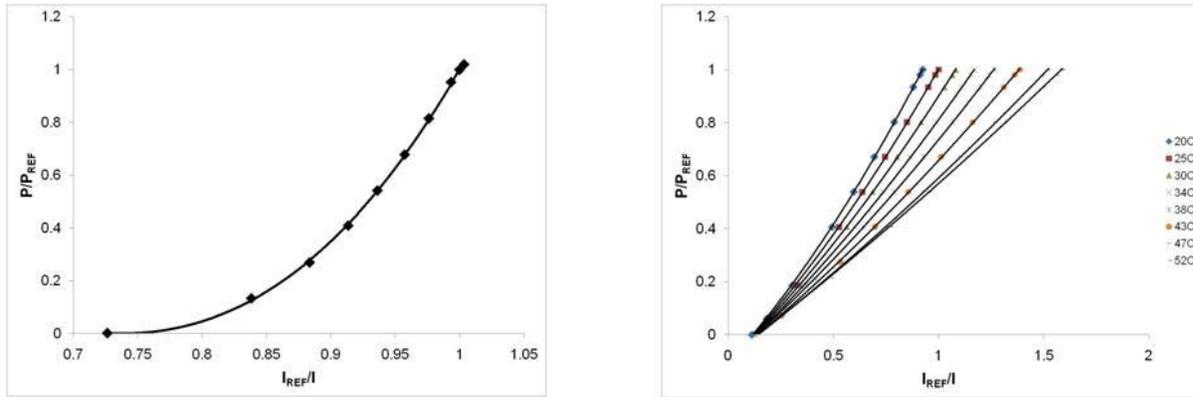


Figure 2. Typical calibration curves for PSP under cryogenic conditions (left) and standard air conditions (right).

the block (B) and heat is applied via resistive heaters (C) imbedded in the block. A thermocouple (D) is also imbedded into the block, which serves as the sensor input to a proportional-integral-derivative (PID) controller capable of regulating both the amount of liquid nitrogen flowing to the cell (via a hardened solenoid valve) and the amount of heat applied. A painted coupon (E) is bolted to the front of the block and thermal contact is ensured using a silicon-free thermal compound. Pressure is controlled by sealing the block in a chamber equipped with a quartz window. An external shutter is affixed to the window to reduce photodegradation of the paint. The chamber is also placed inside a dark enclosure to minimize background illumination. The cell is capable of operating from vacuum to room atmosphere and to temperatures as low as $-196\text{ }^{\circ}\text{C}$ ($-321\text{ }^{\circ}\text{F}$, boiling point of liquid nitrogen) to $\sim 100\text{ }^{\circ}\text{C}$ ($212\text{ }^{\circ}\text{F}$). Illumination of the painted coupon is achieved using a 400 nm LED array and luminescent images are acquired using a CCD camera equipped with a band-pass filter to block excitation light. For cryogenic PSP calibration, oxygen-nitrogen gas mixtures were used to mimic the expected condition in the test section. For air mode operation, dried air was used as the calibration gas. A typical PSP response at cryogenic conditions to increasing pressure of a 3000 ppm oxygen-nitrogen mix is shown in the left of Figure 2 and a typical PSP response for air is shown in the right of Figure 2.

Facility

The NTF is one of the world's leading facilities for providing high quality flight Reynolds number aeronautical data and has been operational since 1982. The tunnel has a test section of 2.5 m x 2.5 m (8.2 ft x 8.2 ft) and is capable of operating at speeds from subsonic ($M = 0.1$) to transonic ($M = 1.1$) with Reynolds numbers from $13.1 \times 10^6/\text{m}$ ($4 \times 10^6/\text{ft}$) to $476 \times 10^6/\text{m}$ ($145 \times 10^6/\text{ft}$) at transonic Mach numbers. The tunnel is capable of operating in either air mode at elevated pressure and temperature or at cryogenic conditions (to $-156\text{ }^{\circ}\text{C}$ or $-249\text{ }^{\circ}\text{F}$) by injecting liquid nitrogen into the tunnel circuit. In the cryogenic operating mode, the NTF is capable of providing full-scale flight Reynolds numbers without an increase in model size. Several optical diagnostic techniques are available in the NTF, including Video Fluorescent Minituft Flow Visualization, Sharp Focusing Schlieren Flow Visualization, Video Model Deformation, and a newly designed and installed PSP/TSP system.

For the cryogenic portion of the test, air injection was accomplished using a valve to regulate the amount of dry air (dew point $< -60\text{ }^{\circ}\text{C}$) introduced into the tunnel. Numerical studies of the flow at the

NTF estimated that approximately 0.9 kg/s dry air would be required to achieve an oxygen concentration of 1000 ppm in the flow at a tunnel temperature of -156 °C (-249 °F) and pressure of 275 kPa (40 psi). Little if any tunnel heating effects were observed using these magnitude flow rates, as determined by the negligible temperature changes noted in the flow. This could be expected as liquid nitrogen is introduced to the flow under these conditions at approximately 130 kg/s. Oxygen monitors (described below) were interfaced into the tunnel and monitored to determine when and how much air would be introduced.

Model

The model is a full-span 0.027 scale model incorporating a wing design based on an open geometry. The overall design of the model is a joint effort between NASA and several other partners to provide a common platform that can be tested in a variety of facilities using a plethora of techniques. The entire model has a finish of approximately 0.2 μm and is mainly composed of stainless steel.

Previous cryogenic PSP¹⁵ and TSP²² tests have shown that highly polished stainless steel models must first be painted with a basecoat before the PSP will adhere to the model. For this test, SpectraPrime (Sherwin Williams) was chosen as the basecoat. Previous tests have shown this paint to be very robust to cryogenic conditions. After curing, the basecoat layer was sanded with 1500-2000 grit paper, which was needed to promote adhesion of the PSP layer. Finally, the PTMSP PSP was applied to the model. The PTMSP PSP could be easily removed by wiping with toluene, allowing for either a re-coating of the cryogenic PSP or re-using the basecoat for the air mode PSP (FEM). However, removal of the FEM PSP cannot be accomplished in such a way that will leave the basecoat intact.

Instrumentation

Illumination: Illumination was achieved using several custom designed LED-based arrays capable of operating at either room temperature (for NTF air model operation) or at cryogenic conditions. The arrays consisted of 80 individual LED elements arranged on a 12.7 cm diameter 4.5 mm 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. The LED arrays are operated using a 1kW switching power supply and can be remotely operated using standard TTL (transistor-transistor logic) pulses. The LED array produces light centered at 400 nm (~20 nm full width at half maximum) at greater than 80 W under nominal forward current conditions. This can also be manually adjusted as needed by controlling the current applied to each array.

Image Acquisition: Images were acquired from cameras placed directly over and under the model. The cameras employed were thermoelectrically-cooled monochrome interline transfer CCD cameras employing 11 Mpixels (4000 x 2672) capable of acquiring images at up to 5 fps at full resolution. The cameras employ an electronic shutter alleviating various frame transfer issues that were seen previously when cameras using mechanical shutters were used. This allows for operation where the LED illuminators are on constantly, alleviating some electrical and timing issues seen previously. The cameras employ 12-bit digital resolution and were interfaced to the computer using custom designed armored fiber optic cables capable of operating at cryogenic temperatures.

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 control loop. Two oxygen monitors were attached to outlets of pressure ports, one from a static port in

the floor and one from a dynamic port in a small pressure rake. Both were mounted approximately 4.5 m forward of the model. The oxygen sensor system employed a zirconium oxide sensor with a time response of less than 10 s. The system was also equipped with an *in situ* calibration option allowing it to maintain linearity and repeatability of less than 2% or reading or 0.5 ppm O₂ absolute. The unit is controlled by a personal computer via RS-232 protocol.

Data Acquisition

For cryogenic operation of the tunnel, data acquisition was performed using a modification of the typical procedure described above. Introduction of dry air into the tunnel was first performed using a valve and the oxygen concentration was monitored until it stabilized. Then wind-off images were acquired at various angles of attack (from 0 to 4 degrees) with a wind speed of ~Mach 0.09 (to ensure adequate circulation of the oxygen). It is realized that this causes as much as 1% error in the pressure measurements. After the initial set of wind-off images were acquired, wind-on images were acquired at the same angles of attack and at various speeds (Mach 0.7, 0.85, and 0.87). The oxygen concentration was continuously monitored and when it began to decrease significantly, more air was introduced to re-establish the baseline value. Wind-off images also were acquired immediately following the last wind-on image. For air mode operation of the tunnel, the standard wind-off/wind-on technique was employed as described in the section above.

Results and Discussion

Cryogenic PSP Results

The basecoat for all of the PSP experiments was applied while the model was installed in the test section. This allowed for the pressure ports to be purged with air, as well as prevented excessive handling of the model that would have occurred if it had to be installed after painting. This first cryogenic PSP coating was then applied in the test section and then the tunnel was purged with nitrogen and prepared for cryogenic operation. After sufficient cooling and treatment, the PSP data was collected and showed unexpected results, including what can only be described as turbulent wedges, as seen in left of Figure 3. These wedges are reminiscent of the turbulent wedges that can be seen in some TSP experiments. However, the image shown in Figure 3 is that of a reference image (pseudo wind-off image taken at Mach ~0.09), which should have little if any temperature effects due to flow. Some sort of irreversible change occurred in the cryogenic PSP that has caused this pattern to occur, which unfortunately overwhelmed any pressure sensitivity of the paint. This necessitated re-painting the model, which was accomplished by simply removing the top layer of PSP using toluene and reapplying a new active layer.

The second layer was applied by inserting the access housing into the tunnel, thus alleviating the need to purge and cool the majority of the tunnel circuit. Thus, the second coating could be tested shortly after completion (requiring only the tunnel temperature to be re-established at ~-150 °C. This coating still showed some of the wedge effect, evident near the leading edge (see the right image of Figure 3). Still, an *in situ* calibration was performed on the PSP using a selection of pressure taps that were visible on the upper portion of the port wing. Specifically, taps from rows “C”, “D”, “F”, and “H” (according to the mechanical drawings on the wing) were employed as the larger pressure gradients should be present in these areas. A complete angle of attack sweep at Mach = 0.85 (run 124) is shown in Figure 4, along with the comparison with the taps in row “G” (not used for calibration). Unfortunately, the PSP data shows some very large noise characteristics and cannot quite follow the tap readings at the leading or trailing



Wind-off Run 119



Wind-off Run 126

Figure 3. Cryogenic wind-off images showing “wedges” which are permanently imposed in the paint. The left image is from run 119 (the first cryogenic PSP application) and the right image is from run 126 (the second cryogenic PSP application).

edge (which could be due to the wedge effect seen in Figure 3, as well as increasing oblique angle due to curvature, especially at the leading edge). However, even with these issues, the PSP measurements are within 30% error compared with the pressure taps. Solving some of these issues should reduce this error to within 10% or less agreement with the taps. Several improvement strategies for the cryogenic PSP will be presented in a future section. Also, it should be noted that all of the data has been analyzed, but only the sample data was provided for brevity.

Air Mode PSP

After the cryogenic testing, the tunnel was warmed to ambient conditions and the cryogenic PSP layer was removed with toluene. After drying, the FEM PSP was applied and allowed to dry for a couple of hours while the tunnel was prepared for operation. For these runs, the exact same angles of attacks and speeds were employed as for the cryogenic runs. Using air mode and elevated temperatures and pressures allowed testing at a Reynolds numbers of approximately $26 \times 10^6/\text{m}$ ($8 \times 10^6/\text{ft}$) as opposed to the cryogenic testing, which used a free stream Reynolds number of approximately $105 \times 10^6/\text{m}$ ($32 \times 10^6/\text{ft}$). However, even with these differences, the qualitative behavior of the wing should be expected to be similar across the two regimes.

Even with the elevated temperatures and pressures employed in air mode, the PSP retains much of its sensitivity. However, the luminescence signal of the paint is significantly quenched, requiring exposure times about ten times larger than that needed for the cryogenic testing. Thus, only two images were able to be acquired during a point as opposed to ten images in the cryogenic testing. Moreover, calibration of the images was accomplished using the same procedure (and same taps) as in the cryogenic mode of operation. These results (as well as tap comparisons to row “G”) are shown in Figure 5. The run at Mach = 0.85 (Run 138) was chosen for comparison with the cryogenic data. The PSP data looks much cleaner in this mode of operation, though the wear on the basecoat is beginning to be seen as certain physical features of the model are easily seen (most notably, the body filler used in certain portion of the wing). Similar to the cryogenic PSP testing, the PSP cannot quite follow the pressure taps at the leading edge,

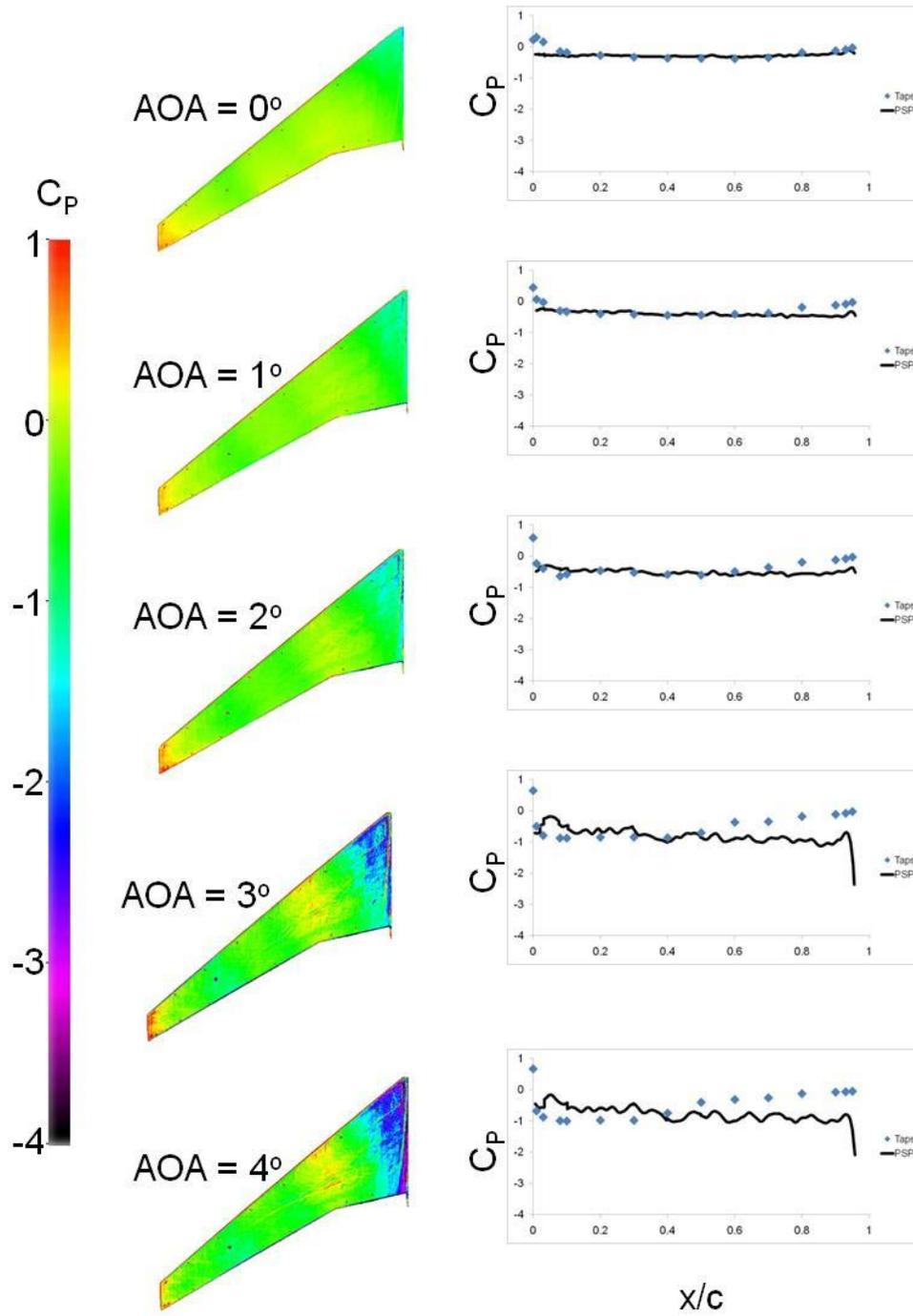


Figure 4. PSP results from run 124 with corresponding pressure tap comparison. Conditions are $M = 0.85$, $T = -156\text{ }^{\circ}\text{C}$ ($-249\text{ }^{\circ}\text{F}$), $P = 124\text{ kPa}$ (18 psi), $Re = 105 \times 10^6/\text{m}$ ($32 \times 10^6/\text{ft}$).

but this is most likely due to the oblique angle between the camera and the surface at the leading edge. If these taps are removed from the fit, then the PSP data agrees well within 5% of the pressure tap values.

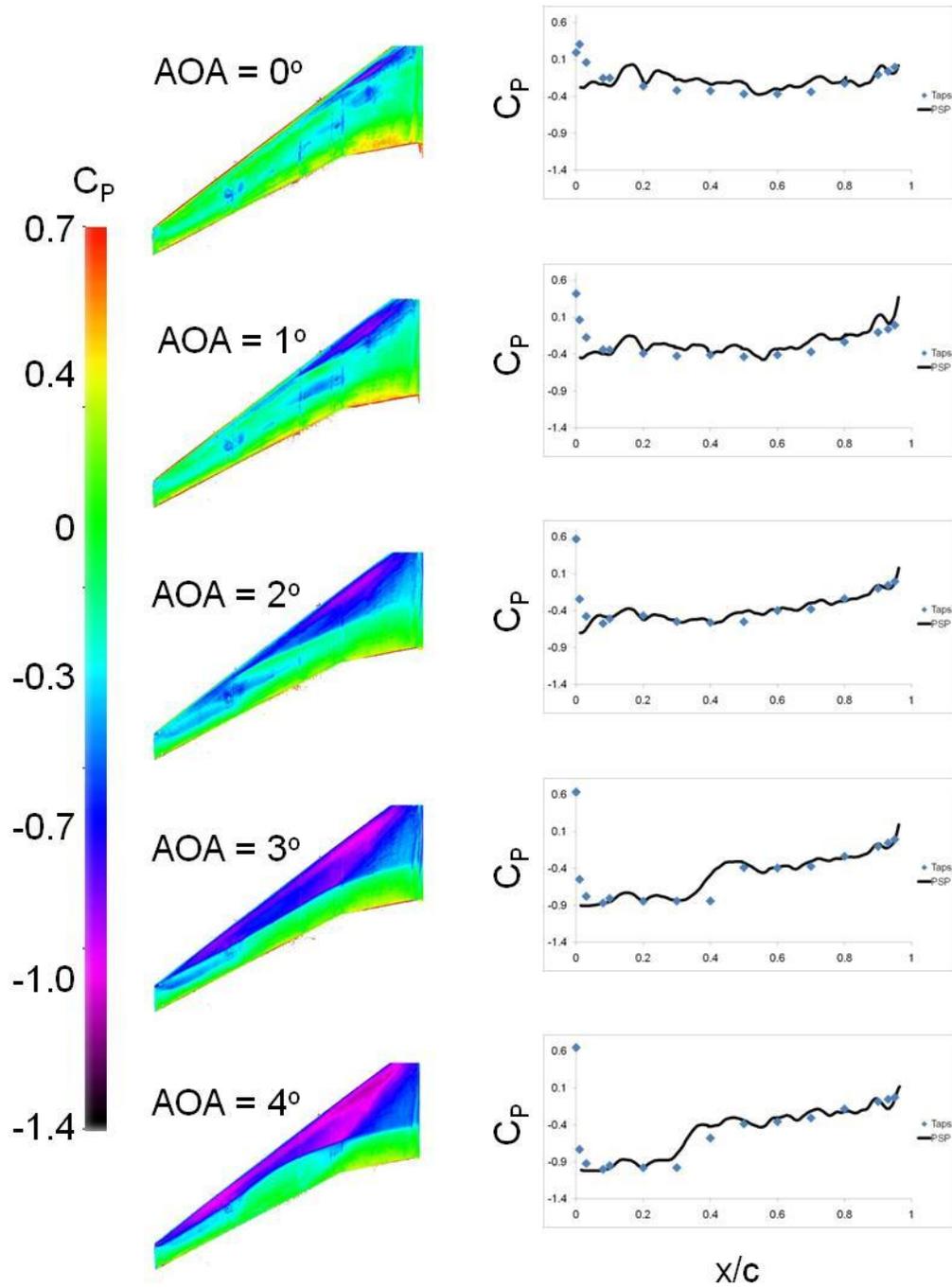


Figure 5. PSP results from run 138 with corresponding pressure tap comparisons. Conditions are $M = 0.85$, $T = 50\text{ }^{\circ}\text{C}$ ($122\text{ }^{\circ}\text{F}$), $P = 124\text{ kPa}$ (18 psi), $Re = 26 \times 10^6/\text{m}$ ($8 \times 10^6/\text{ft}$).

Proposed Improvements/Lessons Learned

While this test was used to build upon the previous test and used several improvements that were

identified, additional improvements in the process, paint, and instrumentation need to be investigated to ensure the technique PSP technique is effective at cryogenic conditions. The data in air mode seems to agree quite well with the pressure tap values, and the sensitivity of the paint is also quite sufficient for testing in this regime. This should be expected because of the legacy of PSP measurements in this pressure and temperature regime.

Improvements in the process entail mostly application of the cryogenic PSP. The cryogenic PSP formulation is notorious for being highly application dependent, and is not sprayed in the traditional manner. Most paint formulations are sprayed to give an even, almost “wet” coating to ensure a good application. However, the cryogenic PSP formulation requires a dry-type of spray; the PTMSP needs to be applied so that the majority of the solvent evaporates before the polymer impact the surface. This causes the PTMSP to be applied as island-like structures that ensure that the porous nature of the polymer remains intact. However, if the PTMSP is not sprayed dry, then the polymer tends to coalesce and form a continuous layer that has similar oxygen permeability as the FEM. Thus, the oxygen sensitivity at cryogenic temperatures is lost as the barrier to oxygen diffusion becomes too great. Additionally, the basecoat applied to the model (SpectraPrime) does have an influence as well, and there were portions of the model that had a thinner basecoat than others. This could lead to issues with spraying and with general interactions of the PTMSP and the SpectraPrime. While it is relatively simple to apply this to test coupons, great care must be taken in applying this formulation to larger areas on the model. The only real solution to this is practice by the appropriate personnel. This practice would just be in the spraying technique, and does not require a full wind tunnel test; large sheets of aluminum flashing could be painted and portions of the aluminum calibrated to provide a measure of the sensitivity across large areas.

For the cryogenic PSP formulation itself, a better grasp of the curing requirements needs to be ascertained as well as any effects of water (ice) contamination on the paint itself. One theory of the wedge formation that appeared in the first cryogenic application was due to contamination from the tunnel itself. Unfortunately, none of the traditional “frost” detection methods (other than manual surveillance) were employed during the cool down of the tunnel. However, during the second application of the cryogenic PSP, the access housing was used to allow entry into the section, thus keeping the majority of the tunnel under a nitrogen atmosphere. This would greatly reduce the amount of possible moisture contamination from air, and there was a correspondingly lesser amount of wedges that were observed. For this run, the PSP was illuminated, and images acquired during the tunnel cool down phase. The wedges were noticed almost immediately after initiation of the fan for purging, though they did eventually fade away. An alternative theory to the wedge formation is that the PSP itself was not cured completely, and that when flow was introduced during the purge cycle, the turbulence caused an uneven curing of the paint. Traditionally, the cryogenic PSP formulation has cured very quickly (within ten minutes), and this is in the published procedure. However, to test this, laboratory experiments looking at different curing times have been developed and are currently being carried out. These experiments will employ larger areas of aluminum flashing as coupons and samples will be taken and calibrated at varying times after spraying. Other experiments will be devised based on these results.

Throughout the test, several instrument failures occurred, some being terminal while others being temporary. The LED wafers used for illumination gradually decreased in functionality throughout the test (especially the cryogenic portion) and could have caused some of the overall challenges (though it is difficult to say as there is no independent method of measuring illumination on the model). This is most likely due to the method of construction of the circuit boards of the wafers. A new procedure for mounting these into the tunnel has been suggested which should alleviate this failure. Additional failures occurred in the cameras themselves. The cameras employ a coverslip of very thin glass over the CCD sensor. This coverslip fractured in one camera and cracked in another camera during the pressure cycles

of the tunnel itself. This could be alleviated by simply removing the coverslip entirely. While the presence of the coverslip is to prevent condensation on the sensor during thermoelectric operation, the cameras are only operated in a dry environment (dew point < -60 °C), and the thermoelectric cooler cannot approach the dew point to allow condensation to occur. Another alternative would be to design and build environmental chambers that could be pressure sealed, though the optical access in the tunnel could preclude this option.

Conclusions

This report has presented representative PSP data acquired at both cryogenic and standard air mode conditions in the National Transonic Facility. Several issues occurred during the cryogenic portion of the test that resulted in the PSP only able to agree with pressure tap readings to ~30%. In addition, several anomalies in the paint itself were noticed, with the biggest impact being the presence of permanent “wedges” that appeared in paint itself during the purge and cool down cycles. This required a re-paint of the model, which still displayed some of the wedges, though not to the large extent as the first application. Work is currently underway to try and ascertain the origin of the wedges, with the initial focus being on possible contamination from the tunnel circuit or an uncured paint application.

The PSP performed admirably in the air mode phase of the test, in which data was collected at slightly elevated temperatures and pressures. This should be expected, and was borne out with the PSP reading agreeing with pressure tap readings to easily within 5%. For both of these portions of the test, all of the data has been analyzed to near completion (resectioning of the data on the surface will need to be completed after an appropriate surface grid is supplied), and is available upon request. Only a portion was presented here for brevity.

Finally, some of lessons learned and possible improvements for future testing were presented. This will focus on general application techniques, improving and fully understanding the nature of the cryogenic paint, and making general improvements and repairs to the equipment will be emphasized.

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14. ABSTRACT This report will serve to present results of a test of the pressure sensitive paint (PSP) technique on the Common Research Model (CRM). This test was conducted at the National Transonic Facility (NTF) at NASA Langley Research Center. PSP data was collected on several surfaces with the tunnel operating in both cryogenic mode and standard air mode. This report will also outline lessons learned from the test as well as possible approaches to challenges faced in the test that can be applied to later entries.					
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