11TH INTERNATIONAL SYMPOSIUM ON FLOW VISUALIZATION
August 9-12, 2004, University of Notre Dame, Notre Dame, Indiana, USA

TEMPERATURE COMPENSATION IN TIME-RESOLVED PRESSURE MEASUREMENTS

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Keywords: *Time-Resolved, Pressure-Sensitive-Paint, Binary Paints*

ABSTRACT

Traditionally measurement techniques for acquiring surface temperature and pressure on wind-tunnel models have utilized embedded arrays of thermocouples and pressure taps. This approach requires significant model construction and setup time while producing data with limited spatial resolution. An alternative approach that has received considerable attention over the past 15 years is the use of luminescent probes that are sensitive to temperature and pressure. These techniques have resulted in high-spatial-resolution measurements of temperature and pressure on surfaces that in the past have proven to be inaccessible.

While Pressure-Sensitive Paint (PSP) has demonstrated significant potential in high-speed wind tunnels, several issues that limit the accuracy of the technique have been identified. Among these issues are errors due to model movement and deformation, instability of the illumination source, photo-degradation and sedimentation of the painted surface, and non-uniform temperatures on the model surface. The implementation of lifetime-based PSP systems has resolved many of these errors; however, non-uniform temperature distributions have remained an issue. This paper describes the development of a lifetime-based binary paint system for temperature compensated pressure measurements. The binary paint combines a temporally fast temperature component with a temporally slow pressure component in an ideal binder to achieve temperature compensation over a wide temperature range. By employing this approach, the temperature sensitivity of ISSI's PtTFFP/FIB pressure paint is reduced from 0.4% per ºC to 0.06% per ºC.

1 PHOTO-PHYSICAL PROCESS

A typical PSP is composed of two main parts, as shown in Fig. 1--an oxygen-sensitive fluorescent molecule and an oxygen-permeable binder. The PSP method is based on the sensitivity of certain luminescent molecules to the presence of oxygen. 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. In some materials oxygen can interact with the molecule such that the transition to the ground state is non-radiative; this process is known as oxygen quenching. The rate at which these two processes compete is dependent on the partial pressure of oxygen present, a higher oxygen concentration causing additional quenching of the molecule, resulting in a lower light intensity.

Unfortunately, PSPs are also sensitive to temperature. A rise in temperature will increase the probability that the molecule will transition back to the ground state through a non-radiative process. This process, known as thermal quenching, is the basis of the temperature-sensitive-paint (TSP)

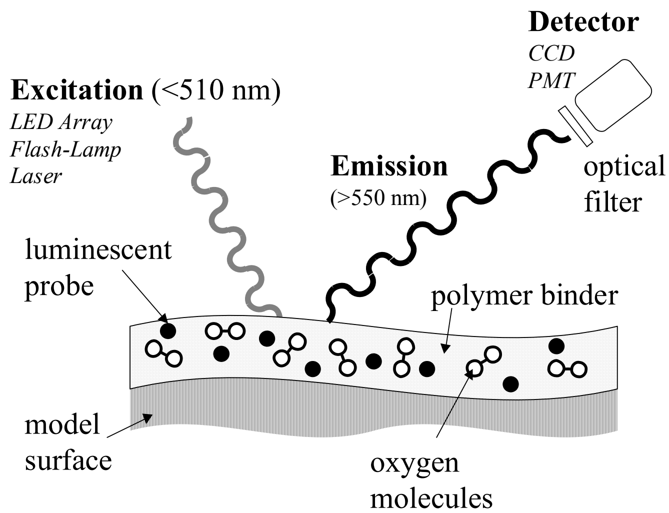


Fig. 1 - Components of a PSP system.

technique. A second source of temperature sensitivity occurs when the binder for the pressure-sensitive luminescent molecule has oxygen permeability that is a function of temperature. This is often the case for the polymer-based binders used for PSP. The calibration of two typical PSPs—Ruthenium-complex in Sol-Gel and PtTFPP in FIB--is shown in Fig. 2. From this figure it is clear that the binder can have a significant impact on both the temperature and pressure sensitivity of the system. Temperature sensitivity can lead to errors in converting the intensity distributions to pressure. Regardless of the paint formulation, effective implementation of a PSP requires that temperature effects be characterized and corrected.

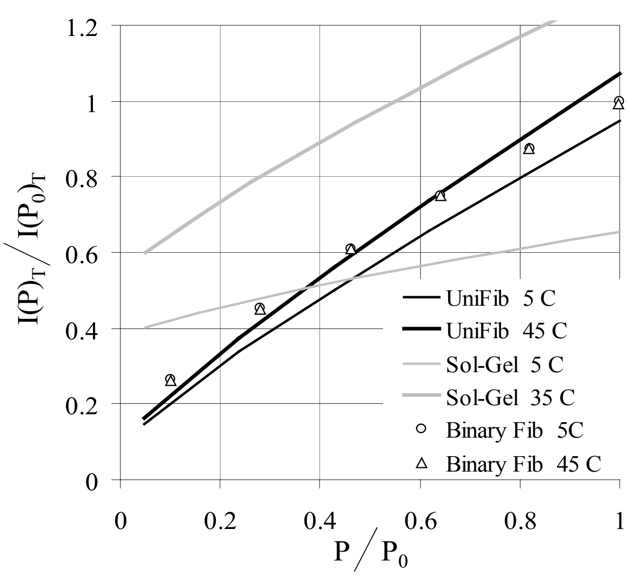


Fig. 2 Calibration of UniFIB, Ruthenium-complex in Sol-Gel, and Binary FIB. Note the high pressure sensitivity and low temperature sensitivity of the FIB binder and the extremely low temperature sensitivity of the intensity-based Binary FIB.

2 SOURCES OF ERROR FOR PSP MEASUREMENTS

Lifetime-based PSP systems have been proven to be very effective in eliminating errors due to illumination. All data are acquired at *wind-on* conditions; therefore, the model and tunnel are under load. Data acquisition occurs in a short time and deformation or displacement of the model is unlikely to occur under these conditions. The second source of illumination errors is the stability of the illumination source. ISSI has developed LED lamps that provide a very stable pulsed illumination source for lifetime-based PSP measurements. These LED pods incorporate a current-stabilizing resistive network and a stiff voltage source.

The origins of the temperature sensitivity of PSP were discussed in Section 1. For radiometric (intensity-based) PSP, errors in pressure measurements due to temperature are largely the result of changes in the temperature of the model surface between the acquisition of the *wind-off* and *wind-on* images. While lifetime-based techniques eliminate the need for a *wind-off* image, temperature errors can still be an issue. Any temperature gradient on the model surface will result in a temperature-induced error in the pressure measurements. These temperature gradients can be the result of model construction, tunnel operation, or fluid dynamics.

Some models are composed of a plastic or metal skin, with an internal metal support structure. The thermal mass of the internal structure will result in a temperature gradient on the surface if the model is subjected to a heat flux. The model is commonly exposed to a heat flux due to changes in tunnel operation--for example, Mach number. As the Mach number or model angle of attach is changed during a wind-tunnel test, the load on the tunnel changes. This change in load results in a slight change in the tunnel equilibrium, and the tunnel temperature changes. This condition is most apparent during tunnel startup, where the tunnel temperature can change significantly. While the model will eventually reach equilibrium with the tunnel, productivity requires that data acquisition continue. Elimination of temperature errors will provide a significant increase in data accuracy under these conditions. Finally, even after the model has reached thermal equilibrium, the temperature distribution on the model is not necessarily uniform. For compressible flows the recovery temperature must be considered. Assuming a moderate Mach number of 0.5, the boundary-layer transition should result in a temperature gradient of about 0.6 K. At Mach 1 this gradient is > 2 K. Next, consider the effects of a shock that could be present on a subsonic model if the airfoil is supercritical. The enthalpy is constant across the shock, but the velocity is not. In this case the temperature gradient will be the result of the velocity defect. Assuming a moderate Mach number of 1.1 and a turbulent boundary layer, a temperature gradient of > 2 K is likely.

Finally, the effect that these temperature gradients will have on the model is a function of the model material. If the model is constructed from a highly conductive metal, the boundary condition is closer to isothermal, and the temperature gradient will be moderated. However, the model will approach a steady-state temperature slowly as a result of conduction within the model. For a model constructed of low-thermal-conductivity material such as plastic, the boundary condition is closer to adiabatic. The temperature gradient will be larger, but the model surface will reach a steady-state temperature rapidly.

3 MULTI-GATE LIFETIME PSP SYSTEM

Lifetime-based PSP measurement systems have been developed by several groups. Techniques for measuring lifetimes have included phase-sensitive detection [1], direct measurements of fluorescent decay [2], and multi-gate integration [3] techniques. In each system all data are acquired at the *wind-on* condition, and this eliminates--or at least minimizes--illumination as a source of error. With illumination errors eliminated, errors due to temperature should become the dominant source of uncertainty in lifetime-based PSP measurements. The goal of the current research efforts is to incorporate a reference probe into the system and employ this probe to measure temperature. The feasibility of incorporating a reference probe into each system was analyzed, and the multi-gate lifetime system was selected for this development.

Goss et al. [4] preformed an analysis and showed that the signal-to-noise ratio could be maximized using a two-gate approach to lifetime measurements by the appropriate selection of the gate location and width. This two-gate approach could be incorporated into an image-based PSP system using a gated CCD camera. A system employing this two-gate approach has been used extensively by Sellers [5] for PSP measurements at AEDC. A schematic of the two-gate lifetime approach is given in Fig. 3. The PSP is illuminated using a pulsed LED array. The illumination pulse is approximated as a square wave and has a width of 10 μs. The response of the paint (shown in Fig. 3) can be modeled using an exponential function. The two-gate lifetime measurement is accomplished by integrating the luminescence from the probe during a specified portion of the rise or decay of the probe luminescence. The luminescence from the paint is a function of the probe distribution, paint thickness, and illumination field. A ratio of the two gates will eliminate these variations, and the resulting function will be sensitive to pressure and temperature only. The position of the gates is selected to optimize the pressure sensitivity of the system while maintaining a favorable signal-to-noise ratio.

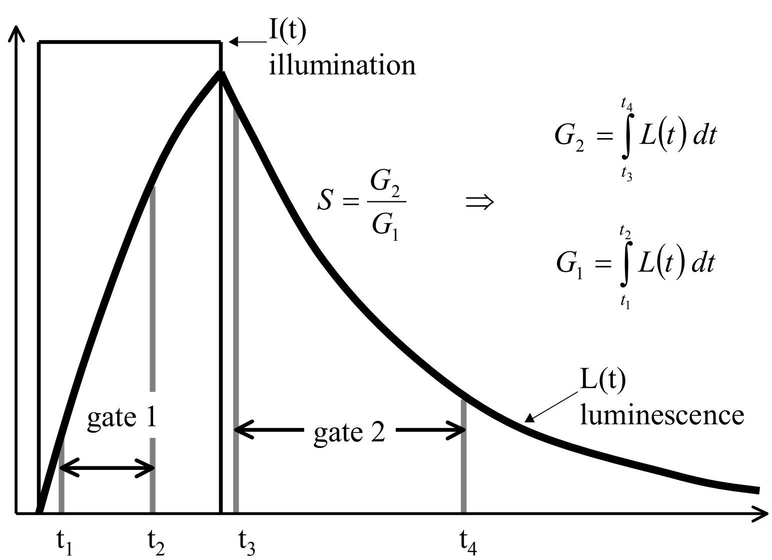


Fig. 3 - Luminescent lifetime of a pressure-sensitive probe, demonstrating the two-gate lifetime measurement approach.

Goss et al. [4] found that the initial rise of the luminescence (when the LED lamp is first turned on) exhibits little sensitivity to pressure, while the decay of the luminescence (after the LED lamp is turned off) exhibits substantial sensitivity to pressure. The ratio of several gates as a function of pressure for ISSI's PtTFPP/FIB paint is shown in Fig. 4. Note that as gate 2 is delayed from gate 1, the sensitivity to both pressure and temperature is increased. A binary approach that utilizes a reference (temperature-sensitive) probe which can compensate for temperature without greatly reducing the pressure sensitivity is the goal of our research efforts.

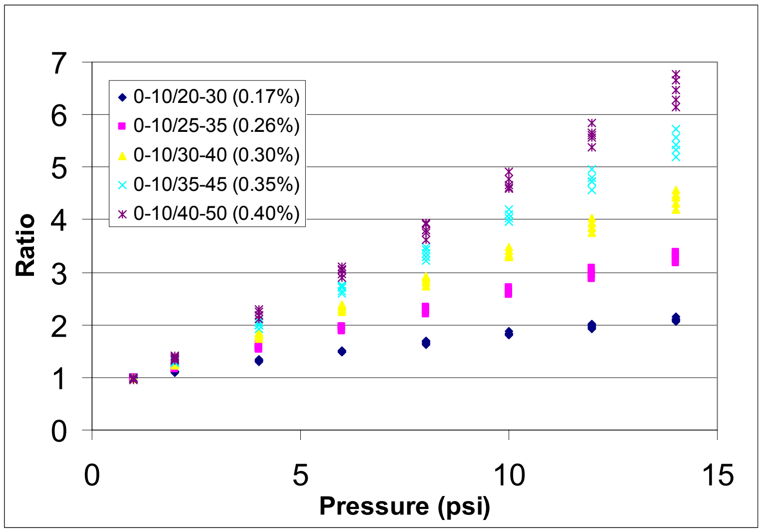


Fig. 4 - Various gate ratios for Pt:TFPP/FIB paint. All gates are in microseconds. Percentage-per-degree temperature sensitivity is given in parentheses.

4 TEMPERATURE COMPENSATION

Several techniques have been demonstrated for measuring model temperature while performing PSP measurements. Hradil [6] demonstrated a dual-lifetime approach using a short-lived Ruthenium complex as the pressure sensor and a long-lived phosphor as the temperature sensor. The temperature measurements are then used to correct the temperature-induced errors in the PSP data. Among the issues of concern for their system are the low temperature sensitivity of the phosphor (~ 0.3%/K) compared to the temperature sensitivity of the pressure sensor (~ 1%/K). The reported accuracy of the temperature measurement was ±3 K. Given the high temperature sensitivity of the pressure sensor, this system does not represent an improvement over the current pressure-measurement systems. Furthermore, the long lifetime of the phosphor is an issue with regard to tunnel productivity.

In the development of a temperature-correcting paint, an issue of significant importance is the type of temperature measurement that is needed (namely, absolute or relative). To understand this issue, one must consider the property of a PSP that Panomorv [7] defined as ideality. For a simple description of ideality, consider the slope of the pressure-calibration curve as a function of temperature. In the case of the calibration data that were shown in Fig. 2, the intensity at a single pressure and temperature was used as the reference point for all data. This plot demonstrates the temperature sensitivity of the paint. To demonstrate the ideality of the paint, data along each isotherm are normalized using the intensity at a reference pressure. The resulting plot (see Fig. 5) shows the slope of the paint curve at different temperatures. If the paint is ideal, the slope will be independent of temperature; the ISSI PtTFPP/FIB, shown in Fig. 5, achieves this result.

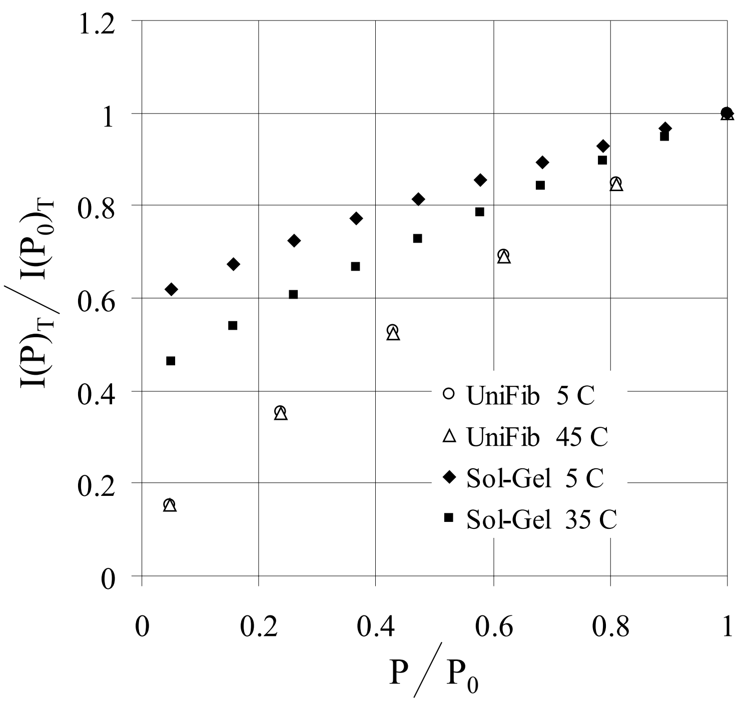


Fig. 5 - Ideality of Pt:TFPP in FIB and Ruthenium-complex in Sol-Gel. Calibration data along each isotherm were normalized using the intensity at that temperature and the reference pressure. The resulting plot shows the sensitivity of the paint at different temperatures.

Two basic approaches can be use for temperature compensation of pressure paint--whether in the time-resolved or in the intensity-measurement mode. The temperature channel can be used for compensation by either directly determining the absolute temperature or matching the temperature sensitivity of the pressure channel. In the former approach, we have the more difficult assignment of making an absolute temperature measurement. In the latter approach, only the relative temperature profile is needed.

In terms of paint ideality, as discussed above, the non-ideal paint is characterized by variable temperature sensitivity, while the ideal paint is characterized by constant temperature sensitivity. Thus, matching the temperature sensitivity of the pressure and temperature channels is much easier in the ideal paint case. In the non-ideal paint case, compensation of temperature by matching sensitivities can only occur over a very limited temperature range. Thus, an absolute temperature measurement is the only way to ensure compensation over a wide temperature range for a non-ideal paint.

Fortunately, the ISSI PtTFPP-FIB is an ideal paint, and temperature compensation over a wide temperature range can be realized by choosing the appropriate temperature probe. ISSI has developed and demonstrated a temperature-compensating binary PSP based using the ideal FIB binder. This binary paint minimizes the impact of temperature over a range of temperatures (5 – 45°C) and pressures (1 – 20 psia). Unfortunately, the system is designed using radiometric detection. However, the system does demonstrate the value of using an ideal paint when developing a temperature-correcting or -compensating system. Absolute measurements of temperature are no longer necessary because the slope of the sensitivity curve is independent of temperature. In fact, no attempt is made to measure temperature directly. The system employs a ratio-of-ratios approach that eliminates the need to measure temperature directly. The calibration of this paint is included in Fig. 2.

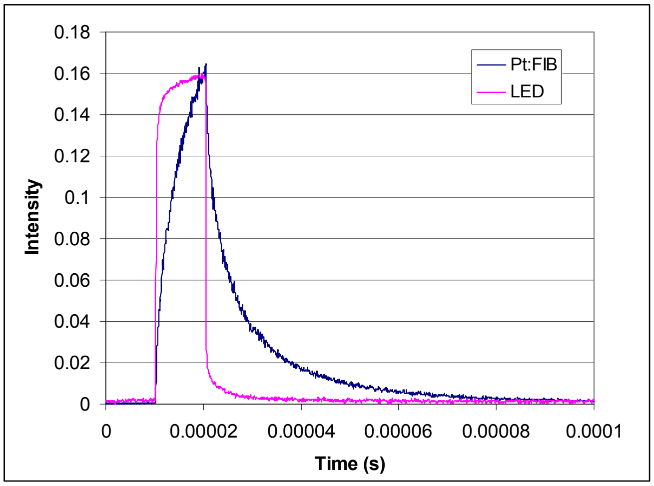
The main objective of this research is to develop a binary paint system which will compensate for temperature in the time-resolved measurement mode. As with our intensity-based binary paint, the ideal binder FIB and pressure probe PtTFPP are utilized. A temperature channel is introduced into this paint, with the goal being to match the temperature sensitivity of the pressure channel. As will be discussed below, this becomes an easier problem to tackle in the time-resolved mode than in the normal-radiometric mode.

4.1 Temperature Compensation Using Multi-Gate Lifetime Methods

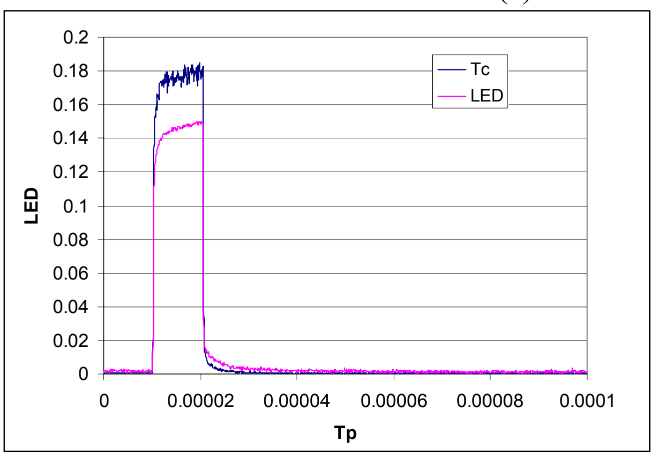
One mode of isolating the emission of the signal and reference probes is based on the luminescent lifetime of the probes, as demonstrated by Hradil [6]. Each probe is pumped using a pulse from a single excitation source, however the luminescence from the probes is distinguished by the difference in the lifetime of the luminescence. Radiometric binary systems based on the idea of temporal isolation have been proposed and demonstrated by Mosorov [8], Orlov [9], and Crafton [10]. In each case, the system was composed of probes with significantly different lifetimes. It can be shown that the degree to which the probes are isolated is a function of the difference in the lifetimes of the probes. Effective isolation requires that the probe lifetimes be different by two to three orders of magnitude.

In principle, complete isolation of the two probes may not be necessary or desirable. Consider the two-gate lifetime calibration of PtTFPP/FIB shown in Fig. 3. As discussed earlier the reference gate, gate 1, exhibits little sensitivity to pressure but also exhibits little sensitivity to temperature. Gate 2, however, exhibits good sensitivity to pressure and some sensitivity to temperature. The temperature sensitivity of the calibration that results from ratioing these two gates (see Fig. 4) is due mostly to gate 2. If one could enhance the temperature sensitivity of gate 1 without affecting gate 2, one could, in principle, nullify or cancel the temperature sensitivity of gate 2. This may be possible by adding a short lived reference (temperature) probe, which has the appropriate temperature sensitivity as the PtTFPP/FIB system. A demonstration of this approach is shown in Fig. 6. The fast reference probe used in this case has a lifetime that is significantly shorter than the LED excitation pulse. Thus, its emission is completely restricted to gate 1. The positive effect on the resulting calibration is evident in Fig. 7. The system maintains the pressure sensitivity, but the temperature sensitivity of the system has been significantly reduced; this was accomplished using only two gates.

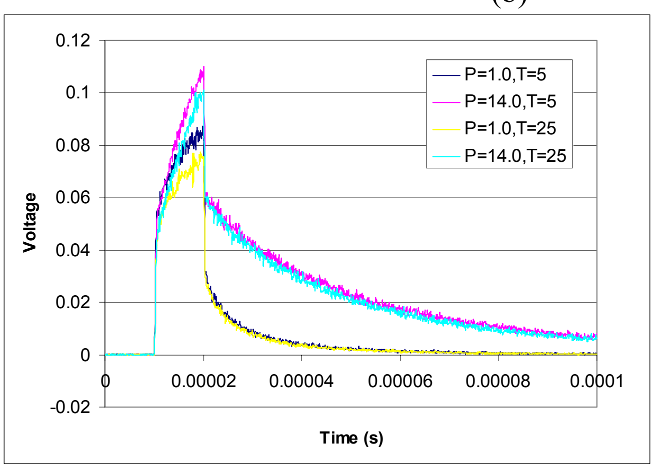
One issue of concern for a two gate binary system is the effect of probe distribution on the image-based result. Radiometric binary systems suffer from noise generated by non-uniform spatial deposition of the signal and reference probes on the painted surface. A simple ratio of the signal image to the reference image generally indicates that the probe deposition can vary by as much as 2%. This translates into an error in pressure of about 0.5 psi. For binary radiometric systems, this



(a)



(b)



(c)

Fig. 6 - Temporal response of (a) PtTFPP/FIB, (b) fast temperature probe, and (c) combined binary paint, illustrating that the fast probe can be used to affect the reference gate only.

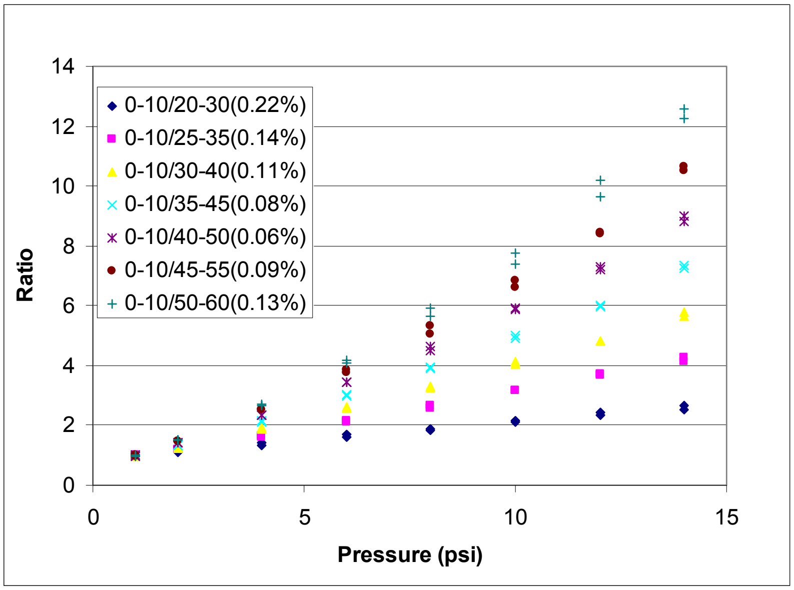


Fig. 7 - Various gate ratios for Pt:FIB/Tc binary paint. All gates are in microseconds. Percentage-per-degree temperature sensitivity is in parentheses.

issue is eliminated by acquiring a single *wind-off* image set. The wind-off image ratio is mapped onto the model geometry. Subsequent *wind-on* ratios are also mapped onto the model geometry, and a ratio of ratios is used to eliminate the non-uniform deposition of the probes. This approach has proven to be very effective in eliminating probe deposition as a source of noise in binary PSP measurements.

If necessary, the issue of non-uniform probe deposition for lifetime based binary paints can be addressed using one of several techniques. The solution to this problem may be as simple as incorporation of a third or fourth gate, which contains information from both temperature and pressure probes. Taking a single *wind-off* image, similar to the technique used for radiometric binary PSP, is also a possible solution. Finally, a solution based on a combination of multi-gate lifetime measurements and spectral isolation is also possible.

An alternative approach to temperature compensation that eliminates the issue of probe distribution involves incorporation of color separation into the multi-gate lifetime system. A second channel could be added to the system that performs an independent measurement of temperature using an identical two-gate lifetime approach. The luminescence of the two probes would be isolated using spectral separation, as in radiometric binary systems. The system would require the incorporation of either a filter switch or a separate reference camera that operates at a different wavelength. The data-reduction procedure would also be slightly different. As opposed to compensation for temperature, this technique would require the measurement of temperature. The separate temperature measurement would then be used to correct the PSP distribution. Even in this case the advantages of the ideal binder are still evident. While some error in the absolute temperature measurement will result in a slight bias error, this error can be corrected using a single in-situ tap. Use of an ideal binder means that only relative temperature measurements are needed to compensate for temperature gradients on the model surface.

5 CONCLUSIONS

A pressure sensitive binary paint has been developed for lifetime based multi-gate systems that compensates for non-uniform temperature distributions. The binary paint combines a temporally fast temperature component with a temporally slow pressure component in an ideal binder to achieve temperature compensation over a wide temperature range. By employing this approach, the temperature sensitivity of ISSI's PtTFFP/FIB pressure paint is reduced from 0.4% per ºC to 0.06% per ºC.

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