Measuring Global Surface Pressures on a Circulation Control Concept Using Pressure Sensitive Paint

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Abstract

This report will present the results obtained from the Pressure Sensitive Paint (PSP) technique on a circulation control concept model. This test was conducted at the National Transonic Facility (NTF) at the NASA Langley Research Center. PSP was collected on the upper wing surface while the facility was operating in cryogenic mode at 227 K (-50 ^{o}F). The test envelope for the PSP portion included Mach numbers from 0.7 to 0.8 with angle of attack varying between 0 and 8 degrees and a total pressure of approximately 168 kPa (24.4 psi), resulting in a chord Reynolds number of approximately 15 million. While the PSP results did exhibit high levels of noise in certain conditions (where the oxygen content of the flow was very small), some conditions provided good correlation between the PSP and pressure taps, showing the ability of the PSP technique. This work also served as a risk reduction opportunity for future testing in cryogenic conditions at the NTF.

I. 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 flows[4-6] 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 O_2 (e.g. air), the recovered luminescence intensity can be described by the Stern-Volmer relationship[12]

$$I_0/I = 1 + K_{SV}(T)P_{O2} \tag{1}$$

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where I_0 is the luminescence intensity in the absence of O_2 (i.e. vacuum), I is the luminescnec intensity at some partial pressure of oxygen P_{O2}, 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

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

where I_{REF} is the recovered luminescence intensity at a reference pressure, P_{REF}. A(T) and B(T) are temperature dependent constants for a given PSP formulaiton and are ususally 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 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 type of 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 Tunnel[15] 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]

The cryogenic PSP test on the traditional commercial transport wing at the NTF highlighted some potential challenges that needed to be overcome. These were confirmed in a follow on test that was performed on the Common Research Model.[20] In this test, severe contamination of the PSP was seen in the PSP that mitigated much if not all of its pressure sensitivity at cryogenic conditions. This contamination occurred if the tunnel required a significant amount of conditioning before cryogenic operations. To overcome this contamination, a two-pronged approach was developed and applied on this test. First, the base coat was cleaned thoroughly using toluene as a solvent to remove as much oil as possible before over-spraying with the PSP layer. Second, the PSP layer was applied in an access insert in the tunnel test section after the majority of the tunnel was conditioned for cryogenic operation. A full detailed procedure for the application and removal of the PSP is provided in the attached appendix.

This report will detail the results of these procedures as they were applied to a circulation control wing concept through a variety of conditions. Overall, the PSP performed much better than previous tests,

though some issues with noise levels still exist, depending on oxygen content in the flow. Additional lessons were also learned, and they will be addressed as well. This test served as a risk reduction opportunity for follow-on tests at this facility.

II. Experimental

A. Paint Formulation and Calibration

The PSP formulation used for this study was made by dissolving an oxygen sensitive luminophore (platinum meso-tetra(pentafluorophenyl) porphine, or Pt(TfPP) in plytrimethylsilylpropine, PTMSP.[15,16,21] PTMSP was chosen as the binder 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.

All paint calibrations were performed separate from the wind tunnel in a laboratory calibration chamber that has been described previously.[20] A typical PSP response at cryogenic conditions to increasing pressure of a 3000 ppm oxygen-nitrogen mix is shown in Figure1. Oxygen-nitrogen mixtures are typically

Figure 1. Typical calibration curve s for PSP under cryogenic conditions using a 3000 ppm O_2 in N_2 to simulate typical NTF conditions.

used to simulate expected NTF conditions with respect to O_2 levels and were chosen based on previously experienced results.[19,20]

B. 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 x 10^6/m (4 x 10^6/ft) to 476 x 10^6/m (145 x10^6/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 ^{o}C or -249 ^{o}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.

As mentioned in the introduction above, PSP requires the presence of O_2 in the flow to operate correctly. In previous tests,[19,20] this was accomplished by injecting dry air into the tunnel using a valve to control the injection. However, in this case, the air injection was only available from the model itself as part of the circulation control configuration. Oxygen monitors (described below) were interfaced into the tunnel and monitored the amount of O_2 at any given time in the flow.

C. Model

The test article for this experiment was a semi-span representation of a generic transonic transport named the Fundamental Aerodynamic Subsonic Transonic Modular Active Control (FASTMAC) model.

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It was designed by Christopher Cagle at NASA LaRC, and was fabricated by the NASA LaRC machine shop as well as Triumph Aerosopace Systems in Newport News, VA. This model was specifically designed for use with the flow control system, and its modular design should provide for easier modifications or augmentation of its assembly. With this flexibility, the model is perfectly suited to act as a testbed for future circulation control studies at the NTF. As with any model at the NTF, all model hardware were designed and fabricated according to the model design criteria dictated in Langley Procedural Requirement (LPR) 1710.15. A planform sketch of the model as assembled is shown in Figure 2 and a side view is shown in Figure 3 with pertinent dimensions in inches (cruise configuration shown).

The model fuselage and non-metric stand-off are composed of 2024-T351 aluminum allow. The wing-balance interface block and the wing assembly, including the flaps, are composed of 13-8Mo H1050 stainless steel. All of the pressure tubing inside the model that directs the high-pressure air from the flow control system out of the trailing edge of the wind is composed of 304 stainless steel. It must be noted here that the model was fabricated with 1.9 cm (0.75 in) diameter 347 stainless steel tubing, but during assembly it was deemed that the 0.12 cm (0.049 in)wall thickness of this tubing was too thin, and 394 stainless steel tubing that had a wall thickness of 0.165 cm (0.065 in) was used inside the model. Fully assembled the model is 2.08 m (82 in) long (fuselage nose to tail) with a wingspan of about 1.29 m (50.72 in) measured from test section wall to wingtip.

The model was designed and fabricated such that it could be configured for low-speed high-lift or for high-speed cruise. Three different flaps were fabricated including a 60° flap, a 30° flap, and a 0° or cruise flap. A leading edge slat was also fabricated that attaches to the leading edge with five slat brackets. Many sets of small shims were fabricated that can be used to change the trailing edge gap height. The gap height can be configured for a constant gap height across the span, or for a variable gap height across the span that is proportional to the chord length.
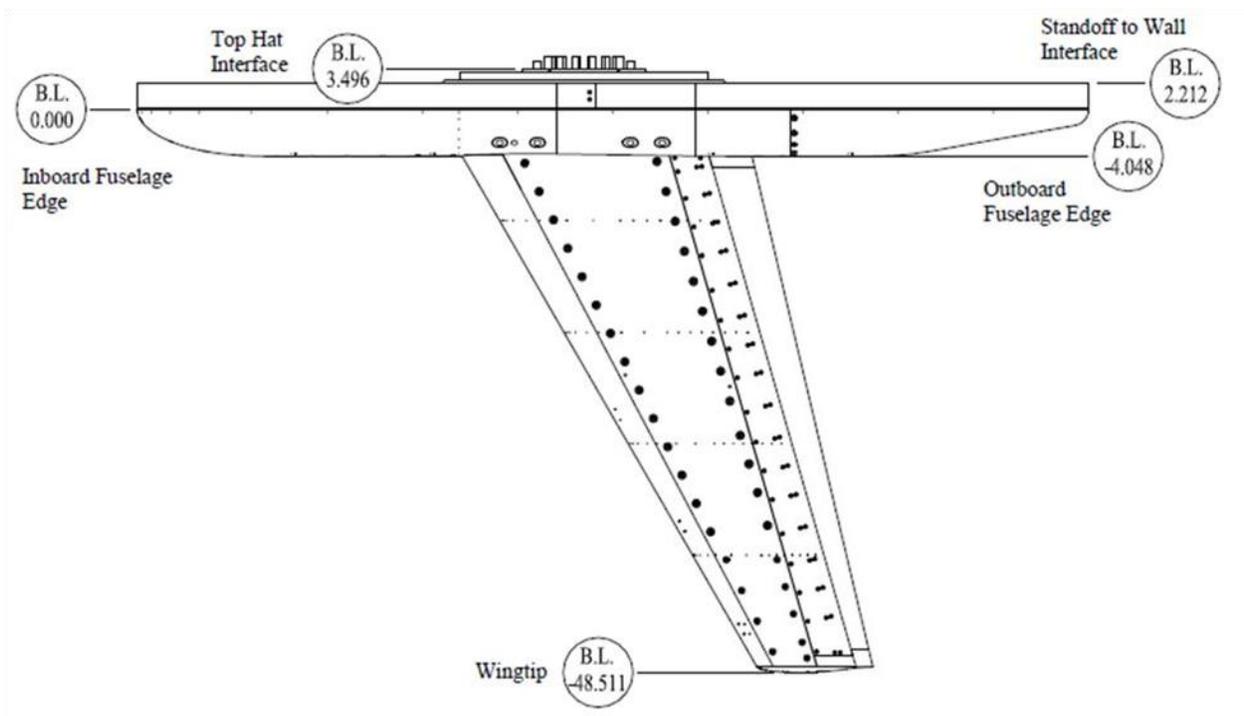

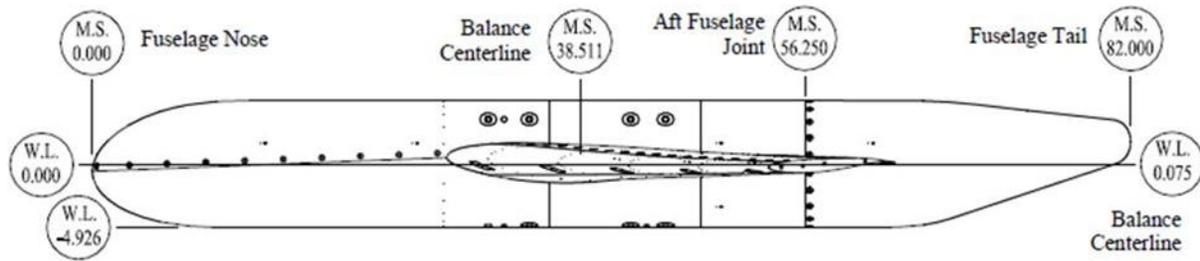**Figure 2.** Planform view of the FASTMAC model.

Figure 3. Side view of the FASTMAC model.

The fuselage assembly consists of a non-metric stand-off and the metric fuselage sections. The non-metric stand-off is approximately two inches wide and is bolted and pinned to the turntable. A spring-loaded Teflon seal is installed in a recessed perimeter around the back side of the standoff, and this serves as a flow blocker between the stand-off and test section wall as the model pitches. The metric upper and lower fuselage sections are bolted and pinned to the wing-balance interface block, and the aft fuselage section is bolted to the upper and lower fuselage sections after they are installed. A labyrinth seal exists between the fuselage sections and the stand-off to act as a flow blocker.

High-pressure air is directed through the model through a series of pipes, valves, and flow splitters. The wing-balance interface block attaches directly to the top hat and to the model interface plate on the bellows. A cap is installed on the wing-balance interface to prevent flow from entering the model from the low-flow side of the flow control system. Air from the high flow side of the flow control system is directed through the wing-balance interface block to fittings on the side of the block (two per side). Four 1.9 cm (0.75 in) diameter tubes are then used to route the air to four independently controlled valves inside the fuselage. Another set of piping is then used to route the air from the four valves through four separate flow splitters, or manifolds, into four different plenums along the trailing edge of the wing spar. The flow then passes through four separate choke plates before entering the aft plenum of the wing and trailing edge flap. Air is ejected out of the wing through a gap between the flap and the upper flap cover.

The fuselage is instrumented with 42 static pressure orifices. It also has threaded holes for installing five pressure taps. The main wing spar and leading edge is instrumented with 111 static pressure orifices. Small blocks are also installed in the wing for the installation of eight pressure taps to measure the pressure inside the four plenums in the aft wing spar. The leading edge slat is instrumented with 32 static pressure orifices. Each of the three trailing edge flaps are also instrumented with 60 static pressure orifices. Four Endevco pressure taps are also permanently installed in each flap to measure the unsteady pressures near the trailing edge gap. With the leading edge installed, the model contains 245 static pressure orifices. All pressure orifices in the wing are arranged in four streamwise rows at four span locations on the upper and lower surfaces of the leading edge slat, wing, and flaps. It must be noted that the pressure rows on the flaps are actually arranged perpendicular to the trailing edge and are not arranged in the streamwise direction.

D. 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

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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 the wing of 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% of reading or 0.5 ppm O_2 absolute. The unit is controlled by a personal computer via RS-232 protocol.

E. Data Acquisition

Data acquisition procedures for this test were modified from the previous cryogenic tests at NTF.[20] In this case; no additional air was injected into the tunnel. All the oxygen was introduced into the tunnel during the normal operation of the circulation control (i.e. all the air was introduced from the blowing flap). As in the previous tests, all wind-off images were acquired using a "slow roll" with the tunnel operating at ~ Mach 0.09 (to ensure adequate circulation of the oxygen). The oxygen concentration was continuously monitored as described above. However, no attempts were made to stabilize the amount of oxygen present. As such, the oxygen concentration varied wildly throughout the tests from only a few hundred ppm to near 1%, depending on the blowing conditions at the time of image acquisition. Because of this, only an *in situ* calibration of the PSP using existing taps was possible.

F. Data Analysis

Data analysis for this work used typical procedures for the analysis of intensity-based data acquisition. The basic data analysis used the following protocol:

1. Background correction of all images
2. Registration of the wind-on images to a suitable slow roll image. The slow roll image chosen for a particular wind-on image matched the angle of attack and was as close in time to the wind-on image as possible.
3. Conversion of the images to pressure was accomplished by using an *in situ* technique[9] in which the pressure taps were used to calibrate the PSP. This was done due to the potentially significant oxygen differences between the flap and the upper surface.

III. Results and Discussion

A. General Considerations

The *in situ* method for the calibration of the paint was accomplished by comparing a subset of pressure taps on the upper surface of the wing with a corresponding PSP area. The general locations of

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the chord-wise rows used for the paint calibration are shown in Figure 4. The row numbering was based on the location titles from the file provided in the tunnel data acquisition system. From the figure, it is readily apparent that Row 1 could not be used as it is in a region of the wing that could not be imaged adequately by the camera. This is most likely due to vignetting that has been seen previously.[20] Additionally, from Figure 4, there is definite evidence that the flap can show large differences than the upper surface of the wing. In the case of Figure4, it is due to the blowing from the slot of the wing. This causes a significant increase in the local concentration of O_2 this is directly behind the slot that is blowing air. Meanwhile the upper surface of the wing is essentially in a region of the facility that has a very low O_2 concentration. The portions of the flap that seem to have no data have actually had the PSP completely quenched so that the camera can pick up no data from these areas. Thus, for this test, all data analysis is concentrated on the upper wing surface. For all of the data runs, PSP was acquired at angles of attack of 0°, 4°, and 8°.
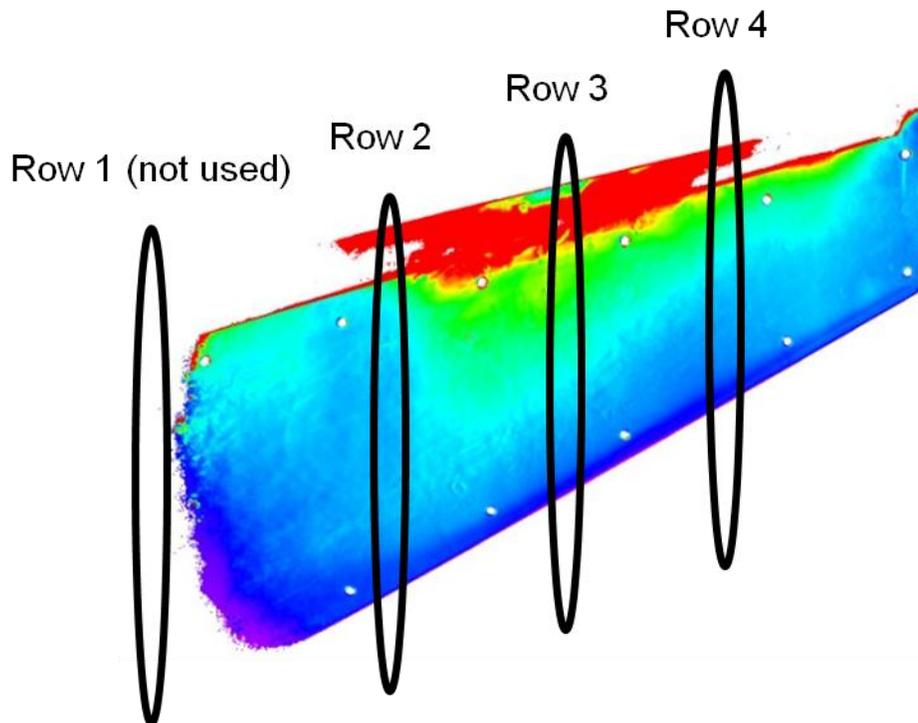
Figure 4. Sample PSP image depicting the general locations of the chord-wise tap rows.

B. Mach 0.7 (Note: Figure 5-10 are placed at the end of the paper for clarity)

Figures 5-7 show the PSP results obtained at Mach 0.7 with no air blowing form the slots. As there was no external air introduced into the N_2 atmosphere of the tunnel, the native O_2 concentration was very low (typically less than 1000 ppm). This has resulted in very noisy data on the upper wing. In addition, the flap shows some strange inconsistencies that arise because some of the valves in the circulation control segment were stuck open in the slow-roll configuration, thus biasing the data. These are manifest as extremely low pressure regions on the flap. While the data on the upper wind surface is noisy and shows many features in the paint that arise from the application (due to very small intensity changes), the actual agreement with the taps is fairly good. These are readily apparent in Figure 5 (0° AOA), where there is little change chord-wise across the wing, and in Figure 7 (8° AOA), in which both the PSP and taps show lower pressure at the leading edge increasing toward the trailing edge. However, the PSP data for Figure 6 (4° AOA) shows significantly more noise in both the image and the tap agreement. It is unknown why this occurred, though it could be due to significant depletion of the O_2 concentration in the facility at this point.

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The corresponding cases where air was actually being blown from the slot are shown in Figures 8-10. For this case, the slow-roll condition was taken after the wind-on acquisition, and the issue with the valves had been resolved, alleviating the issue with the flap. Unfortunately, the noise in the PSP data for Figure 8 (0° AOA) is quite excessive. However, the other two conditions, shown in Figures 9 and 10 (4° and 8° AOA, respectively), show much cleaner PSP data which agrees with the taps quite well. From the two sets of data collected at Mach 0.7, the 8° AOA case was the only one that can be directly compared as the PSP was the cleanest in each instance. This comparison, along with the tap comparison from Row 3 is shown in Figure 11. The comparison shows that there is a slight effect from the blowing over the flap. However, there is another anomaly that seems to occur near the trailing edge in the PSP. As seen in the tap comparison at Row 3, the PSP begins to deviate at x/c ~ 0.8. This can be seen in the PSP image as higher pressure region that seems to be extending from the flap *towards* the leading edge. This will be explored in more detail in the next conditions.
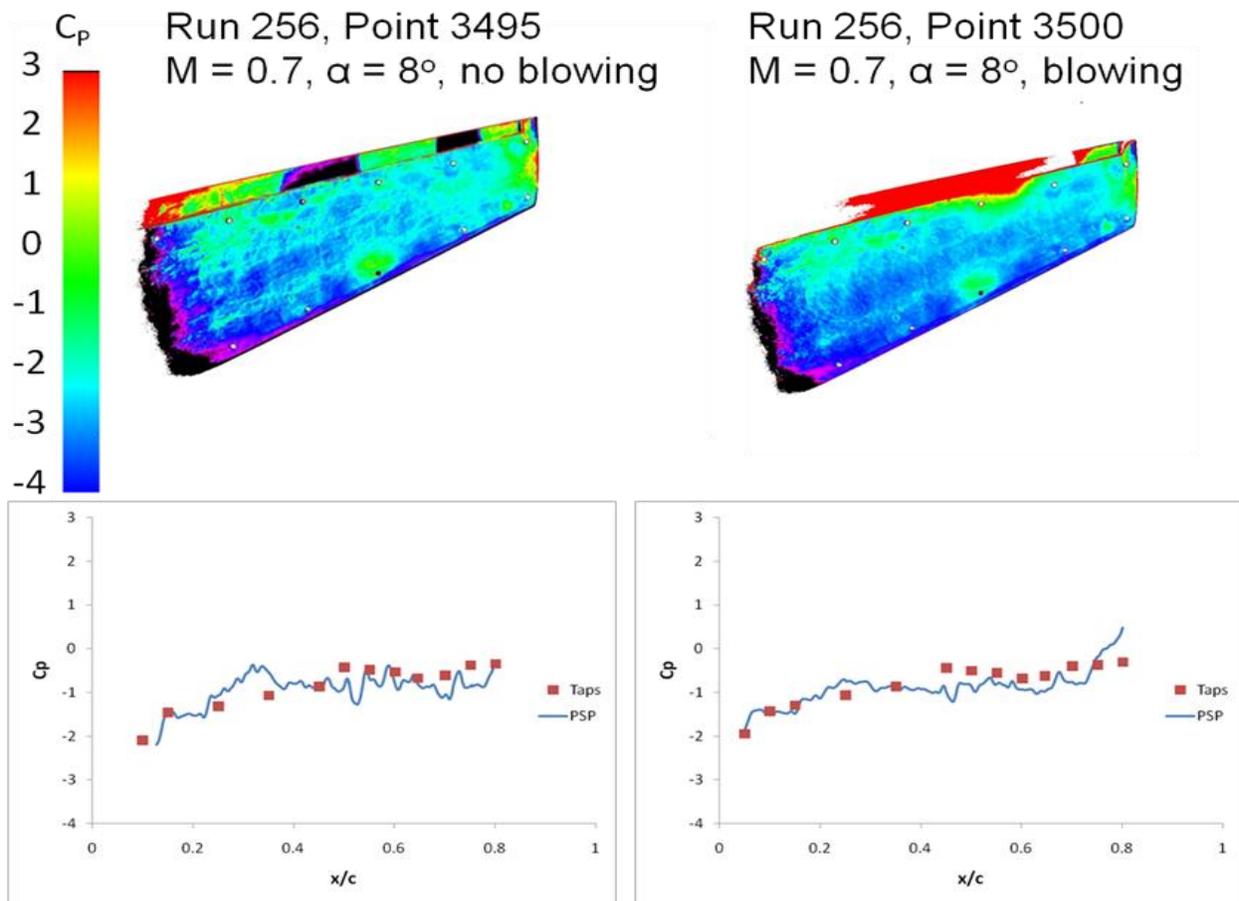
Figure 11. Comparison of PSP data acquired at Mach 0.7, 8° AOA with and without blowing through CCW. The PSP comparison to the taps in both cases is taken at Row 3 from Figure 4.

C. Mach 0.8 (Note: Figure 12-17 are placed at the end of the paper for clarity)

The next set of runs was acquired at Mach 0.8. Figures 12 -14 show the PSP results for the case where air is not being blown through the slot. This used the same slow-roll condition as the Mach 0.7 case, so the flap anomalies are present. Again, as in the Mach 0.7 condition, the PSP is very noisy due to low O_2 concentration. In this case, the 0° AOA (Figure 12) case was run first and shows fairly good agreement with the taps. For the 4° AOA condition (Figure 13), the PSP data was much cleaner than the Mach 0.7 condition, and shows the existence of a separation bubble near the leading edge. The boundary of this bubble can be seen in the tap measurements as well as the PSP, which tracks very well. For the 8°

AOA (Figure 14) condition, the PSP is again very noisy. However, this was taken at the end of the data run, so the O_2 concentrations were at their lowest. Still, the PSP does seem to be following the trend from the taps.

The PSP results are cleanest at Mach 0.8 when the slots are set for blowing air. This should be expected as this is the condition in which both the O_2 concentration in the tunnel and the pressure changes over the wing should be the greatest. These results are detailed in Figures 15-17. At the 0° AOA (Figure 15) condition, the wing shows relatively little pressure change across the surface, as seen in both the tap readings as well as the PSP. The good agreement between the PSP and the pressure taps is also seen in the 4° (Figure 16) case. In this case, the separation bubble is present and has shifted rearward a large amount when compared to the 4° case at Mach 0.7 (as seen in Figure 9). At Mach 0.7, the bubble if fairly small and reattaches at x/c ~ 0.15. However, at Mach 0.8, this reattachment occurs at x/c ~ 0.45. While the reattachment location is evident in both the tap data as well as the PSP, the PSP provides a means to view the entire separation bubble to ascertain shape over the wing.

For the 8° case (Figure 17) at Mach 0.8 *with blowing*, there is a large deviation of the PSP from the taps at the trailing edge of the upper wing surface. Evidence for this could be seen beginning at the 8° condition at Mach 0.7 (Figures 10 and 11), but is readily seen at Mach 0.8, Because the phenomenon is only seen in the PSP, it can be assumed that this is a significantly large temperature gradient from inside the model caused by the air being introduced through the bellows. Unfortunately, only the three angles of attack were investigated, though even from this limited data, it seems to follow that this heating event seems to only occur at higher angles. Ideally, with adequate run time, a full angle of attack sweep would be needed to confirm this, as well as identify when this begins to occur as it could indicate potential issues with the circulation control system at the facility.

IV. Conclusions

This report presented results from a PSP test performed at cryogenic conditions at the National Transonic Facility on a circulation control wing concept. This test built upon the lessons learned from a PSP test described previously,[20] especially in regards to the paint application. The proper application of PSP is the most critical stage to ensure adequate performance in cryogenic testing, especially in an environment with greatly reduced O_2 levels. The main result of this test was the development of these procedures that are presented in the appendix of this report. Following these procedures resulted in a viable coating that required no repainting and had much less contamination than the previous test.

As for the PSP results, data acquired while the circulation control was off (i.e. no blowing) produced noisy data which can be traced back to the fact that the only O_2 introduced into the facility was by the circulation control itself. Thus, in these conditions, the O_2 levels were very small. However, even in these cases, the PSP generally agreed with the tap readings, and certain conditions did provide some insight into the flow over the upper wing surface. However, when the circulation control was active (i.e. blowing), the O_2 levels generally rose to acceptable levels, resulting in very clean PSP data that generally agreed well with the taps. The PSP was able to ascertain separation and reattachment regions (especially at Mach 0.8), but did show a probable temperature anomaly at the leading edge of the upper wing surface at the highest angle of attack (8°). This resulted in a significant deviation between the taps and PSP.

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Appendix: Procedure for Applying and Removing Pressure Sensitive Paint for Cryogenic Testing at the National Transonic Facility

This appendix will serve as a Standard Operating Procedure for applying and removing Pressure Sensitive Paint for cryogenic testing at the National Transonic Facility. This also serves as one of the main lessons learned during this testing and these practices were refined during this tunnel entry.

Preparation of Model

1. Mask off the model areas that will not be painted. Use 3M Scotch Brand 218 MQA striping tape or equivalent.

2. If taps are present, apply an air purge to the model taps to prevent particles or paint spray from entering the taps. Determine how many pressure tap openings will need to be purged and adjust the air flow such that no cratering occurs around the taps. Use your tongue to gauge the amount of pressure from each pressure tap opening. (For Example: If there are 10 pressure tap openings use approx. 7-12 psi of nitrogen or clean, dry air depending on the size of the pressure tap openings.)

3. If unable to purge pressure taps, use a hole punch, hammer and 3M Scotch Brand 218 MQA striping tape or equivalent to create a circular mask. **MUST BE APPROVED PRIOR TO INSTALLATION AND/OR HAVE FACILITY PERSONNEL INSTALL CIRCULAR MASK!** If circular masks are approved for installation, determine what the diameter of the pressure tap hole is and prepare a circular mask of the appropriate size to be placed over top of the pressure tap hole using fine tip tweezers. (For Example: If the pressure tap hole is 0.020" wide use a 1/8 inch circular mask.)

    <u>NOTE:</u> *If used during painting, the circular mask may create a circular indention after painting is complete. Indentions on the surface may also cause varying results during data acquisition due to variations of the flow.*

4. Once pressure taps are protected, lightly spray solvent onto a paint towel and/or rag and gently wipe surface of the model to remove all traces of oil, grease, debris and surface impurities

5. Wipe the surface with a tack cloth just prior to spraying to remove any dust, dirt and/or debris.

Application of PSP

1. Paint the model with GBP 988 Self Etching Primer. The Self Etching Primer should air cure for 30 minutes.

    <u>NOTE:</u> *Spray several light coats of self etching primer to make sure surface stays as smooth and clean of debris as possible when spraying inside the tunnel due to heat and humidity of tunnel conditions. When spraying in the test section and/or wind tunnel, make sure a fan and/or air filtering machine (portable paint booth) is used at all times to remove all paint and solvent fumes.*

2. Then wet sand the model with 1500 grit sand paper to a roughness of 5 μin (R_a), as measured with the Mitutoyo Surftest 211.

3. Spray the surface with Spectra Prime. Cure the primer for 2 hours at 65° C. The Spectra Prime must be cured until it can be rubbed with a cloth soaked in THF and will not become gummy.

NOTE: *Add 1 oz more activator/reducer to allow for better flow of Spectra Prime base coat when spraying inside the tunnel due to heat and humidity of tunnel conditions. Spray several heavy coats to ensure the primer stays wet during the application which will provide a smoother surface for wet sanding. When spraying in the test section and/or wind tunnel, make sure a fan and/or air filtering machine (portable paint booth) is used at all times to remove all paint and solvent fumes.*

4. Wet sand the cured primer with 2000 grit wet sand paper until a roughness below 5μin (R_a) (as measured with the Mitutoyo Surftest 211 roughness meter) and the allowed thickness is achieved.

5. Rub the primed, sanded surface with a soft cloth or tissue soaked with tetrahydrofuran (THF).

6. The entire surface should have a dull finish. Any glossy spots should be rubbed until dull.

7. Spray the binder/toluene solution on the THF treated Spectra Prime primer in 15 - 20 light coats, allowing each coat to dry (this should take only a second or two; otherwise the coats are too heavy).

NOTE: *Use a cross pattern when spraying the binder on the model and a sweeping motion for each pass. The binder must be sprayed approx. 10-12 inches away in the test section and 6-10 inches away in the tunnel due to the heat and humidity of the tunnel conditions. When spraying in the test section and/or wind tunnel, make sure a fan and/or air filtering machine (portable paint booth) is used at all times to remove all paint and solvent fumes.*

8. When the model has been adequately coated the surface should have a uniform sheen.

9. After coating the entire model surface with the low temperature binder, allow it to dry for 10 minutes at room temperature.

10. Clean the spray gun with toluene.

11. Spray the polymer coated surface with a 600 ppm solution of PtT(PFP)P in methyethylketone (MEK) (also called 2-butanone) to give a uniform medium shade of pink. Allow to dry for 10 minutes at room temperature.

NOTE: *Use a sweeping motion when spraying the luminophore on the model and do not repeat the same pass until the previous coat has cured for 1 minute. The luminophore must also be sprayed approx. 10-12 inches away in the test section and 6-10 inches away in the tunnel due to the heat and humidity of the tunnel conditions. When spraying in the test section and/or wind tunnel, make sure a fan and/or air filtering machine (portable paint booth) is used at all times to remove all paint and solvent fumes.*

12. Clean the spray gun with toluene. Check the roughness. It should be less than 10 μin (R_a).

Removal of PSP

If the PSP has not cured for a long period of time (more than 12 hours) it may be removed with acetone; however, it will also remove some and/or most of the primer. If acetone will not remove the PSP, Tal Strip 2 aircraft coating remover can be used. The area must be well ventilated and the paint remover must be sprayed 10-12 inches away from the model in light fluid movements until the entire model has been covered. Wait 10-20 minutes and then the model must be checked to see if most or all of the paint has begun to bubble and/or strip away from the model. Once most of the paint has bubbled and/or stripped away, the model should be thoroughly sprayed with deionized water while being wiped

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with a Kimwipe™. The model can then be thoroughly cleaned with acetone until all the paint has been removed and the model is clean of grease, dust, debris, paint, etc.
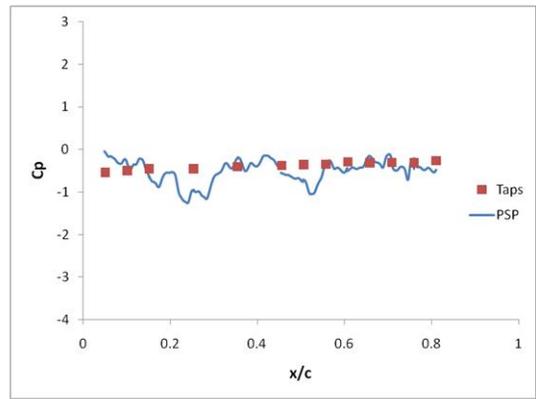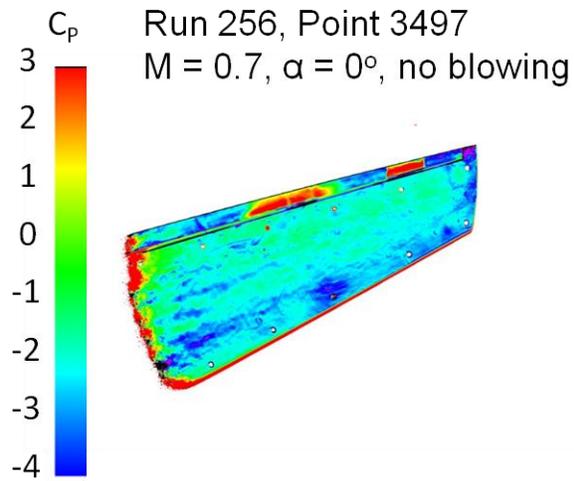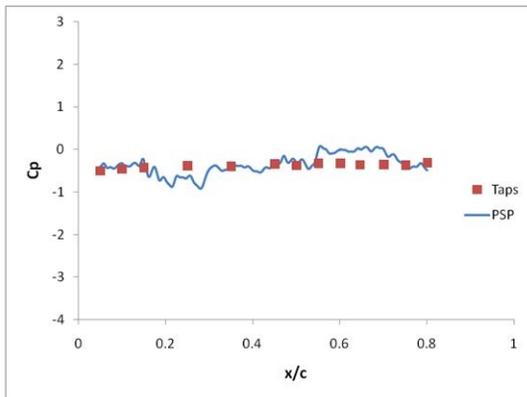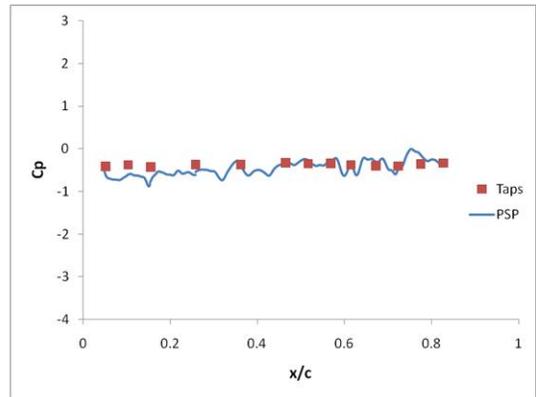
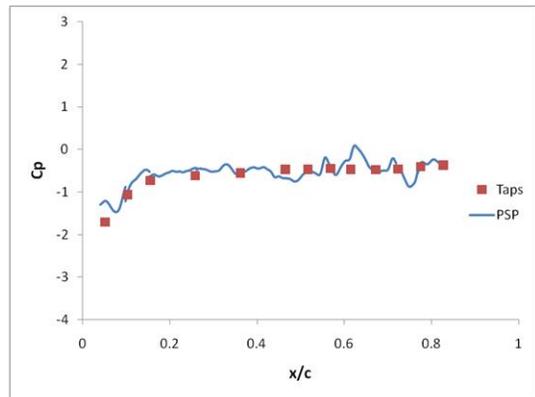**Figure 5.** PSP image and comparison of PSP data with taps for Mach 0.7, 0° AOA, and no blowing through CCW slot.
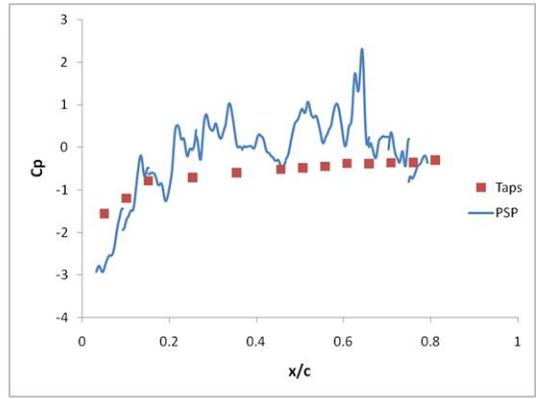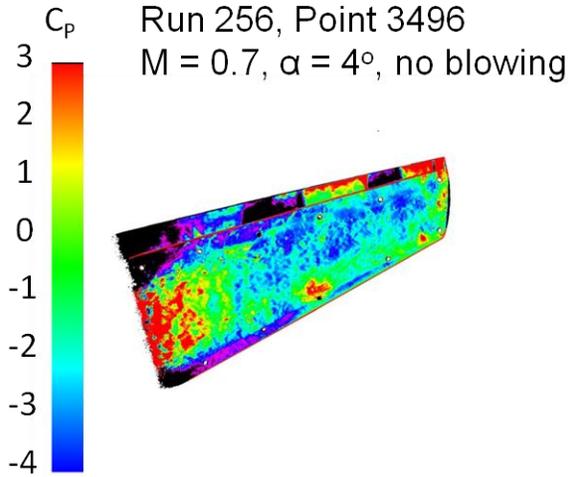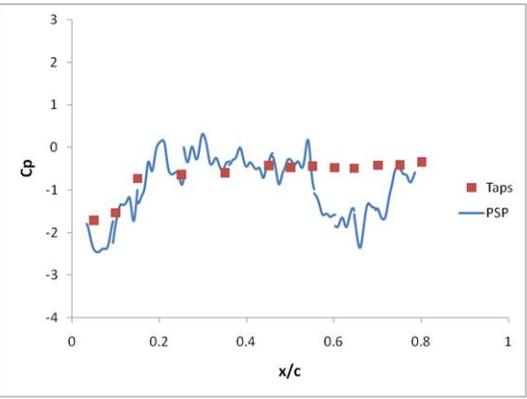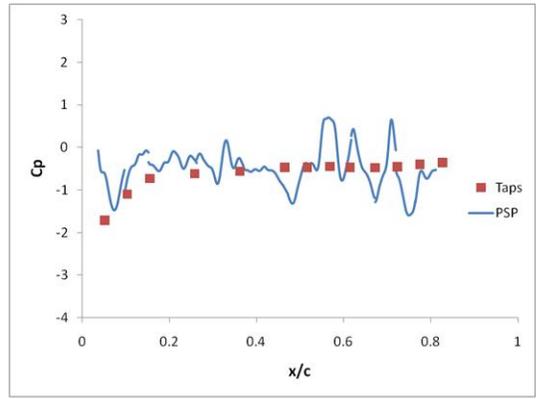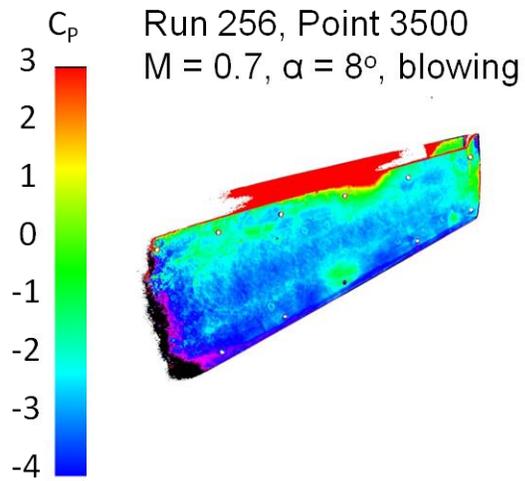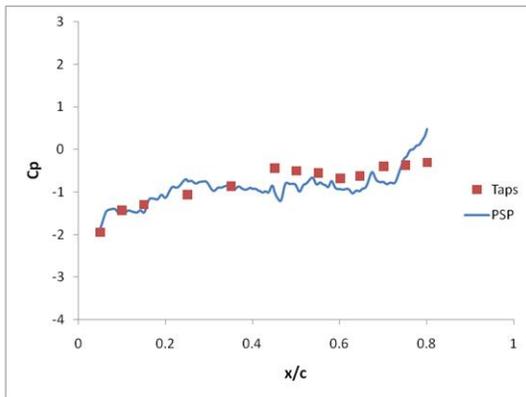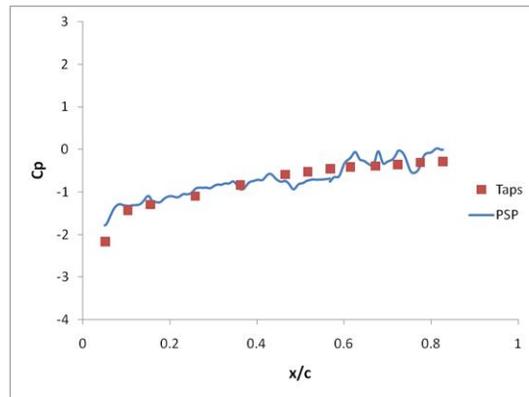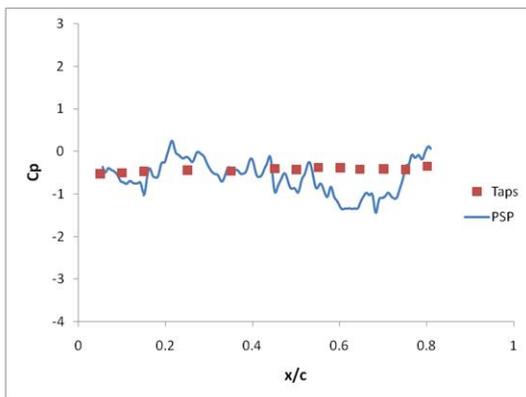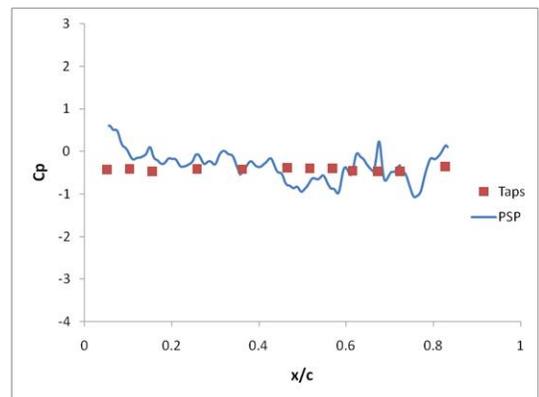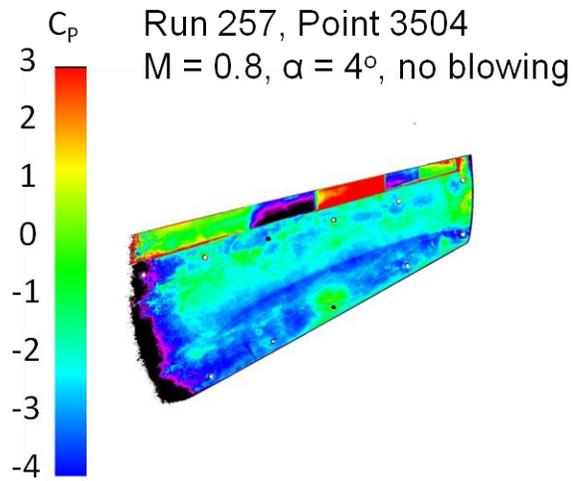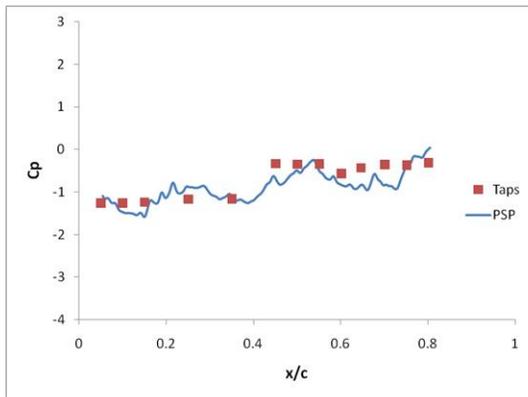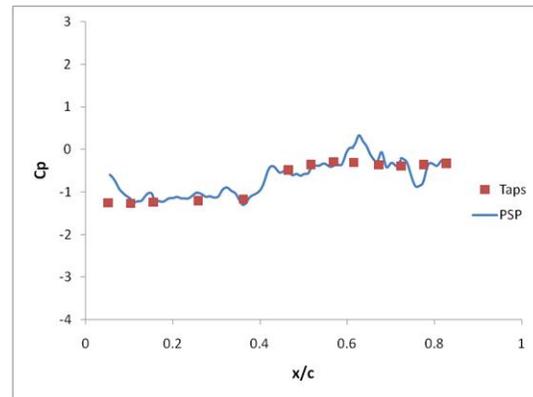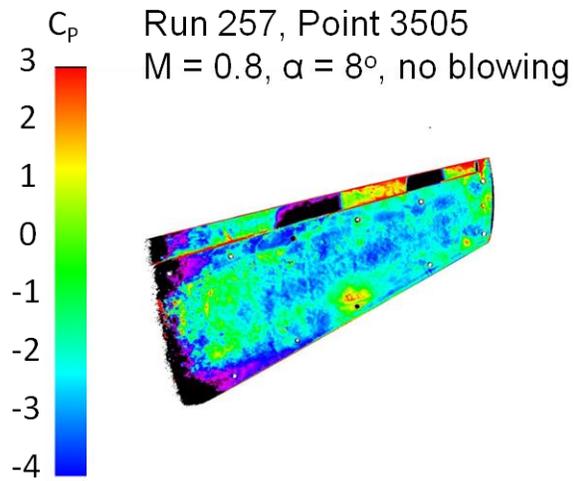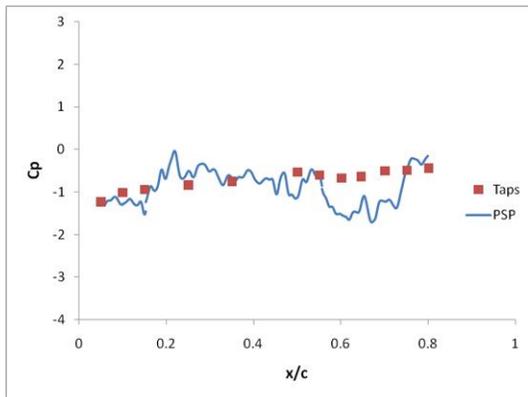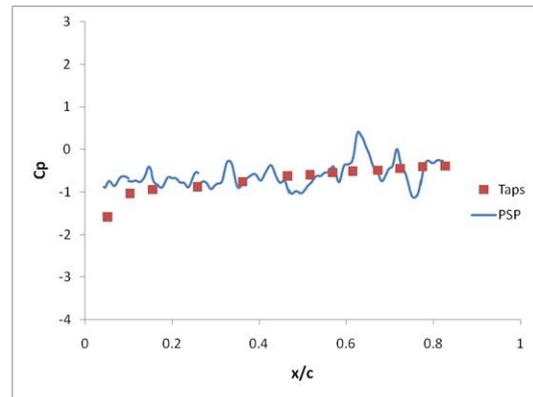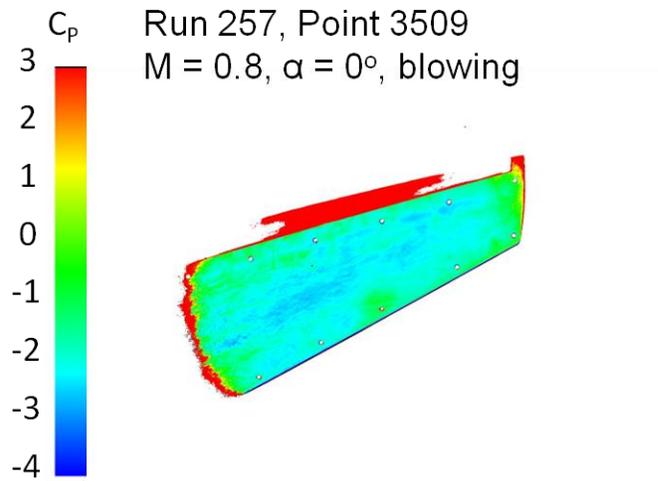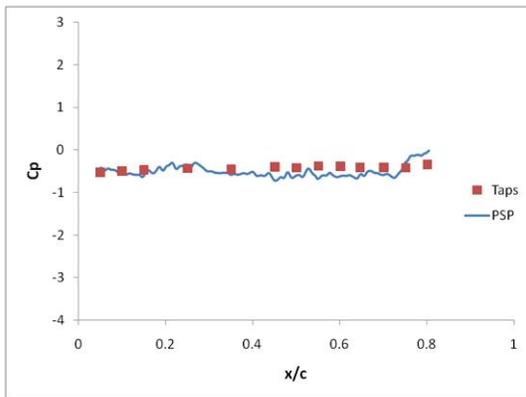
Figure 6. PSP image and comparison of PSP data with taps for Mach 0.7, 4° AOA, and no blowing through CCW slot.
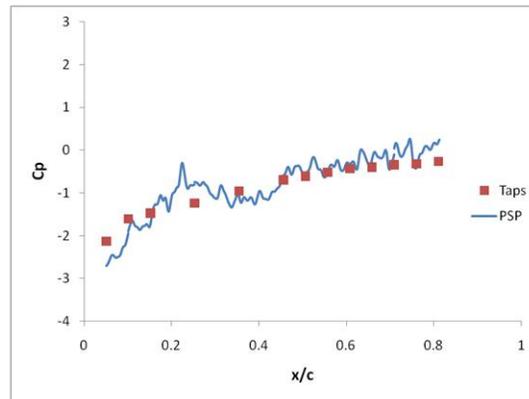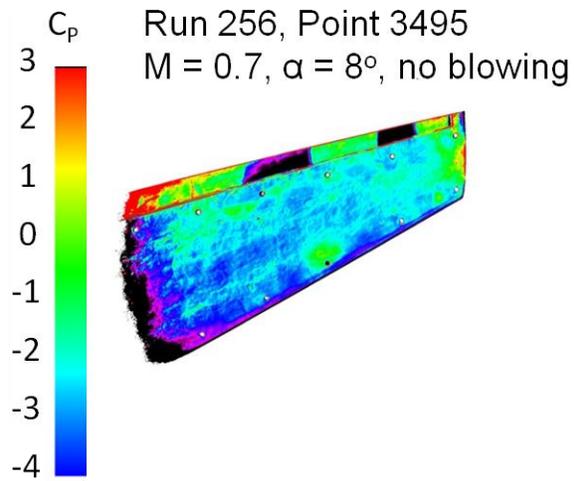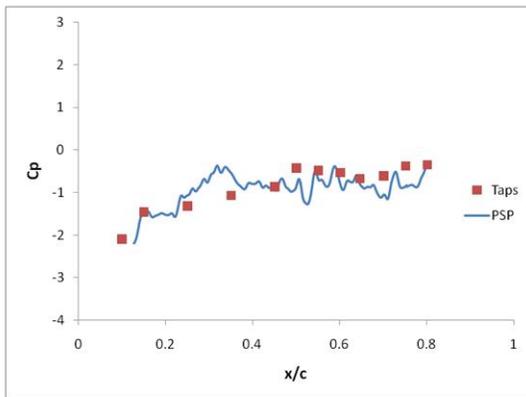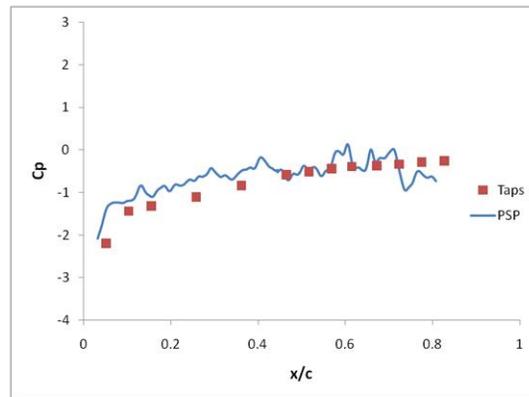
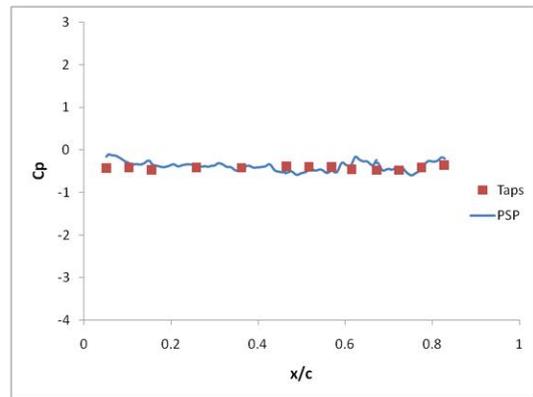**Figure 7.** PSP image and comparison of PSP data with taps for Mach 0.7, 8° AOA, and no blowing through CCW slot.
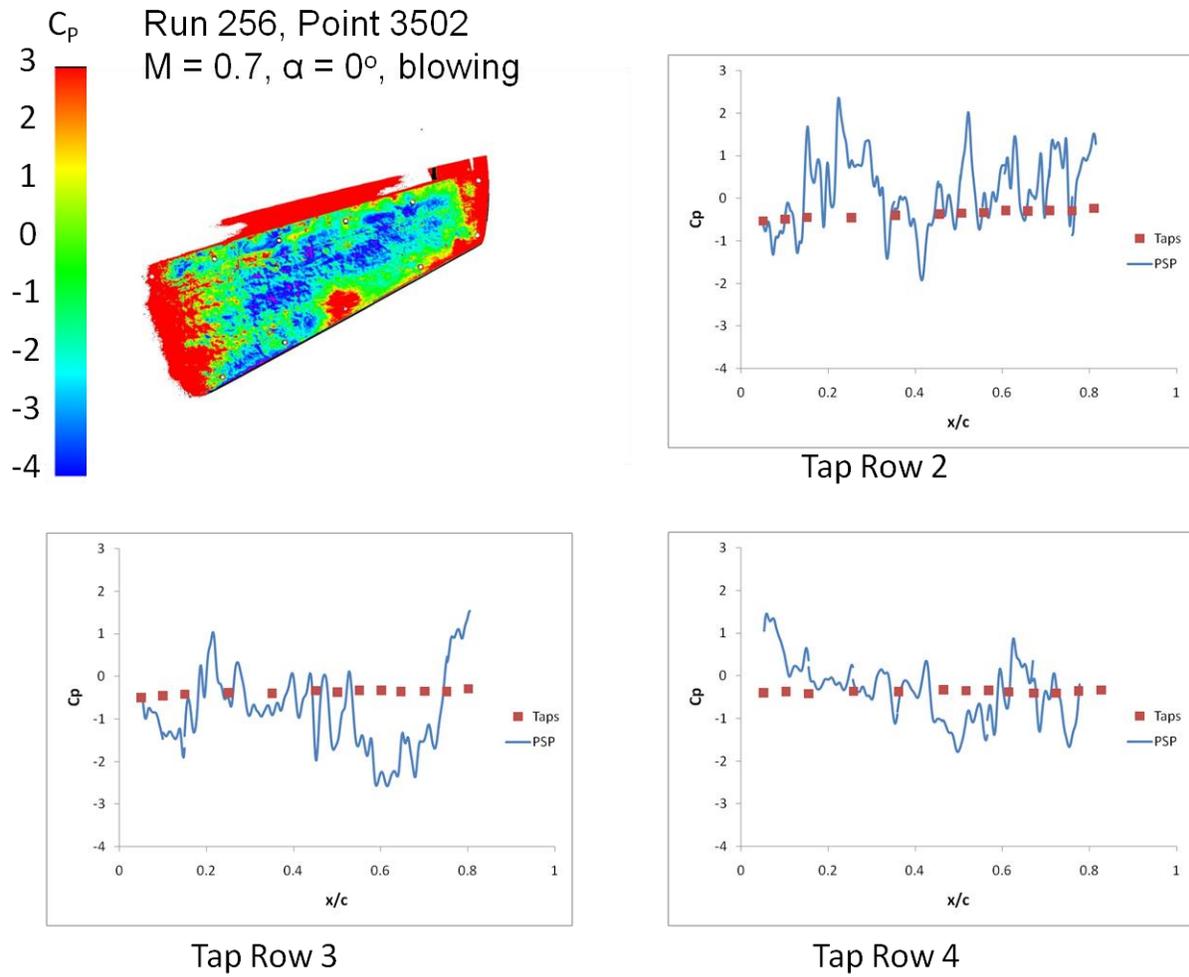
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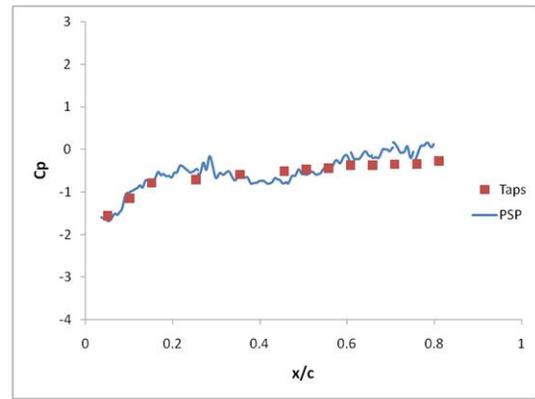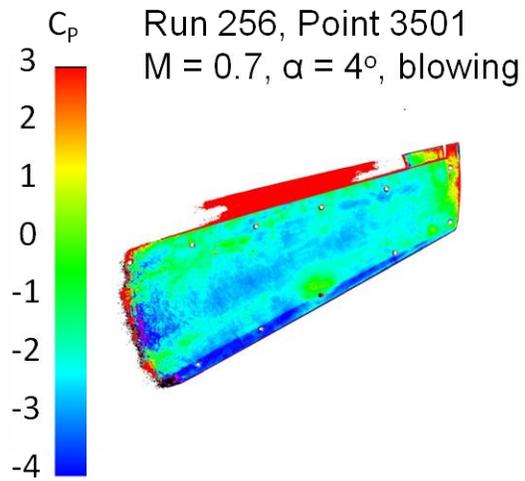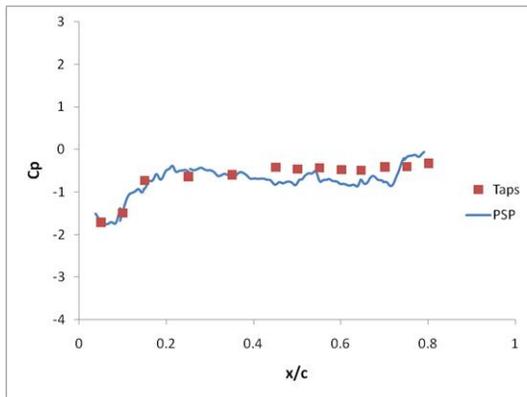
Figure 9. PSP image and comparison of PSP data with taps for Mach 0.7, 4° AOA, and air blowing through CCW slot.
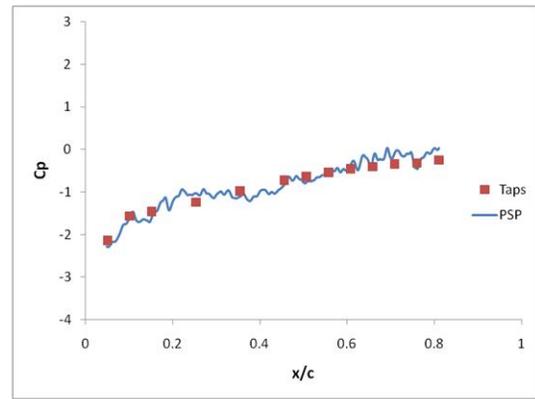
Figure 10. PSP image and comparison of PSP data with taps for Mach 0.7, 8° AOA, and air blowing through CCW slot.
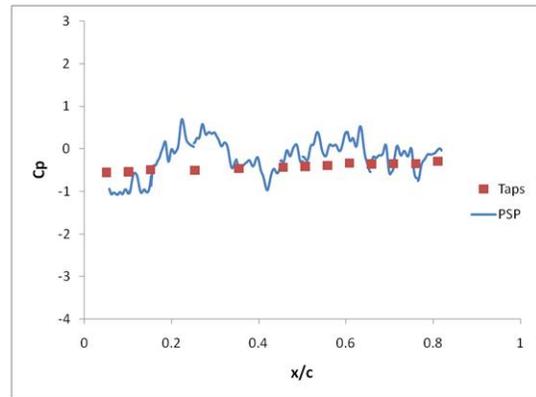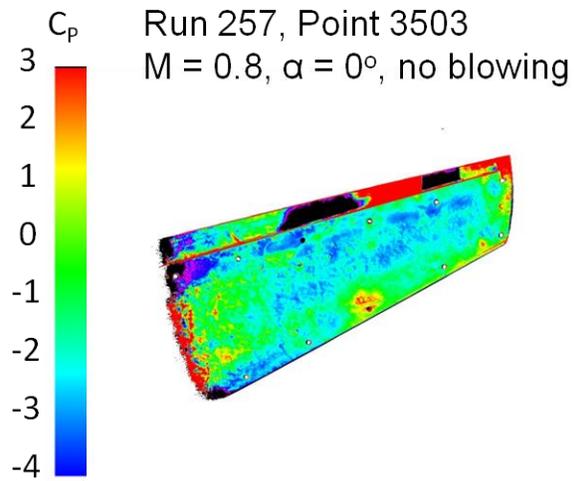
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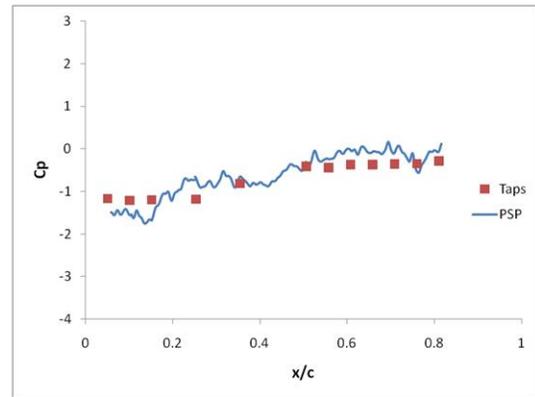
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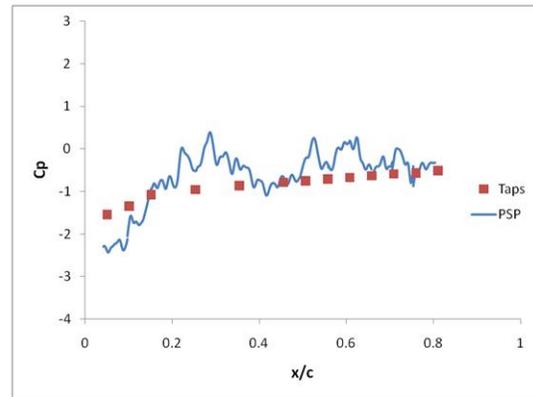
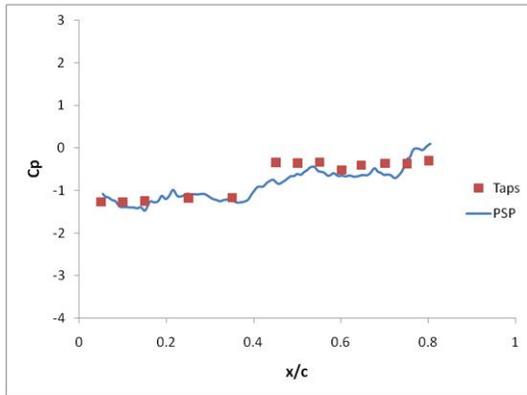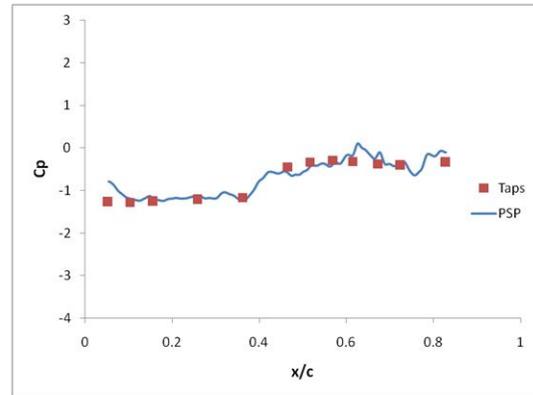**Figure 14.** PSP image and comparison of PSP data with taps for Mach 0.8, 8° AOA, and no blowing through CCW slot.
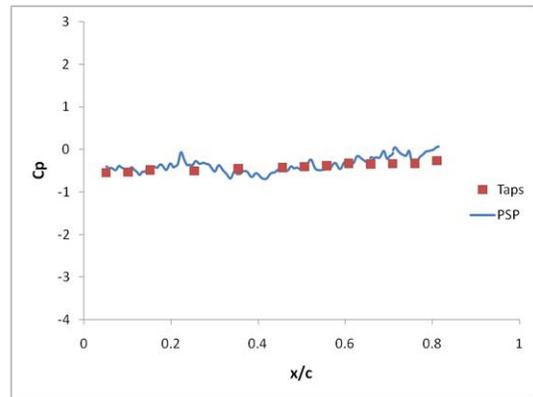
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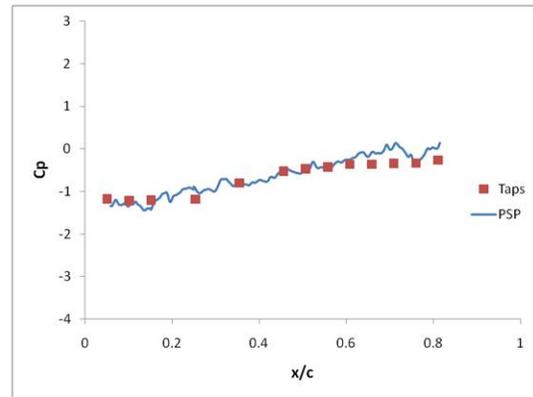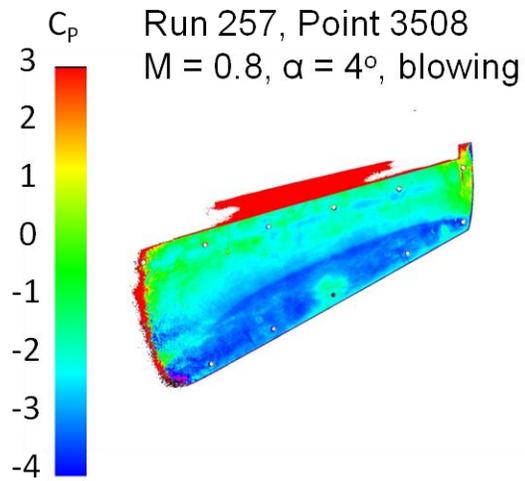
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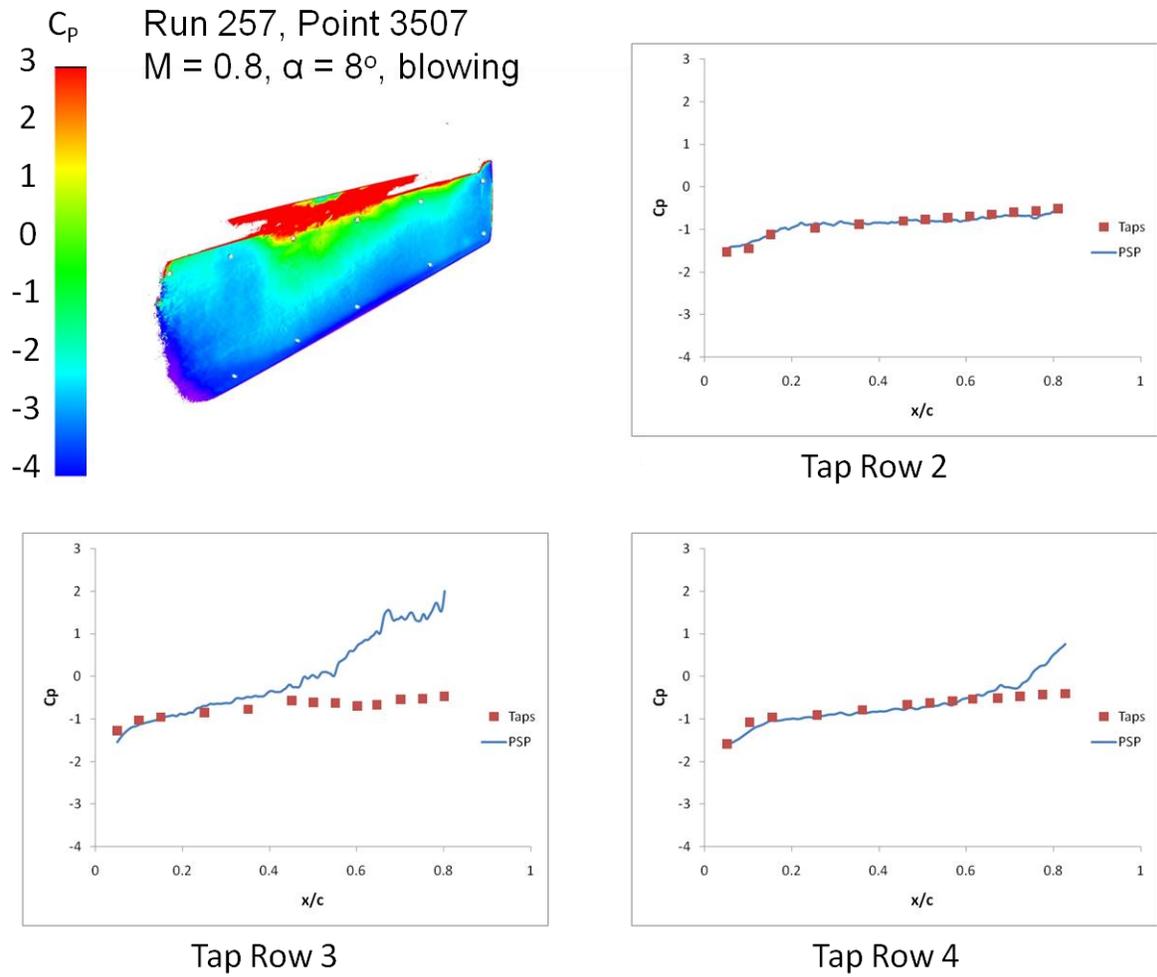
Figure 17. PSP image and comparison of PSP data with taps for Mach 0.8, 8° AOA, and air blowing through CCW slot.

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14. ABSTRACT

This report presents the results obtained from the Pressure Sensitive Paint (PSP) technique on a circulation control concept model. This test was conducted at the National Transonic Facility (NTF) at the NASA Langley Research Center. PSP was collected on the upper wing surface while the facility was operating in cryogenic mode at 227 K (-50 oF). The test envelope for the PSP portion included Mach numbers from 0.7 to 0.8 with angle of attack varying between 0 and 8 degrees and a total pressure of approximately 168 kPa (24.4 psi), resulting in a chord Reynolds number of approximately 15 million. While the PSP results did exhibit high levels of noise in certain conditions (where the oxygen content of the flow was very small), some conditions provided good correlation between the PSP and pressure taps, showing the ability of the PSP technique. This work also serves as a risk reduction opportunity for future testing in cryogenic conditions at the NTF.

15. SUBJECT TERMS

Cryogenic Testing; Global Pressure Measurement; Non-intrusive Sensing; Optical Pressure Measurement; Pressure Sensitive Paint

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