Pressure and Temperature Sensitive Paint

Pressure Sensitive Paints (PSP) and Temperature Sensitive Paints (TSP) are optical sensors for measureing the temperature and pressure of a remote surface. These sensors are based on the quenching of luminescent molecules that are sensitive to the local temperature or pressure. The following document describes the basics of TSP and PSP. More detailed reviews of PSP and TSP are given by Liu[1] and Sullivan as well as Mosharov[2], Radchenko, and Fonov. Finally, calibrations for several commercially available temperature and pressure sensitive paints are included.

Temperature Sensitive Paint

High resolution non-intrusive measurements of temperature using temperature sensitive paint have been demonstrated by several researchers. These measurements include boundary layer transition in a cryogenic wind tunnel[3] and heat transfer measurements on the impingements surface of compressible impinging jets[4]. A typical TSP consists of the luminescent molecule and an oxygen impermeable binder. The basis of the temperature sensitive paint method is the sensitivity of the luminescent molecules to their thermal environment. The luminescent molecule is placed in an excited state by absorption of a photon. The excited molecule deactivates through the emission of a photon. A rise in temperature of the luminescent molecule will increase the probability that the molecule will return to the ground state by a radiationless process, this is known as thermal quenching. The temperature of the painted surface can be meaetermined by monitoring the fluorescent intensity of the painted surface.

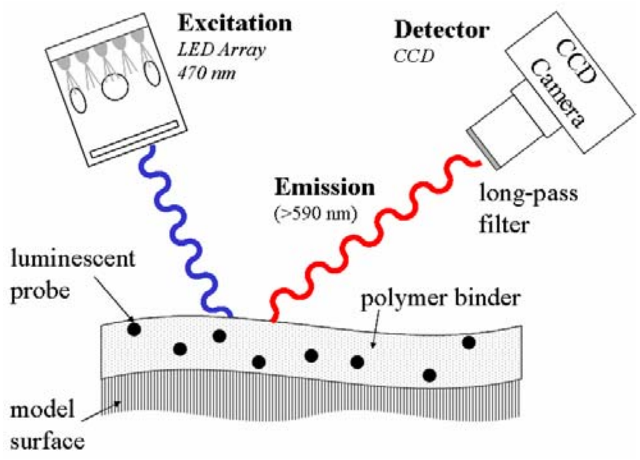

Figure 1 Basic Temperature Sensitive Paint system.

The luminescent intensity of the temperature sensitive paint at a given point is not only a function of temperature. For practical applications of TSP, spatial variations in illumination, probe concentration, paint layer thickness, and camera sensitivity will result in a variation in the detected luminescent intensity from the painted surface. These spatial variations are eliminated by taking the ratio of the luminescent intensity of the paint at the unknown test condition (***wind-off***) with the luminescent intensity of the paint at a known reference condition (***wind-on***). The experimental setup for temperature sensitive paint measurements is shown in Figure 1.

The relationship between paint temperature and paint luminescence is determined by calibrating the paint. This is accomplished by painting a small coupon with the TSP and exposing the coupon to a series of temperatures while monitoring the luminescent intensity from the painted surface. The luminescence at each temperature is normalized by the luminescence at a refernce condition and plotted versus temperature. The calibration of two typical temperature-sensitive paints are shown in Figure 2.

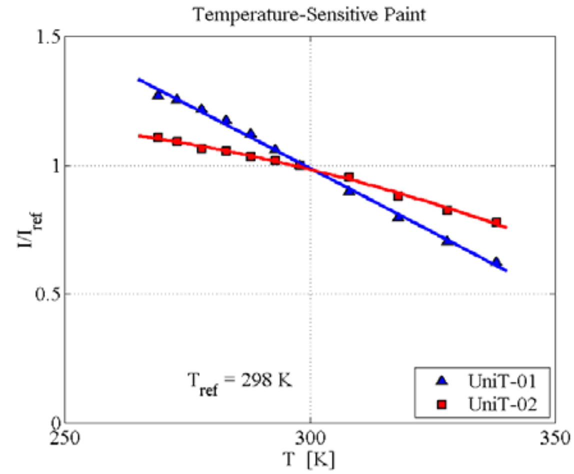

Figure 2 Calibration of two temperature sensitive paints. Simple application and storage (shipped in a spray paint can) and long shelf life. Exhibits good temperature sensitivity (1% per K).

Pressure-Sensitive Paint

Traditional measurement techniques for acquiring surface pressure distributions on models have utilized embedded arrays of pressure taps. This requires extensive construction time while producing data with limited spatial resolution. An alternative approach is to use Pressure-Sensitive Paint to measure surface pressure. Pressure measurements using PSP have been demonstrated in several challenging flow fields such as on the suction surface of an advanced compressor blade[5] and an aircraft wing[6] in flight. The advantages of PSP include non-intrusive pressure measurements and high spatial resolution when compared to conventional measurement techniques.

The PSP method is based on the sensitivity of certain luminescent molecules to the presence of oxygen. A typical PSP is comprised of two main parts, an oxygen-sensitive fluorescent molecule, and an oxygen-permeable binder. When a luminescent molecule absorbs a photon, it is excited to an upper singlet energy state. The molecule then typically recovers to the ground state by the emission of a photon of a longer wavelength. Pressure sensitivity of the luminescent molecules results when an excited luminophore interacts with an oxygen molecule and transfers some of the excited state energy to a vibrational mode of the oxygen molecule. The resulting transition to the ground state is radiationless, this process is

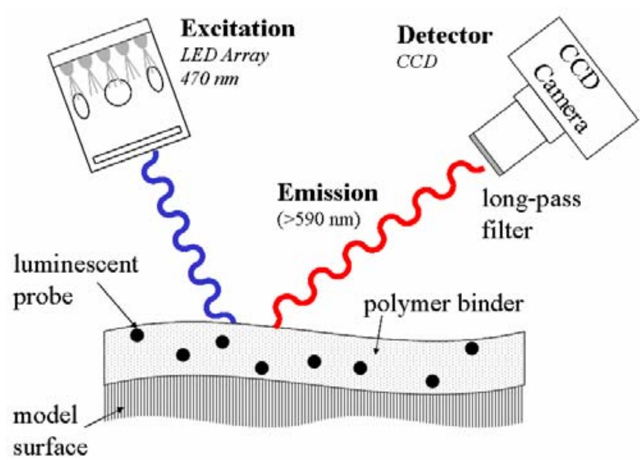

Figure 3 Basic Pressure Sensitive Paint system.

known as oxygen quenching. The rate at which the quenching process competes with the radiation process is dependent on the partial pressure of oxygen present, with a higher oxygen pressure quenching the molecule more, thus reducing fluorescence.

Conceptually a PSP system (Figure 3) is composed of a PSP, an illumination source, a detector, and a long-pass filter. The PSP is distributed over the model surface and the surface is then illuminated by the excitation source causing the PSP to luminesce. The luminescent intensity from the PSP is recorded by the detector and converted to pressure using a previously determined calibration. Unfortunately, the luminescent intensity from a pressure-sensitive coating can be a function of several parameters such as; spatial variations in excitation illumination, pressure-sensitive luminophore concentration, paint layer thickness, and camera sensitivity. These spatial variations are minimized by ratioing the luminescent intensity of the paint at the test or ***wind-on*** condition (I_T T_T) with the luminescent intensity of the paint at a known reference or ***wind-off*** condition (I_{ref}, T_{ref}).

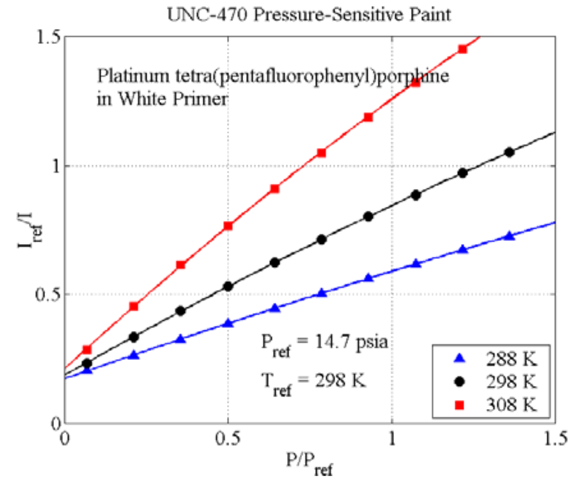

Figure 4 ISSI Unicoat. Simple application and storage (shipped in a spray paint can) and long shelf life. Exhibits good pressure sensitivity (4% per psi) but is also very sensitive to temperature (2% per K) Recommended for entry level PSP studies.

A final issue of concern for PSP is the dependence of luminescence on temperature. Temperature sensitivity of a PSP is generated by two mechanisms, thermal quenching of the luminescent probe and temperature dependent oxygen permeability within the polymer matrix that holds the pressure sensitive probe. Regardless of the mechanism, temperature sensitivity must be considered a major source of error[7], particularly for low-speed measurements. Generally a pressure sensitive paint is calibrated at a series of temperatures (as demonstrated in Figure 4 and Figure 5) and the appropriate calibration is applied in the data reduction process. The topic of minimizing errors in pressure sensitive paint measurements caused by variations

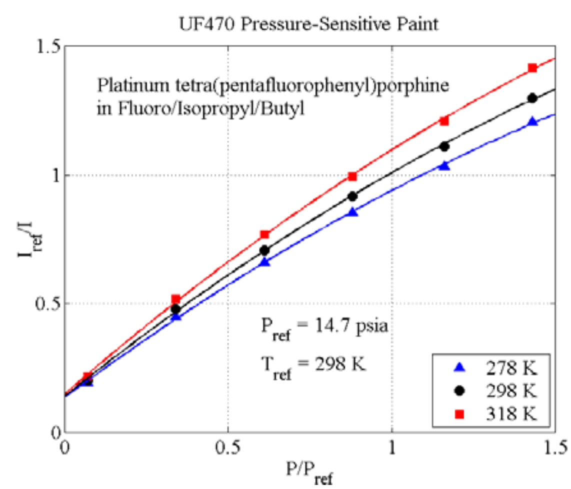

Figure 5 ISSI UniFIB. Exhibits good pressure sensitivity (5.5% per psi) and low temperature sensitivity. (0.5% per K) Advantages are single coat application, high pressure sensitivity, and low temperature sensitivity. Reccomended for quantitiative PSP studies.

in temperature and illumination is discussed in more detail in the Binary Pressure-Sensitive Paint wection of this document.

Calibration of Pressure Sensitive Paint

The functional relationship between luminescent intensity from a paint and the pressure and temperature experianced is determined using the PSP calibration chamber (Figure 6). A small aluminum coupon is painted with the PSP to be calibrated and this coupon is mounted onto a temperature controlled heat sink and mounted inside the calibration chamber. The pressure inside the calibration chamber is controlled using a pressure controller. The sample is illuminated using an ISSI LM2X LED, this lamp uses an array of LEDs' to produce excitation at 397 ± 10 nm . The luminescence from the sample is collected through a long-pass filter onto a PCO Series 1600 CCD camera. The calibration is begun by recording the luminescence of the sample at 298 K and 14.696 psia, this serves as the reference condition. The temperature and pressure within the chamber are then varied over a range of temperatures and pressures. The luminescence from the sample is recorded at each condition and the ratio $I(T_{ref},P_{ref})$ over $I(T,P)$ is computed and plotted versus pressure. Calibrations for two PSP formulation are shown in Figure 4 and Figure 5. A quick description of each paint formulation is included.

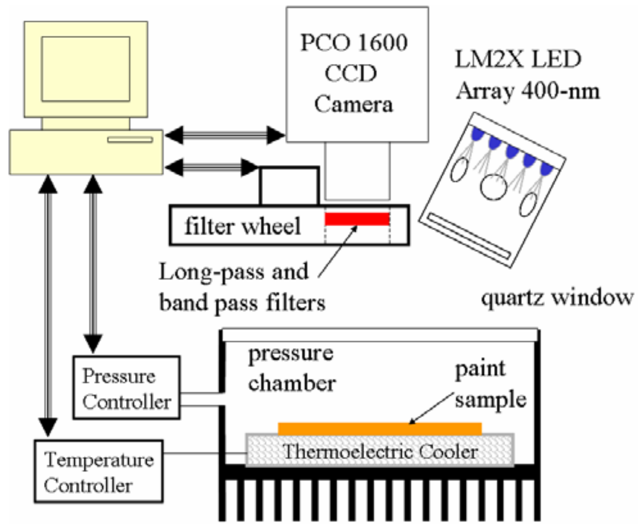

Figure 6: Pressure-Sensitive Paint calibration system.

Binary Pressure-Sensitive Paint

It is well documented in the literature that pressure sensitive paints exhibit undesirable sensitivity to variations in temperature and illumination. In fact, these variations in temperature and illumination are identified as the major sources of error in pressure sensitive paint measurements[7]. Several techniques for minimizing errors due to variations in temperature and illumination have been demonstrated, among the most promising is the concept of using a reference luminophor that compensates for illumination and decreases the sensitivity of the system to temperature[8]. It is in fact possible to generate a system where the temperature sensitivity is close to zero. This concept is the basis of the Binary pressure sensitive paint developed by ISSI.

Compensation for Variations in Illumination

The common approach to eliminating variations in illumination involves taking the ratio of a ***wind off*** image to that of a ***wind on*** image. This approach however assumes that the illumination at any point on the model surface is constant. The assumption of constant illumination is easily violated by slight variations in illumination intensity from the lamps, or more commonly, by slight movement or deformation of the model within the illumination field due to aerodynamic loads. The errors that result from these slight variations in illumination are more pronounced at low speeds where small changes in pressure (less than 1 psi) yield small changes in pressure sensitive paint luminescence (less than 1%). Therefore small variations in illumination significantly degrade the quality of the pressure data in low speeds.

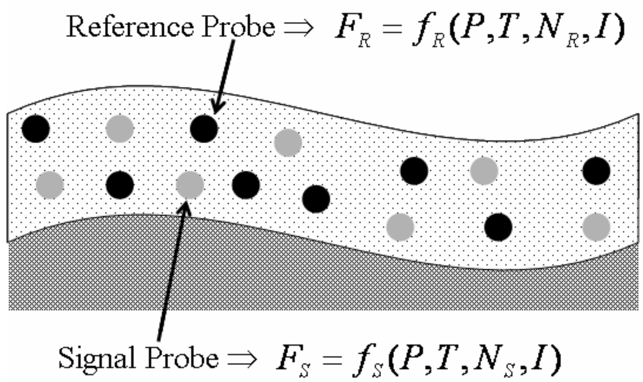

Figure 7: Binary PSP combines two luminescent probes into a single layer. The luminescent intensity F, of each probe is a function of pressure (P), temperature (T), luminophor concentration (N), and illumination (I):
$F = f(P,T,N,I)$

One means of dealing with the issue of variations in illumination is to employ a reference luminophor as shown in Figure 7. The goal is to use the luminescence of the reference probe, F_R to correct for variations in the luminescence of the signal probe, F_S (the pressure sensitive probe) that are caused by variations in paint illumination. This is accomplished by taking a ratio of the luminescence of the signal probe, to the luminescence of the reference probe. Assuming that both the reference and signal probes response is linearly proportional to the local illumination and probe number density the resulting function r is

$$r(P,T) = \frac{F_S(P,T)\,N_S * I}{F_R(P,T)\,N_R * I} = \frac{F_S(P,T)\,N_S}{F_R(P,T)\,N_R}\,. \qquad \text{Equation 1}$$

The dependence of r(P,T) on illumination has been removed, however the system is still a function of temperature, pressure, and relative luminophor concentration. Theoretically, the paint components are homogeneous and the ratio of signal probe to reference probe (N_S/N_R) is constant, experience has shown that this is not the case. An example of this non-uniform probe deposition for a binary paint is shown in the top portion of Figure 8. To remove the variations in the relative number density of the two probes, a ***wind on*** and ***wind off*** ratio is used.

$$L(P,T) = \frac{r_0(P_0,T_0)\, {}^{N_S}\!/_{N_R}}{r(P,T)\, {}^{N_S}\!/_{N_R}} = \frac{r_0(P_0,T_0)}{r(P,T)}\,. \qquad \text{Equation 2}$$

The effectivness of this approach is demonstrated in Figure 8. Here, the data presented at the top of Figure 8 has been divided by a second set of ratioed data. The noise caused by the non-uniform probe concentration has been significantly reduced and the system response is now a function of pressure and temperature only.

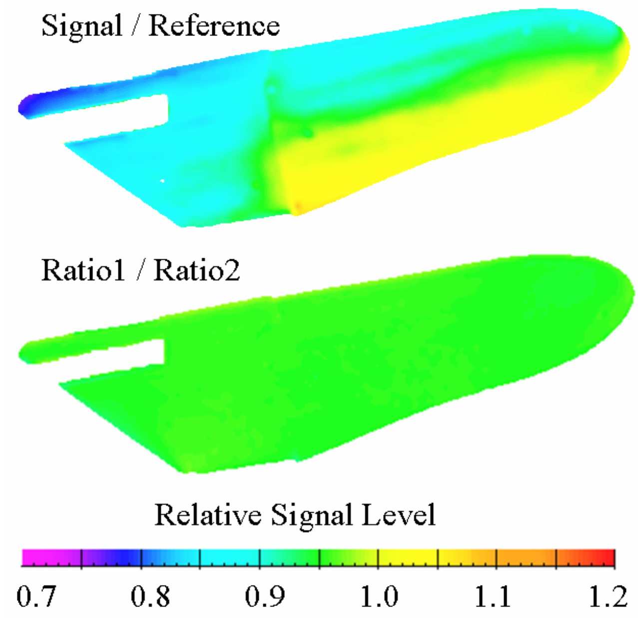

Figure 8: Ratio of sigal probe to reference probe (top) in a binary PSP showing the spatial variation in the concentration of the two probes. This spatial variation is removed by dividing the wind-off ratio by the wind-on ratio, a ratio of ratios.

At first it may appear that little has been gained by the system described in Equation 2. The experimentalist is still required to acquire a ***wind off*** image, in fact two images are now required at each condition rather than one. To demonstrate the power of the binary paint technique the user must also incorporate the process of image alignment or image mapping. The data reduction process described by Equation 2 is carried out in two steps. First the ratio of the signal probe to the reference probe is computed for both the ***wind off*** and ***wind on*** conditions. This ratio eliminates illumination from the system. Now to remove probe concentration, the ***wind on*** ratio image is mapped onto the ***wind off*** ratio image and the ratio of ratios is computed to remove the effects of probe concentration. Note that since all ***wind on*** images can be mapped back onto a single ***wind off*** image only a single ***wind off*** image is required. Used in this mode, the binary paint effectively eliminates half of the model configurations because only a single ***wind off*** condition is necessary. This represents a significant improvement in tunnel productivity. At the same time the errors in the pressure measurements caused by illumination have also been minimized therefore, the binary paint system provides several significant improvements over a traditional pressure sensitive paint system.

Selection of the reference probe is by no means trivial. The reference probe must be excited by the same illumination source that is used to excite the signal probe and the luminescence of the reference probe must be spectrally separated from the luminescence of the signal probe. The emission spectra of the ISSI BF405 PSP is shown in Figure 9. Finally to maximize the pressure sensitivity of the system, the reference probe should exhibit as little sensitivity to pressure as possible.

Compensation for Temperature

With illumination removed from Equation 2 the goal becomes minimizing the sensitivity of the system to temperature. The approach utilized involves allowing the reference probe, which is eliminating sensitivity to illumination, to compensate for the temperature sensitivity as well. While any degree of temperature sensitivity in the reference probe will yield a reduction in the temperature-sensitivty of the final pressure sensitive paint calibration, effective temperature compensation over a wide range of pressures is most easily attained by using an ideal paint.

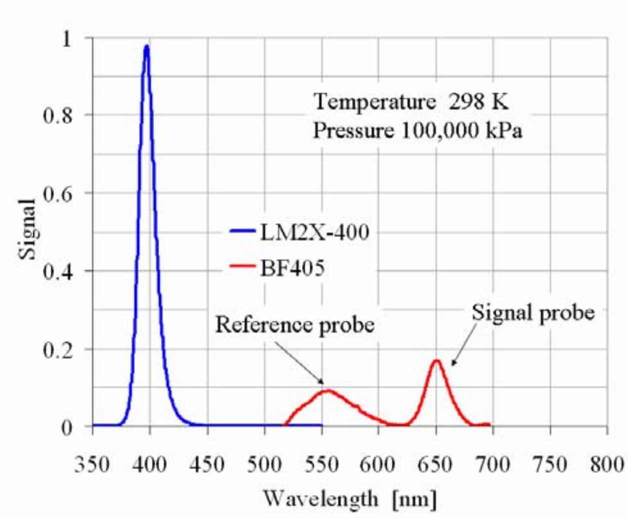

Figure 9: Emission of ISSI BF405 upon excitation at 397-nm.

All pressure sensitive paints exhibit some temperature-sensitivity. Temperature sensitivity of pressure sensitive paint is caused by several physical processes such as temperature-dependent oxygen permeability in the paint binder and thermal quenching of the luminescent probe. For most pressure sensitive paints the temperature-sensitivity of the paint is a function of pressure and the pressure sensitivity of the paint is a function of temperature. This coupling of temperature and pressure sensitivity was recognized as an undesirable feature by Puklin[9] et. al., who outlined the concept of the ideal paint. In an ideal paint the pressure dependence is not a function of temperature and the temperature dependence is not a function of pressure.

Eliminating sensitivity to temperature sensitivity is accomplished by adding two constraints to the selection criteria already outlined for a the binary paint. The combination of the signal probe and paint binder must form an ideal paint; and the temperature sensitivity of the reference probe must match the temperature sensitivity of the ideal paint. ISSI has developed a binary paint based on the PtTFPP/FIB pressure sensitive paint. PtTFPP/FIB is an ideal paint as defined above and therefore compensation of the temperature sensitivity over a wide range of pressures is possible.

Calibration of Binary Pressure Sensitive Paint

The equipment and procedure for calibration of a binary pressure-sensitive paint is similar to that used for single component paint systems. Once again, the ISSI pressure sensitive paint calibration chamber (Figure 6) is used to control the temperature and pressures to which the paint is exposed. A coupon is painted with the binary pressure sensitive paint and this coupon is mounted inside the calibration chamber and the sample is illuminated using an ISSI LM2X LED. The sample is imaged through a filter wheel onto a PCO Series 1600 CCD camera. The filter wheel contains a 645-nm long pass filter for the signal probe and a 550 ± 40-nm band-pass filter for the reference probe. The calibration is begun by recording the luminescence of the signal (F_S) and reference (F_R) probes at 298 K and 14.696 psia, this serves as the reference condition. The temperature and pressure within the chamber are then varied over a range of temperatures and pressures. The luminescence from each probe is recorded at each condition and the ratio of ratios as defined in Equation 2 is computed and plotted versus pressure. A calibrations for binary this binary paint (BF405) is shown in Figure 10, this paint exhibits good pressure sensitivity (4.5% per psi) with very little temperature sensitivity (less than 0.03 % per K).

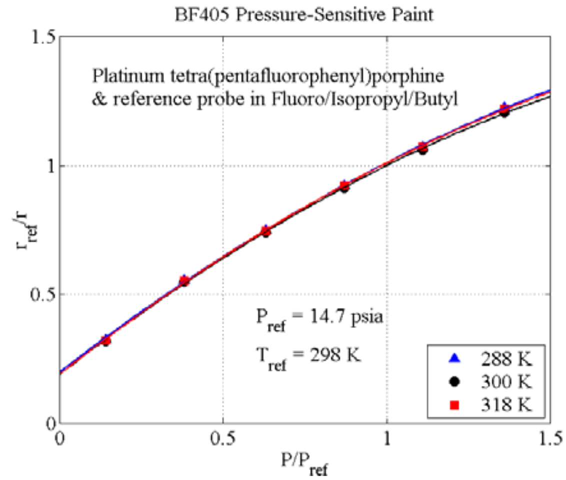

Figure 10: Calibration of ISSI Binary FIB. Exhibits good pressure sensitivity (4.5% per psi) and low temperature sensitivity. (0.03% per K.).

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