Pressure Sensitive Paint (PSP) / Temperature Sensitive Paint (TSP)
Part 1

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Introduction

Pressure measurements are the primary measurements made in most practical aerodynamic testing or basic fluid mechanics experiments.

Surface pressure measurements are used for:

• Identifying specific flow phenomena (boundary layer separation, shock wave impingement, etc) that are not easily measured by “standard pressure tap” measurements.

• Validation of computational codes

• Loads calculations by integration of the surfaces pressures
**Conventional pressure measurements: Transducers or taps:**

- **Discrete pre-determined locations**
- **Very high accuracy (< 0.05% FS)**
- **Well understood with long testing background**
- **High data rate with scanned systems (1000+)**
- **Limitations to where they can be installed**
- **Potential effect on the flow field – intrusive measurements**
- **Expensive installation costs**
Pressure Sensitive Paint (PSP)

- Sprayed over entire exterior surface
- Non-intrusive pressure measurements
- High spatial resolution with resolution limited only by detection system
- Limited to optical access applications
- Inexpensive application costs
- Relatively expensive initial costs to setup the system
- High-speed applications
- Newer method that is still being fully explored for low-speed applications.
Basic Principles of Pressure Sensitive Paint (PSP)

- Composition of Air: 78.08% $N_2$, 20.95% $O_2$, 0.93% Ar, 0.03% $CO_2$, 0.002% Ne, plus lesser amounts of Methane, Helium, Krypton, Hydrogen, Xenon.

- The pressure of air can be determined if the particle pressure of oxygen (i.e. oxygen concentration) can be measured.

- A typical pressure sensitive paint is comprised of two main parts: an oxygen sensitive fluorescent molecule and an oxygen permeable binder.
Basic Principles of Pressure Sensitive Paint (PSP)

- The pressure sensitive paint 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 (i.e. fluorescence or phosphorescence).
  - In some materials, oxygen can interact with the molecule so that the transition to the ground state is radiationless, this process is known as oxygen quenching.
  - The rate at which these two processes compete is dependent on the partial pressure of oxygen present, with a higher oxygen pressure quenching the molecule more, thus giving off a lower intensity of light.
Basic Principles of Pressure Sensitive Paint (PSP)

- For oxygen quenching, the intensity decrease can be described by the well-known Stern-Volmer equation:

\[
\frac{\tau_0}{\tau} = 1 + K_{SV} Q \quad \text{or} \quad \frac{\tau_0}{\tau_{O_2}} = \frac{I_0}{I_{O_2}} = 1 + K_{SV} P_{O_2}
\]

- \( \tau \) is the lifetime, \( I \) is the intensity
- \( K_{SV} \) is the Stern-Volmer constant
- \( Q \) is the quencher or partial pressure of oxygen
Advantages of Pressure Sensitive Paint (PSP)

• Pressure sensitive paint has numerous advantages over conventional pressure taps and transducers.
  – The most obvious is that PSP is a field measurement, allowing for a surface pressure determination over the entire model, not just at discrete points. Hence, PSP provides a much greater spatial resolution than pressure taps, and disturbances in the flow are immediately observable.

• PSP also has the advantage of being a non-intrusive technique.
  – Use of PSP, for the most part, does not affect the flow around the model, allowing its use over the entire model surface.
  – The use of PSP eliminates the need for a large number of pressure taps, which leads to more than one benefit. Since pressure taps do not need to be installed, models can be constructed in less time, and with less money than before.
  – Also, since holes do not need to be drilled in the model for the installation of taps, the model strength is increased, and higher Reynolds numbers can be obtained.
  – Not only does the PSP method reduce the cost of the model construction, but it also reduces the cost of the instrumentation needed for data collection. In addition, the equipment needed for PSP costs less than pressure taps, but it can also be easily reused for numerous models.

• In aircraft design, PSP has the potential to save both time and money.
  – The continuous data distribution on the model provided by PSP can easily be integrated over specific components, which can provide detailed surface loads.
  – Since a model for use with the PSP technique is faster to construct, this allows for load data to be known much earlier in the design process.
Disadvantages of Pressure Sensitive Paint (PSP)

- One of these characteristics is that the response of the luminescent molecules in the PSP coating degrades with time of exposure to the excitation illumination.
  - This degradation occurs because of a photochemical reaction that occurs when the molecules are excited.
  - Eventually, this degradation of the molecules determines the useful life of the PSP coating.
  - This characteristic becomes more important for larger models, as the cost and time of PSP reapplication becomes a significant factor.

- A second undesirable characteristic of PSP is that the emission intensity is affected by the local temperature.
  - This behavior is due to the effect temperature has on the energy state of the luminescent molecules, and the oxygen permeability of the binder.
  - This temperature dependence becomes even more significant in compressible flow tests, where the recovery temperature over the model surface is not uniform.
Basic Principles of Pressure Sensitive Paint (PSP)

- **Intensity based Methods (most common)**
  - Full-field using camera
  - Point systems using scanning laser

- **lifetime based Methods (lifetime decay)**
  - Full-field using camera
  - Point systems using scanning laser
Intensity based PSP

- The Stern-Volmer equation is rewritten in the popular intensity ratio form:
  \[
  \frac{P}{P_{REF}} = A + B \frac{I_{REF}}{I}
  \]

- A and B are highly dependent on the luminophore and binder material as well as the temperature sensitivity of the materials used to make the paint. A 2nd order curve generated from calibration data is most often used.
• Pressure air pipe to control the pressure in the chamber
• Water recirculation to control the temperature on the sample plate
Intensity based PSP

\[ \frac{P}{P_{REF}} = A + B \frac{I_{REF}}{I} \]

- Requires two readings, a reference at constant pressure (wind off) and an unknown data point (wind-on)
- Ratio of intensities \( \frac{I_{REF}}{I} \) is inversely proportional to the air pressure
- The excitation and detection systems must be spectrally separated, (>10^-6 attenuation in stop band)
- Simplest technique, most sensitive
- Very sensitive to motion between wind-off and wind-on
- A long period of time can elapse between reference and data.
- Images resulting in significant changes in contamination of paint, light stability, etc that cannot be normalized by the reference condition.
Intensity based PSP

\[
\frac{P}{P_{REF}} = A + B \frac{I_{REF}}{I}
\]

- **Advantages:**
- **Eliminate wind off images and image registration problems. It works in theory**
- **In practice, due to homogeneity problems of dispersing of two kinds of molecules, it actually requires a double set of ratios, often called ratio of ratios method.**

**Self-Referencing paints**

Pressure insensitive molecule

Pressure sensitive molecule
Intensity based PSP-temperature compensation

Temperature sensitive molecule

Pressure sensitive molecule

Advantages:

- Measure temperature to compensate for temperature sensitivity of PSP.
- This technique requires all four images to be aligned.