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New Self-Referencing Pressure-Sensitive-Paint Measurement

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I. Introduction

FOR most pressure-sensitive paints (PSP) the intensity ratio (I_0/I) and pressure ratio (P/P_0) relationship is nonlinear at low pressures (<0.2 psia when the oxygen level is low). This nonlinearity can be attributed to variations in the oxygen quenching rates. Other studies suggest that some paints also have nonlinear calibrations at high pressures because of heterogeneous (nonuniform) oxygen diffusion and quenching. In such cases errors caused by nonlinearity in calibration could be significant if the Stern–Volmer linear equation is used. Moreover, PSPs require correction for the output intensity as a result of light intensity variation, paint coating variation, model dynamics, wind off reference pressure variation, and temperature sensitivity. Here an in-situ intensity correction method is attempted to simplify the correction procedure. A nonoxygen quenched paint [which provides a constant intensity at all pressures, called

nonpressure sensitive paint (NPSP)] was used for the reference intensity I_{NPSP} with respect to which all of the PSP intensities I were measured.

PSP measurements provide a means for the recovery of global surface-pressure distributions on aerodynamic test articles.¹ A typical PSP consists of a 25–40 μm -thick reflective undercoat and a 25–40- μm thick coating of a luminophore dispersed in a binder layer. The binder is usually a polymeric material. The principle of operation of pressure sensitive paints is well described in the literature.^{2–5}

Under the appropriate illumination and constant quenching rates of fluorescence and internal conversion, the intensity of the luminescence emission from the paint is inversely proportional to the oxygen concentration and, hence, the air pressure on the surface. The luminescence of PSP can be expressed in terms of the well-known Stern–Volmer relation:

$$I_0/I = 1 + KP \quad (1)$$

where I_0 is the emission at zero-oxygen level and I is the emission at any pressure P . K is assumed to be a constant. It is generally not practical to measure I_0 in the wind-tunnel environment because the tunnel would have to be pumped down to a vacuum. Instead of trying to achieve zero-oxygen conditions, the intensity of emission at "wind off" I_1 is used as the reference intensity, and the pressure at wind off is considered the reference pressure P_1 . In practice, this is usually the local barometric pressure. In terms of the Stern–Volmer equation, this takes the form of the ratio of the Stern–Volmer relation for two pressures:

$$I_1/I_2 = A + BP_2 \quad (2)$$

Because luminescence intensity depends on illumination intensity, values for I are determined for each point on the wind-tunnel model at each angle of attack. The values for A and B are then determined from a plot of I_1/I_2 vs pressure, using pressure taps on the model for calibration. The accuracy of this type of calibration depends on maintaining constant and reproducible illumination at every model position. Because the light intensity at the surface of the model changes with the angle of attack, the reference intensity I_1 at every model position must be measured. To ratio correctly these wind-off measurements to the wind-on measurements, spatial registration dots must be placed on the model. These enable the wind-off and wind-on images to be aligned correctly.

The objective of this study is to develop a paint and measurement system that would not require the wind-off calibration and would correct for differences in illumination intensity over the model surface. Others have used dual luminophore PSPs to correct for light intensity variations and also temperature variations.^{5–8} However, mixing different luminophores in the same paint matrix nearly always produces spectral interference between the different luminophores. If the registration dots could be prepared from paint containing a luminophore that is not quenched by oxygen, the emission from the dots can also serve as a light intensity reference. The luminophore in the registration dots should be one that is excited by the same illumination used to excite the pressure-sensing luminophores in the PSP. Theoretically, the optimum system would have the same luminophore in the registration dots as in the paint but contained in a binder that is oxygen impermeable. This way the pixel intensity at the dot can be used as the light reference intensity. Having the same luminophore in the dot would eliminate the need for a filter wheel or filter shuttle on the camera in order to observe different wavelengths of light. However, practical binders have some oxygen permeability, and even a small amount of quenching of the luminophore in the dot would cause serious errors. It is easier to find a luminophore, which is not quenched by oxygen, than it is to find a totally impermeable polymer paint matrix. This would mean that the target dots would emit at a different wavelength of light than the PSP. Therefore, the reference luminophore should emit at a wavelength sufficiently different from that emitted by the pressure sensing luminophore to be resolved with different filters over the camera lens. Instead of taking the ratio of wind-off intensity to the wind-on intensity, the ratio of the intensity of emission from the nearest registration mark to

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Table 1 Paint and binder combinations that were tested

Spec	PSP Lum.	PSP binder	NPSP Lum.	NPSP binder
1	PtPFPP ^a	FEM-IBM ^c	Ru-bypy ^c	Clear coat
2	PtPFPP	FEM-IBM	PtPFPP	Clear coat
3	Ru-bath ^b	RTV-118 ^d	Ru-bath	Clear coat
4	PtPFPP	FEM-IBM	PtPFPP	PMMA ^f
5	PtPFPP	FEM-IBM	PtPFPP	Clear coat
6	PtPFPP	FEM-IBM	Ru-bypy	Clear coat

^aPlatinum tetra(pentafluorophenyl)porphyrine.^bRuthenium(II) tris 4,7-diphenyl-1,10-phenanthrolinechloride.^c2,2,2-trifluoroethylmethacrylate-co-isobutylmethacrylate.^dRoom temperature vulcanized 118.^eRuthenium(II), 2,2'-bipyridyl chloride.^fPolymethyl methacrylate.

the PSP emission intensity of interest would be used. Although this might not give a perfect correction for variations in light intensity, it should give a reasonably good correction.

The presented approach avoids the low reference intensity problems normally encountered in atmospheric pressure referencing. Although it might be difficult, if the intensity variation from the temperature of the NPSP is made the same as the PSP, then the proposed referencing method can be also used for temperature sensitivity correction of the PSP. Also, the NPSP can be used as target markers for model deformation determination in wind-tunnel testing. The following sections describe the tests that were performed in the NASA Langley Laboratory on a painted circular coupon in a test chamber to demonstrate the potential of this technique.

II. Experimental Setup and Procedure

The experimental setup⁹ consists of an adjustable pressure-vacuum chamber, a pressure transducer, two lamps for excitation, two 12-bit charge-coupled device (CCD) digital cameras or two 16-bit CCD cameras, two T-type thermocouple thermometers to monitor the specimen and test chamber temperatures, and a data acquisition system for the specified cameras. The test coupon size was 76 mm diam. In the center of the coupon, a 7-mm-diam circle was painted with NPSP, and the remaining surface was painted with regular PSP paint. Six specimens of different PSPs and NPSPs (as listed in Table 1) and camera combinations were tested. The pressure was varied from 0.001–2.7 atm, and the temperature range was varied from 15–35°C.

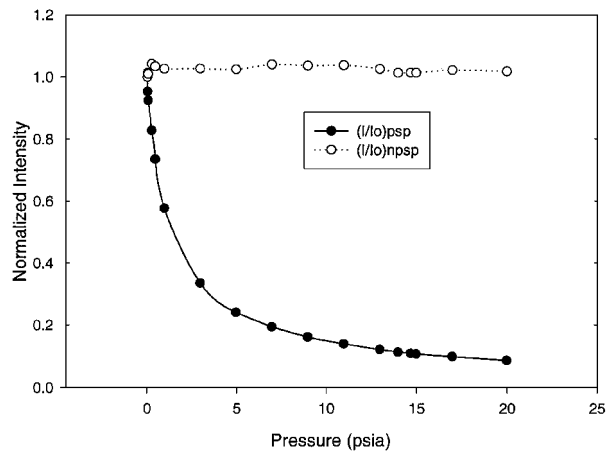
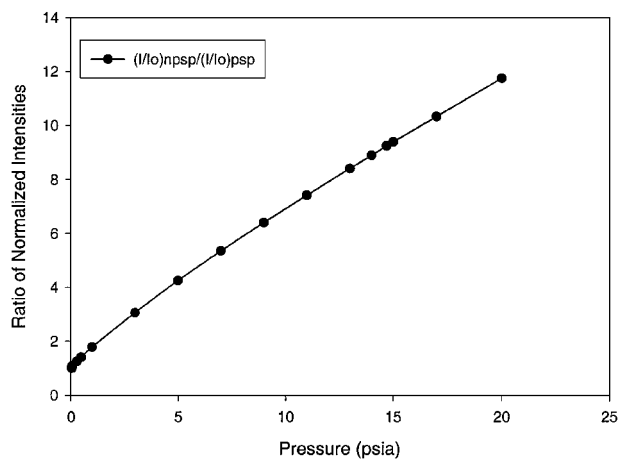
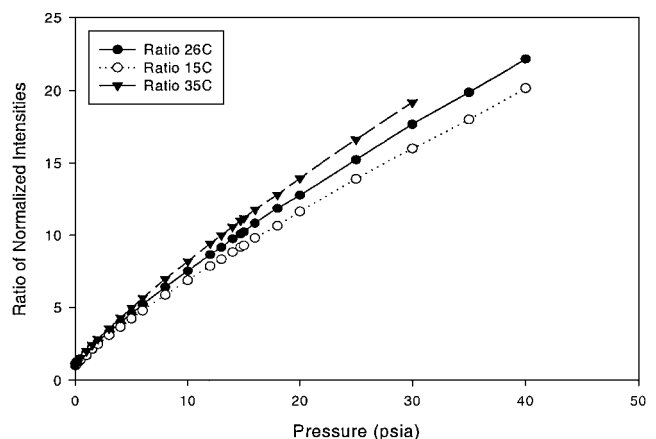
III. Results and Discussion

The results presented in the following figures show how the PSP and NPSP intensities vary with respect to pressure, temperature, paint type, and time (age).

Figure 1a shows the pressure response curves of the PSP and NPSP for the specimen 6 at 26°C. The PSP intensity is found to decrease by a factor of 10 when the pressure is increased from 0.01 to 20 psia, whereas the NPSP intensity changed only by a factor of 1.025. Thus for this specimen the NPSP provides a nearly constant intensity to which the PSP intensity can be referenced.

Figure 1b is a plot of the ratio of the NPSP and the PSP normalized intensities, which can be used for calibrating a given PSP and NPSP combination. For the specimen 6 tests one light source with a 390 ± 40 nm filter was used to excite both NPSP and PSP. A 16-bit Photometrics camera with a 650 ± 10 nm filter was used for the PSP imaging, and a 16-bit Photometric camera with a 580 ± 9 nm filter was used for the NPSP imaging. There was a 6.25-mm (0.25-in.) wide darkened ring around the NPSP.

Figure 2 shows the effect of temperature on the calibration curves for specimen 1. The plots in the figure were based on using intensity reference at the temperature of the run. The changes in the shapes of the calibration curves show that the PSP binders were temperature sensitive. Intensity reference I_{ref} also changed with temperature, which shows that the luminophore was also sensitive to temperature. In this case the use of the PSP and the NPSP does very little to correct for the effect of the temperature on the PSP calibration curves. The intensity ratio variations show that the intensity ratio increased for

NPSP & PSP Normalized Intensities, Specimen 6 at 26 deg C**Fig. 1a Normalized PSP and NPSP intensities. Uncertainties in pressure ± 0.02 psia at 20:1 odds.****Ratio of Normalized Intensities, Specimen 6 at 26 deg C****Fig. 1b Ratio of PSP and NPSP normalized intensities vs pressure for specimen 6.****Effect of Temperature, Specimen 1****Fig. 2 Effect of temperature on the ratio for specimen 1. Uncertainties in temperature $\pm 0.1^\circ\text{C}$ at 20:1 odds.**

Effect of Paint Specimen, at 26°C

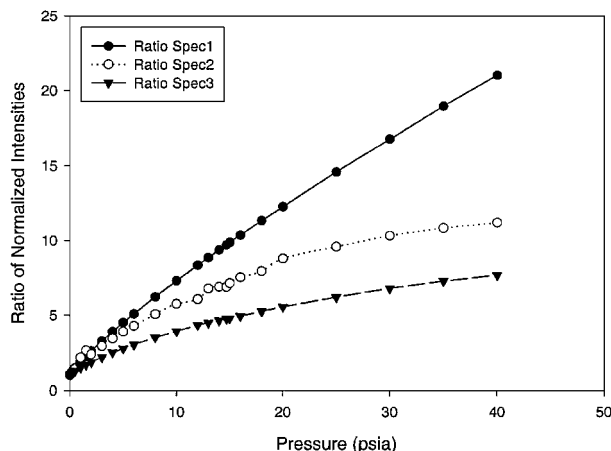


Fig. 3 Ratio of NPSP and PSP normalized intensities vs pressure for different paint specimens.

Effect of Replicates, Specimen 3

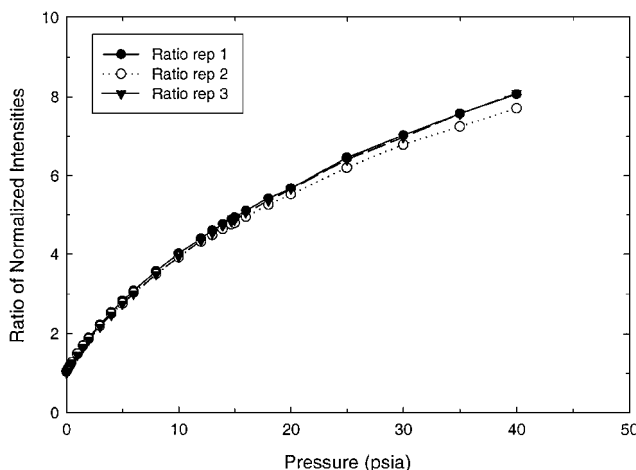


Fig. 4 Effect of replicates on the ratio for specimen 3 at 26°C.

increasing temperatures. For the specimen 1 tests one light source with a 450 ± 40 nm filter is used to excite both NPSP and PSP. However, a 12-bit Photometrics camera with a 650 ± 10 nm filter is used for the PSP imaging, and a 16-bit Photometric camera with a 580 ± 9 nm filter is used for the NPSP imaging. There was no darkened ring around the NPSP. Because of the emission spectral intensity separation, no cross talk between PSP and NPSP intensities is evident.

To understand the effect of different binders and luminophore combinations better, the calibration plots were developed for three different paint specimens—1, 2, and 3 (see Table 1) as shown in Fig. 3. When each specimen was analyzed separately, one can notice the effect of each paint combination. For example, specimen 1, which had Ru-bpy as the luminophores for the NPSP, was not quenched at all. This gave a good light reference. Specimens 2 and 3 use the same luminophore for PSP and NPSP, but with different binders. In this case because the emission wavelength was the same for NPSP and PSP, significant spectral leakage of intensity occurred. The spectral leakage was minimized by placing a darkened ring around the NPSP. Moreover, in contrast for the specimen 1 the NPSP intensities for the specimens 2 and 3 were decreasing with increasing pressure because their binders were not totally oxygen impermeable. The calibration sensitivity is more linear for specimen 1 as compared to specimens 2 and 3.

Figure 4 shows the result of three repeated calibration of specimen 3 at 26°C. Replicates 1 and 2 were done without the darkened

ring around NPSP, but replicate 3 was obtained with a 6.25-mm darkened ring. Each replicate took about 3 h to complete. All three replicates were performed over a period of about 30 h. The excitation source filter wavelength was 450 ± 40 nm, and the emission filter wavelength was 580 ± 9 nm. The isolation of NPSP from PSP by the darkened ring is found to minimize the spectral leakage of intensity. In the figure there is no noticeable change in the paint performance between the replicates up to 1 atmosphere pressure.

The sources of uncertainty in PSP measurement are generally from variations in source lighting, camera characteristics, and from pressure and temperature measurement errors. In the present case repeated measurements with the same camera and light settings produced about $\pm 2.5\%$ variations in the intensity ratios. The uncertainty estimate for the pressure measurements is ± 0.02 psia, and for the temperature measurements it is $\pm 0.1^\circ\text{C}$.

Conclusions

The results of the laboratory tests performed on six specimens of different PSP and NPSP, and camera combinations in a pressure-vacuum chamber over a pressure range of 0.001–2.7 atm, and temperature range of 15–35°C show the following:

- 1) The technique works well when the PSP and NPSP have distinctly different spectral emissivity.
- 2) The repeatability of the calibration relation is good, but the temperature dependence of the calibration is not small for the tested specimens.
- 3) The NPSP could be used as registration points in wind-tunnel testing.
- 4) When PSP and NPSP have the same luminescence probe molecules (in a different binder), spectral leakage/interference problems occur.
- 5) None of the tested NPSP binders for the single-luminophore binary paint were completely impermeable to oxygen.
- 6) This method does not provide a true globalized intensity correction, but only localized correction.

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