Implementation of Alternative Pressure-Sensitive Paint for Future Ground Testing

Meghan E. Smitherman[1]
The University of Tennessee, Knoxville, TN, 37996

This experiment performed a static calibration test on an in-house mixed pressure-sensitive paint (PSP) to compare its behavior with a commercially produced PSP. The commercially produced PSP was purchased from Innovative Scientific Solutions Inc. (ISSI), and the static calibration tests were conducted by measuring the PSP's light intensity at various pressures. Calibration curves for the two paints were then plotted for behavior comparison. It was found that both paints showed the same general trend in their curves while not behaving precisely the same due to the sensitivity of PSP calibration. Conclusions were drawn about the viability of this in-house mixed PSP to be used as a cheaper, alternative PSP in future ground testing, specifically wind tunnel testing.

I. Nomenclature

$A_n(T)$	=	temperature-dependent Stern-Volmer coefficient
I	=	light emission intensity
I_{ref}	=	light emission intensity at reference (atmospheric) condition
n	=	curve fit order number
P	=	air pressure
P_{ref}	=	air pressure at reference (atmospheric) condition
T	=	temperature

II. Introduction

Ground testing for high-speed flows has become more prevalent over the years as scientists and engineers work towards the overarching goal of faster and more efficient commercial transportation. Ground testing allows for studying of the various aerothermodynamic phenomena that occur when a vehicle operates at Mach 1 and beyond, such as boundary layer dynamics, formation of shock waves, or a combination of both known as shock-wave boundary layer interactions (SBLIs). SBLIs can be particularly harmful to a vehicle, as they lead to significant thermomechanical loads and aerodynamic heating on vehicle surfaces as well as structural damage caused by low-frequency flow features [1, 2]. It is important to understand such phenomena and their behavior to improve future vehicles. However, using conventional methods of measurement that are physically placed into a test environment poses a problem in obtaining accurate data. Since downstream obstacles cause shock waves to form in supersonic flow, any physical sensor placed into a supersonic or hypersonic test flow will create its own set of shock waves and potentially SBLIs, disturbing the flow environment and destroying the original flow conditions that were being measured [2]. Thus, new technologies and methods of measurement are being developed and utilized to study these phenomena non-intrusively and minimize flow disturbance. One of these new non-intrusive methods of measurement is pressure-sensitive paint (PSP).

PSP was first developed around the late 1980s and early 1990s and tested in wind tunnels to demonstrate its ability to fully resolve the pressure distribution on an airfoil model [3, 4]. Traditionally, to get good spatial resolution of the pressure distribution on a wind tunnel model would require 200 to 300 pressure transducers to be integrated into the model surface, with each transducer costing close to $2,000 and uncertainties still being present in the calculated loads experienced by the model due to insufficient data [5]. With PSP, the spatial resolution is exceedingly higher than any number of collective transducers on a model due to each image pixel "acting" as a transducer, with the resolution of accurate pressure measurements being limited merely by the resolution of the imaging device used to capture the data

[1] Undergraduate Student, AIAA Student Member, Member Number 1463343

[4]. PSP also allows for pressure measurements to be taken from locations that would be difficult or even impossible for traditional sensors to measure, such as thin or complicated geometries, sharp trailing edges, and rotating surfaces [3, 6]. In recent years, there has been a large focus in researching and implementing fast-responding versions of PSP (fast PSP). Due to the unsteady nature of many aerodynamic phenomena, the slow response time of conventional PSP limits its usability in high-speed flows and requires the development of a paint formulation that will reach steady-state values within the short-duration test times of many test facilities [4, 7].

Innovative Scientific Solutions Inc. (ISSI) has commercially implemented large-scale production of fast PSP, and their Porous, Fast-Response PSP has been used by government agencies such as NASA and the US Air Force in their wind tunnel tests of various aerodynamic phenomena. While ISSI's fast PSP is well-known and trusted in providing accurate data for wind tunnel tests, it is also overly expensive for small quantities and does not have a long shelf life. Recent researchers have been formulating and testing their own alternative fast PSPs that are both cheaper and available in larger quantities. As such, this study aims to formulate one of these alternative PSPs and test its behavior compared to ISSI's fast PSP. As ISSI has produced their own static calibration curves of their PSP for consumer availability, a static calibration test will be performed on the alternative PSP to then compare behavior quantitatively.

III. Relevant Theory

A. PSP and Fast PSP Fundamentals

Conventional PSP typically consists of luminescent molecules (luminophore) and a binder, typically a polymer, to adhere the luminophore to a model surface. A typical PSP measurement system also includes an excitation light, a camera, and data acquisition/processing equipment [7]. The luminophore molecules absorb photons from the excitation light and excite to a higher energy state, whereby they can return to ground state through radiative or radiationless processes [6]. The radiative process, called luminescence, causes the luminophore to release photons of a wavelength longer than the excitation source, while the radiationless process, termed "oxygen quenching," occurs when oxygen molecules that have permeated the binder interact with the excited luminophore molecules and quench their luminescence [6, 8]. These processes are shown on a conventional PSP layer in Fig. 1. The partial pressure of oxygen, and thus the overall static pressure, at the model's surface is proportional to the oxygen concentration within the binder and inversely proportional to the intensity of the light given off by the luminophore [6, 8]. Thus, the less intensity the luminophore gives off, the more oxygen is present at that location and the higher the static pressure is there, whereas the greater intensity the luminophore gives off, the less oxygen is present at that location and the lower the static pressure is there.

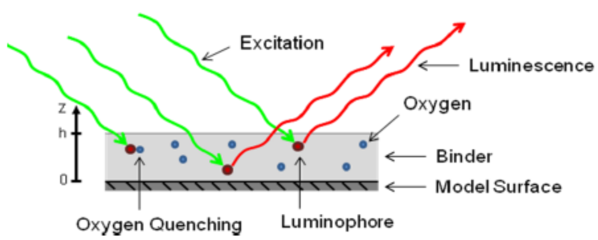

Fig. 1 Luminescence and Oxygen Quenching Processes on Conventional PSP [6].

The response time of PSP is generally dependent on paint thickness, binder diffusivity, and luminescent lifetime [4]. For conventional PSP, response time is mainly governed by the rate of oxygen diffusion into the binder, but due to the low oxygen diffusivity of polymer binders, response times can be as slow as seconds or tens of seconds [8]. As this makes conventional PSP inapt for measuring unsteady or short-duration flows, researchers have attempted to find other binders with greater diffusivity, such as porous structures with large surface areas, to create fast PSPs [4]. These porous PSPs allow the luminophore molecules to be directly applied to a model surface and exposed to the air, allowing the oxygen molecules to rapidly interact with the luminophore and thus produce response times as quick as milliseconds or even microseconds [3, 7]. While there are many types of porous binders for fast PSP, the three commonly used are thin-layer chromatography plate (TLC-PSP), anodized aluminum (AA-PSP), and polymer/ceramic (PC-PSP) [3].

Of the three common porous PSPs, PC-PSP is the one with the most widespread use in wind tunnel testing. While TLC-PSP is easy to prepare and has a response time of tens of microseconds, its fragile nature prevents it from being easily used in wind tunnel testing and limits its use to flat, simple shapes [4]. AA-PSP can be applied to arbitrarily shaped models compared to TLC-PSP, but the anodization process limits the model material to only aluminum [4]. Unlike all other fast, porous PSPs, PC-PSP can be applied to any model geometry and material, and even its response time is not dependent on paint thickness compared to other PSPs [9]. Figure 2 depicts a schematic of PC-PSP. PC-PSP consists of a high concentration of ceramic particles and a small amount of polymer to physically adhere the particles to a model surface [7]. This mixture serves as a basecoat to provide binding locations for the luminophore molecules. The concentration of ceramic particles in PC-PSP is large enough to vastly surpass the critical pigment volume concentration, the concentration above which there no longer remains sufficient polymer to fill in the gaps between ceramic particles, creating a porous surface with many voids [9].

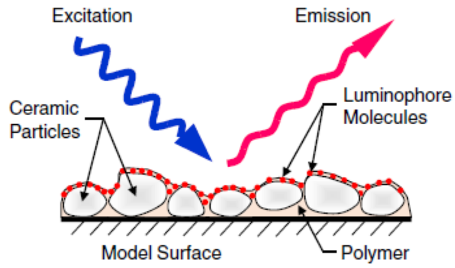

Fig. 2 PC-PSP Schematic [9].

While the disadvantages of using PSP over conventional pressure taps seem minimal, it is important to note some of the potential uncertainties and errors associated with PSP. In testing unsteady low-pressure flows, the applied PSP needs to have high pressure sensitivity to detect the small pressure fluctuations present in low-pressure environments. However, exposure to low pressure causes the PSP to lose its pressure sensitivity at higher pressures [10]. While this is not a major concern as typical wind tunnel tests have ambient test pressures above these low pressures, one of the predominant sources of error is the temperature sensitivity of PSP. This temperature sensitivity is due to the temperature dependence of the luminophore's decay rate as well as the luminescence process, as increasing temperature increases the frequency of collisions between oxygen molecules and excited luminophore molecules, decreasing overall luminescence [4, 7]. Porous PSPs are highly temperature sensitive due to the luminophore being directly exposed to the outer environment and more susceptible to temperature changes. Fortunately, when these PSPs are applied in short-duration wind tunnel tests (e.g., shock tubes and Ludwieg tubes), the temperature effects are usually negligible because of small heat loads [4, 7].

B. PSP Static Calibrations

To accurately determine the pressure distributions measured by PSP, static calibrations need to be done to determine the relationship between PSP intensity and surface pressure. Static calibrations can be done either *a priori*, painting a sample coupon at the same time as the test model and performing calibrations on the coupon, or *in situ*, placing conventional pressure transducers on the test model and correlating data between transducer and PSP readings [7, 11]. The relationship between luminescent intensity and pressure can be explained by the Stern-Volmer equation [11]. Equation (1) is a general form of this equation that holds for any curve fit order n, where I_{ref} and P_{ref} are the values taken at a reference condition, typically atmospheric, and $A_n(T)$ is a temperature-dependent coefficient that is experimentally determined. In wind tunnel testing, I_{ref} and P_{ref} are also referred to as "wind-off" conditions when the tunnel is not running, and the test values I and P are referred to as "wind-on" conditions [7]. Due to the temperature sensitivity of PSP, a full static calibration typically involves determining the pressure and intensity ratios across a range of temperatures.

$$\frac{I_{ref}}{I} = \sum_{n=0}^{N} A_n(T)\left(\frac{P}{P_{ref}}\right)^n \tag{1}$$

For conventional PSPs, Eq. (1) reduces to a linear form that holds true over a wide range of pressures according to Henry's law, but for porous PSPs, this linear relation only holds for pressures near atmospheric [4]. Instead, Eq. (2) shows a second-order curve fit of Stern-Volmer that is more representative of the behavior of porous PSPs due to their decreasing pressure sensitivity with increasing pressure [4]. A_2, A_1, and A_0 are again experimentally determined temperature-dependent coefficients.

$$\frac{I_{ref}}{I} = A_2\left(\frac{P}{P_{ref}}\right)^2 + A_1\left(\frac{P}{P_{ref}}\right) + A_0 \tag{2}$$

IV. Experimental Method

A. PSP Formulation and Model Preparation

To accurately compare ISSI's PSP to an alternative PSP, a paint with characteristics like ISSI's paint needed to be formulated. ISSI produces many types of PSP, but their Porous, Fast-Response PSP is one commonly used in wind tunnel applications as its base is a polymer/ceramic form. Thus, the alternative PSP will also need to have a polymer/ceramic base for the best comparison as each type of PSP binder behaves in its own way. The PC-PSP formulation that had the most similar characteristics to ISSI's Porous, Fast-Response PSP was the formulation in Ref. [9]. Thus, the formulation steps laid out in Ref. [9] used to create the alternative PSP for this experiment are as follows: prepare a basecoat slurry by mixing 12 mg of ceramic dispersant and 1.5 g of TiO_2 particles per 1 g distilled water and ball-mill for several hours, then add 3% weight fraction of binding polymer and airbrush onto a clean model surface. While the basecoat is allowed to dry overnight, prepare the luminophore solution by dissolving 0.3 mg of platinum tetra (pentafluorophenyl) porphyrin (PtTFPP) per 1 mL of methanol. Once the basecoat is fully cured, airbrush the luminophore solution onto the model and let cure for approximately 15 minutes before performing calibration tests.

To preserve luminescent lifetime and limit light exposure, the luminophore solution bottle was stored in a closed cabinet and wrapped up in packing paper when not in use. All airbrush painting was done in a fume hood, as shown in Fig. 3, with a respirator always on. An important note is that at the time of this experiment, a bottle of luminophore solution was already present and had been mixed a couple of months prior. This bottle of luminophore solution was the luminophore used for this experiment.

Since the purpose of this experiment was to test the performance of the PSP itself and not to measure any physical aerodynamic phenomena present on the surface of flight vehicles, the model used only needed to have a flat surface and be small enough to fit within the vacuum cube used for the calibration tests. A sample vertical wedge model shown in Fig. 3 was found and used for all PSP applications. To prevent interference in measurements, painter's tape was applied to the bottom half and sides of the model so that only the luminophore-covered area (i.e., the pink area) provided the luminescence captured by the camera.

Fig. 3 Fume Hood for PSP Airbrush Painting and Wedge Model for PSP Applications

B. Experimental Setup

This experiment took place in the University of Tennessee Space Institute's (UTSI's) Mach 2 Wind Tunnel, due to the limited available space in their Tennessee Aerothermodynamics Laboratory (TALon). The overall setup of the experiment is shown in Fig. 4. An Ideal Vacuum Cube was used to contain the model within an isothermal and isobaric environment, with a pressure transducer attached to accurately read pressure values. Pressure was changed within the vacuum cube by either venting to the atmosphere through a valve attached to the back or turning on the vacuum pump until the desired pressure value was reached. Typical excitation ranges for PC-PSP, both alternative and commercial, are from 380 nm to 420 nm [4]. Since 400 nm is the ideal excitation wavelength for ISSI's porous fast-response PSP, which is the type of PSP currently used by UTSI, a 400 nm LED was used as the excitation source to better compare PSP behaviors. As Fig. 4 shows, two 400 nm LEDs were placed on either side of the vacuum to facilitate even lighting of the model, as well as a parabolic reflector on each LED to further concentrate the light onto the model. To capture the luminescence given off by the PSP, a Photron Fastcam SA-Z camera with an attached 50 mm lens was utilized to accurately capture the paint's fast response at a high enough spatial resolution. Since typical emission ranges for PC-PSP are from 600 nm to 720 nm, dual 450 nm and 610 nm long-pass filters were also attached to the camera to ensure that only the PSP's emission wavelength was recorded and not the LEDs or any other outside noise [4]. Though not shown in Fig. 4, a thermocouple was also set up to accurately record temperature conditions. Finally, a delay generator was connected to both LEDs and the camera to ensure consistent recording and timing for every run. The LEDs were programmed to turn on for three seconds to prevent overexposure to the PSP, but the camera was delayed one second before recording for two seconds to allow the LEDs to reach full intensity.

Fig. 4 Experimental Setup for PSP Static Calibration

C. Test Procedure

Due to the availability of space and the experimental setup, a static calibration test was only performed at one temperature, being the ambient room temperature of 22.61°C. Once all equipment was set up, the camera was then focused onto the model, and camera settings (e.g., bit resolution, shading, and frames per second) were adjusted through the camera's compatible Photron Fastcam Viewer software to ensure that a wide range of intensity values could be recorded accurately. Camera shading was a critical setting to adjust, as too low of a shading led to "maxed-out" intensity values at vacuum, but too high of a shading led to nonexistent intensity values at atmosphere. Once all camera settings were determined to be appropriate, PSP images were recorded at ten different pressure values ranging from vacuum (13.3 Pa) to atmospheric pressure (98.6 kPa). The images were recorded in a randomized order of pressures to minimize hysteresis errors as well as to better imitate the fast-changing, random pressure fluctuations that are present in wind tunnel testing. The only exception to this randomized order was that vacuum and atmospheric pressure were the first and second tests, respectively, to correctly set the camera shading. Table 1 shows the order of tests for the ten different pressure values.

Table 1 Test Order of Pressures for PSP Static Calibration

Test Order	Pressure (kPa)	Pressure (psi)
1st	0.0133	1.9×10^{-3}
2nd	98.6	14.3
3rd	41.3	6
4th	55.1	8
5th	34.4	5
6th	27.6	4
7th	68.7	10
8th	13.7	2
9th	20.7	3
10th	6.92	1

Once all ten images were recorded, the images were loaded into MATLAB for post-processing and analysis. The Photron Fastcam Viewer software saves its data in a .mraw file format, so a MATLAB function was developed to accurately read this file type into the MATLAB workspace. This function script was modified by UTSI's own Dr. Phillip Kreth and can be found on MATLAB's help site. Once the .mraw files were successfully loaded in, MATLAB's image analysis and processing capabilities were utilized to crop each image down to an area depicting nothing but PSP luminescence and calculate the average intensity of each cropped image.

V. Results and Discussion

A. Alternative PSP Images

Figure 5 shows the PSP images captured by the SA-Z camera for each of the ten pressure values tested. From merely a qualitative view, one can see that the image for vacuum pressure appears to be brighter than the image for atmospheric pressure. Table 2 quantifies this observation by showing the average intensity values calculated within MATLAB for each of the ten pressure values. Again, the vacuum pressure intensity value of 2575 counts is much higher than the atmospheric pressure intensity value of 299 counts. This means that the alternative PSP's porous binder is accurately allowing oxygen molecules to interact with the luminophore molecules, and the luminophore is responding accordingly to changes in pressure. Due to limited quantities of ISSI PSP available at UTSI, no physical calibration tests were performed on ISSI's PSP in the same test environment as for the alternative PSP. However, ISSI has performed their own static calibration tests on their porous, fast-response PSP, and these results are posted on their website for public viewing. Their posted results include only a graph of calibration curves performed at 5 different temperatures: 10°C, 15°C, 20°C, 25°C, and 30°C. The x and y axes on these curves were the traditional x and y axes used when evaluating static PSP calibration: P / P_{ref} and I_{ref} / I.

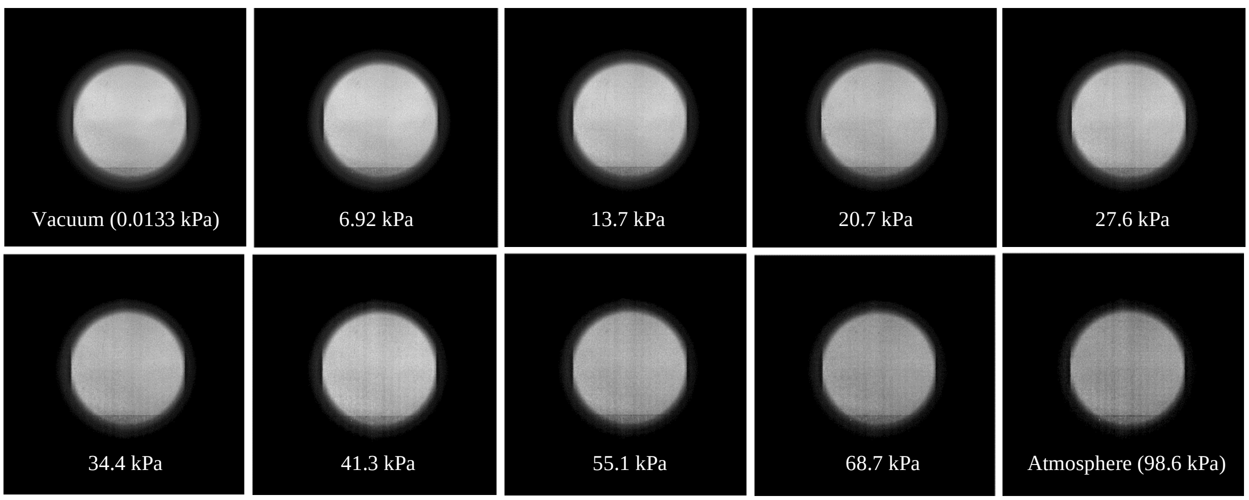

Fig. 5 Alternative PSP's Qualitative Response to Pressure Changes

Table 2 Alternative PSP's Quantitative Response to Pressure Changes

P_{avg} (kPa)	I_{avg} (counts)
98.6	299
68.7	393
55.1	473
41.3	582
34.4	662
27.6	761
20.7	893
13.7	1124
6.92	1498
0.0133	2575

B. Alternative PSP Behavior

Figure 6 shows the experimental static calibration curve for the alternative PSP as well as reference ISSI calibration curves. An online web plot digitizer was used to pick data points off each curve of ISSI's website graph that were then plotted in MATLAB with the experimental data points. For the experimental data, I_{ref} and P_{ref} were taken to be the intensity and pressure values at atmospheric pressure, respectively. Theoretically, if the alternative PSP was to be an exact replica of ISSI's PSP, since they are both fast-response PC-PSP, the black experiment curve at 22.61°C should fall between the teal and blue ISSI curves at 20°C and 25°C, respectively. As Fig. 6 shows, that is not the case, meaning that the alternative PSP is not an exact replica of the ISSI PSP, nor does it behave the exact same way as the ISSI PSP. However, the alternative PSP does behave in an equivalent way to the ISSI PSP, as the alternative PSP data follows the same type of second-order curve fit with an upward trend, symbolizing that both paints experience lower intensity values as pressure increases. Table 3 displays the Stern-Volmer coefficients for the second-order curve fits plotted in Fig. 6. While the coefficients for the experimental data do not all precisely fall between the 20°C and 25°C coefficients for the ISSI data, the experimental coefficients are close and fall within a range ± 0.15 outside either temperature boundary.

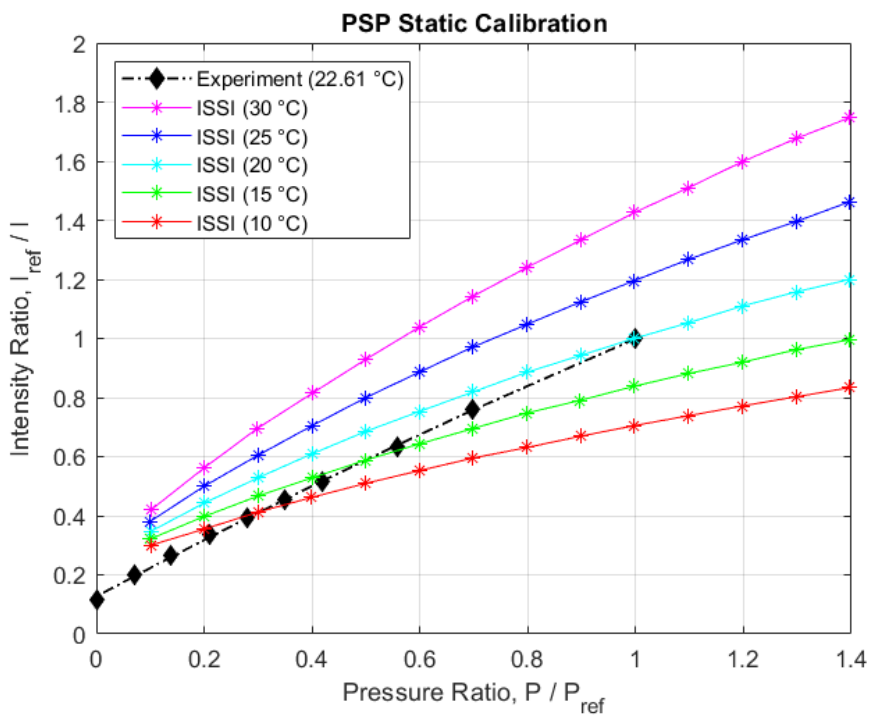

Fig. 6 PSP Static Calibration Curves for Alternative and ISSI PSP

Table 3 2^{nd} Order Stern-Volmer Coefficients for Alternative and ISSI PSP

	A_2	A_1	A_0
Experiment (22.61 °C)	-0.1041	0.9768	0.1266
ISSI (30 °C)	-0.2538	1.3935	0.2925
ISSI (25 °C)	-0.2090	1.1321	0.2800
ISSI (20 °C)	-0.1849	0.9269	0.2634
ISSI (15 °C)	-0.1465	0.7319	0.2561
ISSI (10 °C)	-0.1130	0.5745	0.2470

The slight discrepancies between the experimental data and the ISSI data are to be expected due to the person-sensitivity of PSP calibration. Any type of variable changed in PSP testing conditions, such as test location, how and where the PSP is applied or formulated, how long the PSP has been sitting on a shelf, or how much photodegradation the PSP has experienced, can all affect how the PSP responds, thus altering its static calibration. Even when UTSI performs wind tunnel tests with ISSI's Porous, Fast-Response PSP, a static calibration test is still performed before any actual experimentation, as their calibration results are often different from the ISSI calibration results posted on the ISSI website. Even with the static calibration discrepancies, the alternative PSP proved to be as viable a paint as ISSI's Porous, Fast-Response PSP for use in ground testing, specifically wind tunnel testing.

VI. Conclusion

This experiment tested the behavior of an alternative PSP prepared in-house to a viable commercially produced PSP (purchased from ISSI) by performing static calibration tests to measure PSP intensity against changes in pressure. Though the alternative PSP did not respond in the exact same way as the ISSI PSP, both paints still behaved in an equivalent manner by following a second-order curve relationship between the intensity and pressure ratios. The Stern-Volmer coefficients for both paints were also shown to be similar, with the experimental data at 22.16°C falling within a range ± 0.15 outside either of its temperature boundaries (i.e., 20°C and 25°C).

These results have proven that the alternative PSP is a viable option for use in ground testing, specifically wind tunnel testing. This means that ground-test facilities can begin using PSP that is both cheaper and available in massive quantities for all their pressure-measurement needs. This also means that even small-scale test facilities with lower budgets can begin using PSP to study aerodynamic phenomena non-intrusively. Due to the ability to formulate massive quantities of this alternative PSP, facilities can now be limited only by the size of their test equipment in determining the size of test models to study.

While the static calibration results prove the viability of this alternative PSP, further testing can still be done to further prove its viability, such as performing dynamic calibration tests. Due to time constraints and limited resources, the scope of this experiment could not afford to perform dynamic calibration tests on either alternative or ISSI PSP. As there is still much debate and research into the most effective way to dynamically calibrate PSP, future work could include performing dynamic calibration tests on both this alternative PSP and ISSI PSP with different methods of calibration to determine an effective alternative-PSP dynamic calibration. Additionally, this experiment could also be redone by physically performing static calibration tests on the ISSI PSP at the same time with the alternative PSP or by using an alternative PSP that was formulated right before calibration testing.

Acknowledgments

The author thanks Dr. Phillip Kreth for his MATLAB code and overall guidance in this experiment, as well as access to the UTSI's TALon, Mach 2 Wind Tunnel, and knowledge base. The author also thanks Jamison Murphree for his participation in the alternative PSP formation and guidance in the setup and execution of this experiment. Without these people, this research would not have been possible.

References

[1] Shinde, V. J., Gaitonde, D. V., and McNamara, J. J., "Supersonic Turbulent Boundary-Layer Separation Control Using a Morphing Surface," *AIAA Journal*, Vol. 59, No. 3, 7 Feb. 2021, pp. 912, 913.
doi: 10.2514/1.J059773

[2] Délery, J., and Dussauge, J.-P., "Some physical aspects of shock wave/boundary layer interactions," *ShockWaves*, Vol. 19, 26 July 2009, pp. 453, 454.
doi: 10.1007/s00193-009-0220-z

[3] Gregory, J. W., Sakaue, H., Liu, T., and Sullivan, J. P., "Fast Pressure-Sensitive Paint for Flow and Acoustic Diagnostics," *Annual Review of Fluid Mechanics*, Vol. 46, Jan. 2014, pp. 303-330.
doi: 10.1146/annurev-fluid-010313-141304

[4] Gregory, J. W., Asai, K., Kameda, M., Liu, T., and Sullivan, J. P., "A review of pressure-sensitive paint for high-speed and unsteady aerodynamics," *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, Vol. 222, No. 2, 1 Feb. 2008, pp. 249-290.
doi: 10.1243/09544100JAERO243

[5] Roozeboom, N., Powell, J., Baerny, J., Murakami, D., Ngo, C., Garbeff, T. J., Ross, J. C., and Flach, R., "Development of Unsteady Pressure-Sensitive Paint Application on NASA Space Launch System," *AIAA Aviation 2019 Forum*, AIAA 2019-3502, Dallas, TX, 2019, pp. 1-16.

[6] McMullen, R. M., Huynh, D. P., Gregory, J. W., and Crafton, J., "Dynamic Calibrations for Fast-Response Porous Polymer/Ceramic Pressure-Sensitive Paint," *AIAA Ground Testing Conference*, AIAA 2013-3123, San Diego, CA, 2013, pp. 1-18.

[7] Peng, D., Jensen, C. D., Juliano, T. J., Gregory, J. W., Crafton, J., Palluconi, S., and Liu, T., "Temperature-Compensated Fast Pressure-Sensitive Paint," *AIAA Journal*, Vol. 51, No. 10, 24 Sep. 2013, pp. 2420-2431.
doi: 10.2514/1.J052318

[8] Sugimoto, T., Kitashima, S., Numata, D., Nagai, H., and Asai, K., "Characterization of Frequency Response of Pressure-Sensitive Paints," *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, AIAA 2012-1185, Nashville, TN, 2012, pp. 1-11.
[9] Gregory, J. W., and Pandey, A., "Frequency-Response Characteristics of Polymer/Ceramic Pressure-Sensitive Paint," *AIAA Journal*, Vol. 54, No. 1, 10 Aug. 2015, pp. 174-185.
doi: 10.2514/1.J054166
[10] Kasai, M., Sasaki, D., Nagata, T., Nonomura, T., and Asai, K., "Frequency Response of Pressure-Sensitive Paints under Low-Pressure Conditions," Sensors, Vol. 21, No. 3187, 4 May 2021, pp. 1-20.
doi: 10.3390/s21093187
[11] Bencic, T. J., "Pressure-Sensitive Paint Measurements on Surfaces with Non-Uniform Temperature," NASA, 1999.