# Luminescent Paint for Air Pressure Sensing*

*R V Lakshmi, S T Aruna, Bharathibai J Basu*

**Luminescent coating, more popularly known as pressure-sensitive paint (PSP) is a relatively new aerodynamic measurement tool for providing a field measurement of pressure over a model surface in wind tunnel testing. It provides information on the flow anomalies present at any point on the surface, unlike the discrete data from pressure taps. The technique is based on the principle of dynamic luminescence quenching of luminescent molecules present in the paint by oxygen molecules. PSP coating comprises luminescent sensor molecules embedded in an oxygen-permeable binder. On illumination with light of an appropriate wavelength, the coating exhibits luminescence. The luminescence of the PSP coating is inversely related to the surface pressure on the coated model. This article discusses these aspects in detail and provides an overview of the work carried out in this direction across the world.**

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## 1. Introduction

The flow of air over the surface of an aircraft wing is the element which influences its lift and causes the aircraft to fly. Hence, the lift of an aircraft is the direct result of the pressure exerted over the surface of the wings by the flow of air. Pressure, which deals with the dynamics of the flow of air, is one of the important physical quantities in aerodynamics, Surface pressure measurements are of fundamental importance in aerodynamic testing. It has long been a desire of aerodynamicists to have this measurement accurately and flexibly. Generally, studies on fluid or gas dynamics are carried out in wind tunnels. Wind tunnels are ground-based experimental facilities where air currents are generated to simulate

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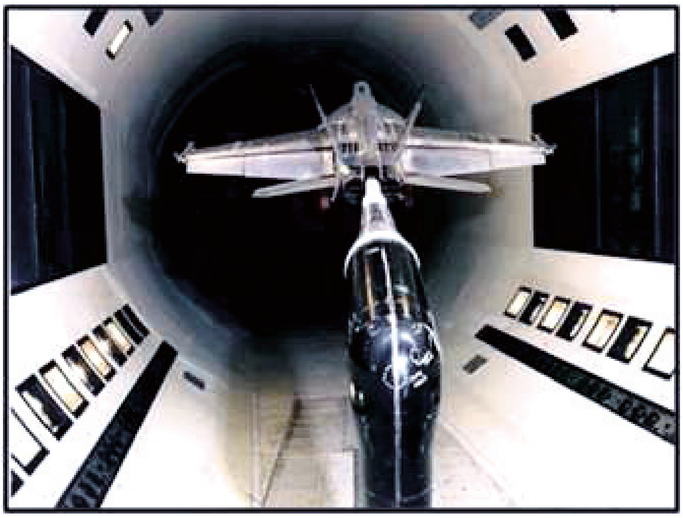

**Figure 1.** Aerodynamic model in a wind tunnel [1].

**Keywords**
Pressure map, oxygen, quenching, luminescence, wind tunnel, luminophores.

the actual airflow in the atmosphere. The aerodynamic models are placed inside the test section of the wind tunnel, and various physical parameters are altered to simulate the flow conditions identical to what the aircraft encounters during actual flight (*Figure* 1). Pressure is one such parameter frequently monitored in the wind tunnels.

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Conventionally, surface pressure measurements are based on data obtained from pressure taps or transducers. This technique, although very well known, and accepted for its accuracy and response time, has several limitations. The entire process of drilling the orifices and connecting the tubing is very tedious, time-consuming, and consequently extremely expensive. Further, when a high spatial resolution is required, the number of such pressure taps to be drilled in the model also increases. This is because of their very nature of providing information only at discrete points on a surface. Further, for model geometries including very thin airfoils, pressure taps embedding is simply not practically realizable. Thus, aerodynamicists have long sought alternate methods for measuring surface pressure.

In this direction, the pressure-sensitive paint (PSP) technique is a relatively new and promising experimental method. John I. Peterson and Raphael V. Fitzgerald introduced the idea of oxygen quenching of fluorescent compounds for flow visualization in wind tunnels [2]. Later, in the late 1980s, Gouterman and coworkers continued the usage of oxygen quenching for surface pressure measurements on aerodynamic models and performed a qualitative experiment at the University of Washington. The first quantitative experiment on PSP was performed at the National Aeronautics and Space Administration's (NASA's) Ames Research Center [3]. Recently, this technique has been extensively used as it has revolutionized the surface pressure measurements in aerodynamic testing. The method uses oxygen sensitivity of certain photoluminescent materials to map the pressure field over aerodynamic surfaces. It is taken in the form of 'paint', in conjunction with quantitative video and image processing techniques. It is a unique technique, wherein pressure variation is mapped on the model at a very high spatial resolution. As a pressure sensor, it can also provide data at "impossible to install taps" locations on the model. Thus, it provides pressure data over the entire model surface without the need for several pressure taps. Flow anomalies on the model surface become apparent with highly informative data. Thus, the construction of wind tunnel models becomes faster and relatively inexpensive. Thus, the PSP method has several advantages compared to the conventional discrete measurement method.

Recently, the pressure-sensitive paint (PSP) technique has been extensively used as it has revolutionized the surface pressure measurements in aerodynamic testing. The method uses oxygen sensitivity of certain photoluminescent materials to map the pressure field over aerodynamic surfaces.

## 2. Pressure Sensitive Paint

PSP is basically a paint that changes the intensity of light as a function of surface pressure. It functions on the principle of dynamic quenching of luminescence by oxygen and has been described in detail in several articles [4–8]. PSP typically comprises three different layers with different functionalities as represented in *Figure* 2. The paint layers are named as follows: (a) screen layer, (b) adhesive layer, and (c) active layer. As the name suggests, the screen layer screens the surface from anomalies. It is a white paint layer applied on the model surface to obtain optical

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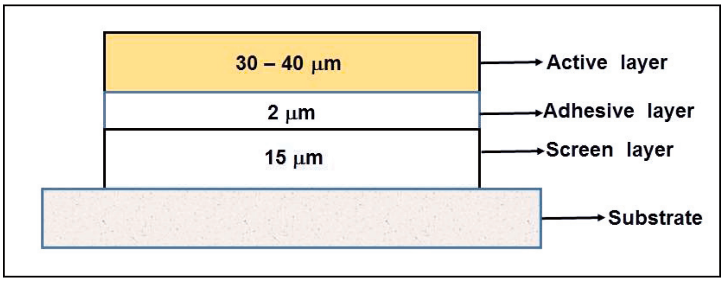


**Figure 2.** Schematic representation of different layers of typical PSP coating.

uniformity. It increases the emission intensity of PSP, aiding for the measurement to be possible on any model material. The second layer, which is the adhesive layer, ensures adhesion between two subsequent layers, the bottom screen layer and the top active layer. The third layer, often termed as the active layer, is the pressure sensor layer. This layer consists of fluorescent dye molecules embedded in an oxygen-permeable polymer binder. The thicknesses of each of these layers are about 15 $\mu$m, 2 $\mu$m, and 40 $\mu$m respectively.

The binder, which is basically a polymer, is the second important component of PSP [9]. It holds the luminophore on the solid support. Only few polymers are suitable for use in PSP formulations. It has to be soluble in a suitable solvent, so that it can be sprayed or applied as a smooth film. It must be inert and should not affect the luminescence of the PSP. Most importantly, it should display high and constant oxygen permeability. This factor depends on the orientation of the molecules, its density and the thickness of the active layer. The most common parameter for quantifying the diffusion of oxygen through a polymer is the permeability coefficient, $P$.

$$P = \frac{\text{(Thickness of the polymer film)} \times \text{(Quantity of oxygen)}}{\text{(Area)} \times \text{(Time)} \times \text{(Pressure drop across the film)}}$$

The luminescence paint is sprayed as a uniform coating of appropriate thickness on wind tunnel models. The paint is suitably illuminated, and the dye molecules get electronically excited to higher energy levels. They transit back to the ground level, and

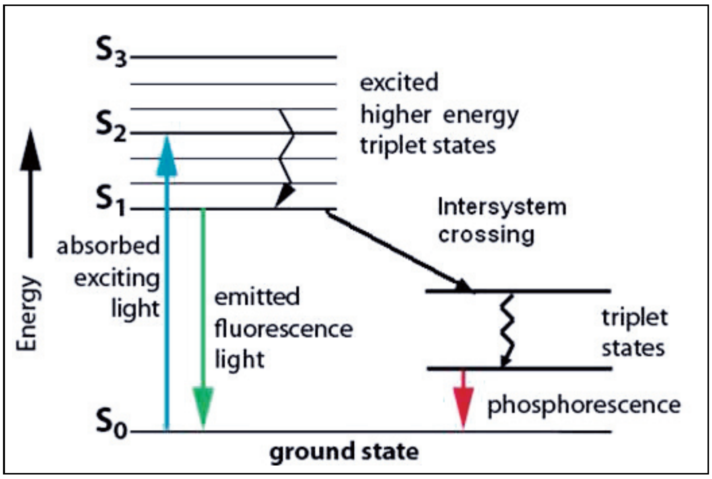


**Figure 3.** Jablonski energy level diagram [10].

the difference in energy is emitted as luminescence. This process can be well understood from the Jablonski diagram, shown in *Figure* 3. Some of the excited molecules collide with oxygen molecules and lose their energy in the process. This phenomenon is known as oxygen quenching. Upon quenching, the intensity of emitted light drops as the energy is taken away by the oxygen molecule. Since it is possible to relate the amount of oxygen in the test gas to static pressures, one can obtain pressure signals from the change in the luminescent intensity of PSP.

Stern–Volmer relation is used to describe the luminescence of molecule in solution that is subject to bimolecular quenching by species like oxygen [11]. According to the relation,

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$$\frac{I_{\max}}{I} = 1 + Kc, \qquad (1)$$

where $I$ is the luminescence intensity, $I_{\max}$ is the luminescence intensity obtained in the absence of oxygen (intensity is maximum because of zero quenching), $K$ is the Stern–Volmer quenching constant which is characteristic of luminescent molecules, and $c$ is the oxygen concentration ($O_2$). The values of both $I_{\max}$ and $K$ are temperature dependent. However, this form of the Stern–Volmer equation is not apt for any experimental setup as it is difficult to obtain luminescence intensity in the absence of oxygen.

A more suitable form of the above equation is derived by taking the ratio of intensities for two different flow conditions:

$$\frac{I_o}{I} = A + B\frac{P_o}{P}. \tag{2}$$

Here, $A$ and $B$ coefficients are coating sensitivities (which are temperature dependent) that are determined by experimental calculations. The parameters with zero subscripts denote measurements under 'no-flow' condition, where the pressure is constant over the entire surface. The intensity measurements are taken for flow on and flow off conditions. Since the pressure in the flow off condition ($P_o$) is known and the intensities $I$ and $I_o$ are measured, the pressure $P$ can be easily determined from the above equation. Also, by taking the ratio of the intensities, the effects of non-uniform illumination and paint distribution are effectively factored out. This is, however, under the condition that the geometry of the experimental setup and the illumination source remains constant between the measurement of $I$ and $I_o$.

The Stern–Volmer coefficients $A$ and $B$ are temperature dependent and are determined experimentally by calibration. Calibration can be a priori calibration carried out in a pressure chamber under controlled conditions or an in-situ calibration carried out in wind tunnels utilizing pressure taps over a model surface. The uncertainties in determining these values are the calibration errors represented by the standard deviation of data collected in replication tests. *Table* 1 list some proprietary PSPs developed by different R&D centres across the world [12]. The magnitudes of $A$ and $B$ for each of the paint are also provided. Generally, the coefficient $B$ that describes the pressure sensitivity of the paint is more important and looked for. Any PSP with $B > 0.5$ is considered acceptable for quantitative pressure measurements.

Most of the PSP systems used worldwide are intensity-based systems. Besides the intensity ratio method, the lifetime-based detection system is also a well-developed approach for PSP measurements.

Most of the PSP systems used worldwide are intensity-based systems. Besides the intensity ratio method, the lifetime-based detection system is also a well-developed approach for PSP measurements. The greatest advantage of the lifetime-based method over intensity-based method is that luminescence lifetime-temperature

| Active Luminophore | Binder | Excitation wavelength (nm) | Emission wavelength (nm) | Stern–Volmer coefficient | | Research group |
|---|---|---|---|---|---|---|
| | | | | A | B | |
| NASA-Ames PSP | Unknown | - | - | 0.38 | 0.62 | NASA-Ames |
| Mc Donnell Douglas PSP | Unknown | - | - | 0.18 | 0.82 | Mc Donnell Douglas |
| TsAGI | Unknown | 320–350 | 425–550 | 0.25 | 0.75 | TsAGI |
| LPSI2 PtTFPP | FEM | 390 | 650 | 0.17 | 0.83 | NASA Langley |
| PtTFPP | FIB | 390 | 650 | 0.13 | 0.87 | ISSI |

**Table 1.** Pressure sensitive paint characteristics reported by various research groups [12].

or –pressure relation is independent of illumination intensity. Therefore, the calibration relation is intrinsic for a particular paint, and the image ratio process is not required. Also, the lifetime measurement is insensitive to luminophore concentration, paint thickness, photodegradation, coating surface roughness, and the quality of optical surfaces. Hence, the lifetime method does not require reference intensity for correction and is ideally immune to problems associated with the above-mentioned factors. There are several lifetime methods namely: pulse method, phase method, amplitude demodulation method, gated intensity ratio method, etc., that can be used for calibration. In a typical lifetime calibration apparatus based on the pulse method, a pulsed excitation light source is used, and the exponential luminescent decay is measured using a fast-responding photodetector. The lifetime is calculated by fitting the time-resolved data with a single exponential or a multi-exponential function.

Generally, PSPs have been successfully applied in low-speed (Mach $< 0.3$), transonic (0.8–1.3 Mach) and supersonic (1.3–5 Mach) flows. Based on the speed, the luminophores and the matrix system of the PSPs differ. The accuracy of the data obtained is generally validated by comparing it with that of pressure port data obtained from a few key locations. It is typical to fix a few static

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pressure ports in the model at known key locations in order to compare the PSP data obtained at those points with that of conventional port data. The measurements are usually carried out in wind tunnel facilities. Flow conditions are decided based upon the study required, whether low speed or high speed or unsteady, and suitable wind tunnels are opted.

## 3. Luminescence Sensor Molecules

The luminophores used in pressure-sensitive coatings should possess high luminescence quantum yield, long emission lifetime, large Stokes shift, and excellent photostability.

The luminophores used in pressure-sensitive coatings should possess high luminescence quantum yield, long emission lifetime, large Stokes shift, and excellent photostability. The fluorescent compounds generally used for PSP studies are classified into three major groups: pyrene or pyrene derivatives, ruthenium compounds, and metalloporphyrins [9]. These luminescent molecules are excited with ultraviolet rays or visible light as needed by the compounds, and they emit luminescence in the visible region. Chemical structures of some of these luminophores are shown in *Figure* 4 [13]. Photophysical properties of some of these luminescent molecules are listed in *Table* 2.

Platinum porphyrins and ruthenium (II) $\alpha$-diimine complexes are very good candidates and preferred since their excitation and emission fall into the visible region of the electromagnetic spectrum. All metallo (Pt, Pd, Mg)-porphyrin complexes are highly stable dyes with large Stokes shift and long luminescence lifetime but have high temperature coefficients which can induce errors in the measurement. Therefore, they need temperature corrections. Pyrene-based pressure-sensitive paints (PSP) have certain advantages compared to other PSPs consisting of ruthenium dyes or porphyrin dyes. Pyrene based paints have relatively high pressure sensitivity and also low temperature coefficients. However, the main drawback is the degradation of the paint under wind tunnel conditions [2–6, 14, 15]. This problem has been dealt with and will be discussed in the later section. The paint is also sometimes referred to as binary PSP. This is because of the addition of a second luminophore as a reference component. This refer-

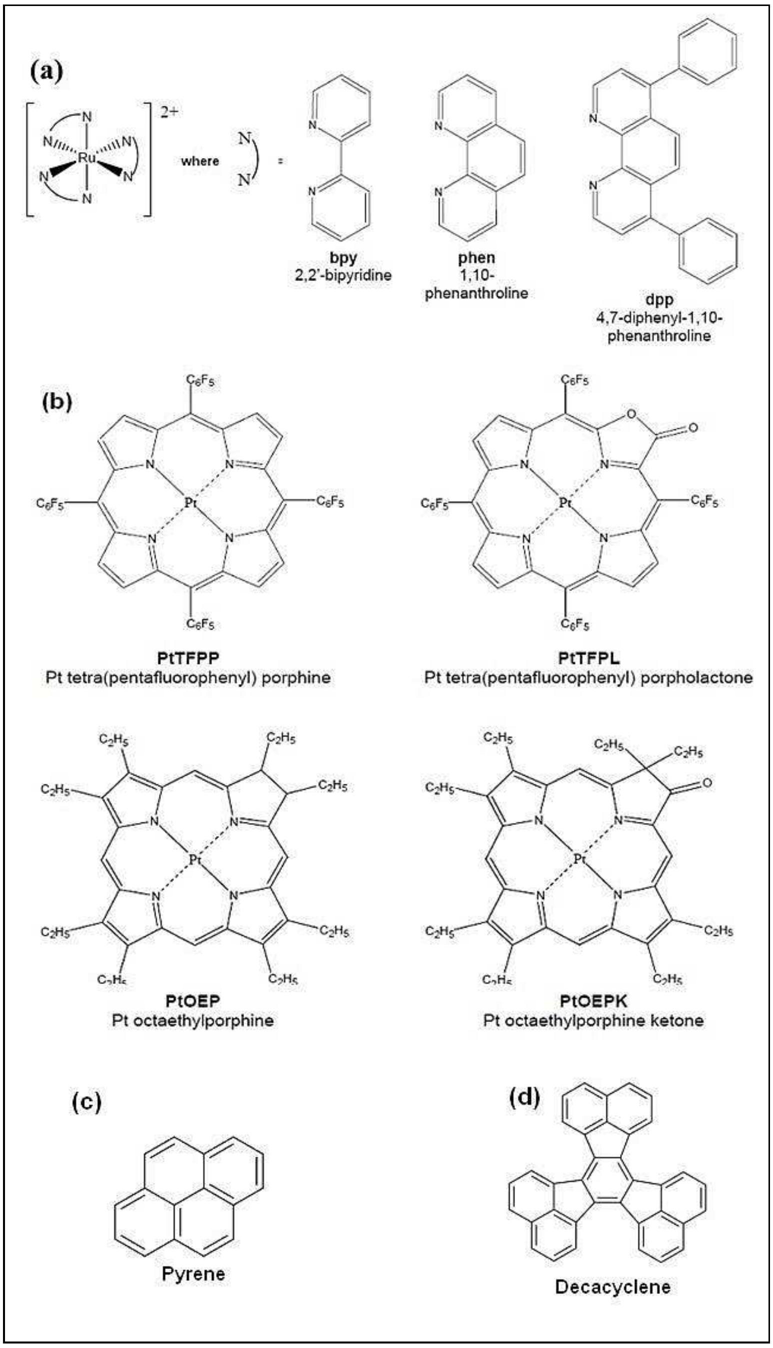


**Figure 4.** Structures of **(a)** Ruthenium(II) $\alpha$-diimine based dyes, **(b)** Porphyrin based luminophores (Pt can be also replaced by Pd), **(c)** Pyrene molecule, and **(d)** Decacyclene used for oxygen sensing [13].

ence luminophore in the binary PSP is sensitive to illumination

**Table 2.** Photophysical properties of commonly used luminophores.

| Luminophore | $\gamma_{abs}$ (max) (nm) | $\gamma_{em}$ (max) (nm) |
|---|---|---|
| Pyrene | 335 | 395 (monomer)<br>475 (excimer) |
| Decacyclene | 385 | 510 |
| [Ruthenium (dpp)$_3$]$^{2+}$ | 460 | 618 |
| [Ruthenium (bpy)$_3$]$^{2+}$ | 456 | 620 |
| [Ruthenium (phen)$_3$]$^{2+}$ | 444 | 596 |
| PtOEP | 381 (soret)<br>535 (non-soret) | 646 |
| PtTFPP | 395 (soret)<br>541 (non-soret) | 648 |
| PdOEP | 393 (soret)<br>512 (non-soret)<br>546 (non-soret) | 663 |
| PdTFPP | 407 (soret)<br>518 (non-soret)<br>552 (non-soret) | 653 |

light intensity variations on the model surface but is insensitive to pressure. Such luminophores are incorporated into the paint mixture to correct the variations in excitation intensity during wind tunnel experiments.

## 4. PSP Calibration System

A PSP measurement system generally consists of luminescent paint, illumination light, photodetector, and data acquisition/processing unit.

A PSP measurement system generally consists of luminescent paint, illumination light, photodetector, and data acquisition/processing unit. A schematic representation of the intensity-based PSP imaging setup is shown in *Figure* 5. The paint is excited with an appropriate excitation source, and the emission is imaged with digital cameras.

The light sources commonly used for illuminating the paint are

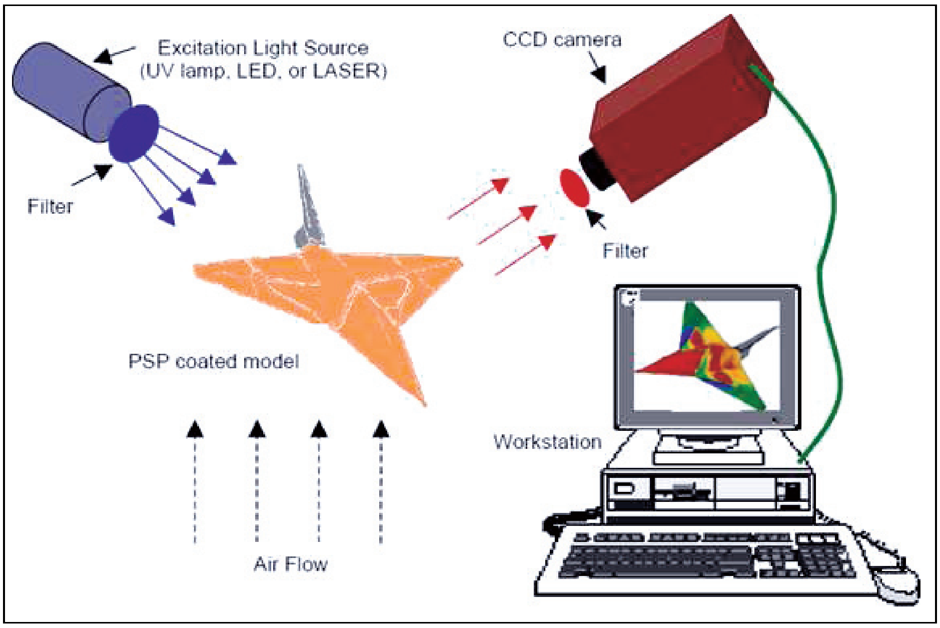


**Figure 5.** Intensity based PSP imaging setup [13].

lasers, ultraviolet lamps, xenon lamps, and light-emitting-diode (LED) arrays. Detectors are generally scientific-grade charge-coupled device (CCD) cameras because of their good linear response, high dynamic range, and low noise. Other commonly used photodetectors are photomultiplier tubes and photodiodes. Luminescent emissions from the paint are separated from the excitation light using optical filters. Stern–Volmer equation is used to deduce pressure data from the luminescent intensity. Since Stern–Volmer coefficients $A$ and $B$ are temperature-dependent, the necessary corrections have to be incorporated as they can form the major source of error in PSP measurements. Thus, accurate conversion of luminescent intensity to pressure using calibration relations with a correction of the temperature effect is a very crucial step in PSP. The final processing step contains the mapping of results in images onto a model surface grid in the object space [16]. The pressure data after PSP measurement will be as shown in *Figure* 6. It is evident that the pressure field measurement is over the entire surface with high resolution. In this image, the blue region indicates low-pressure areas and red indicate high-

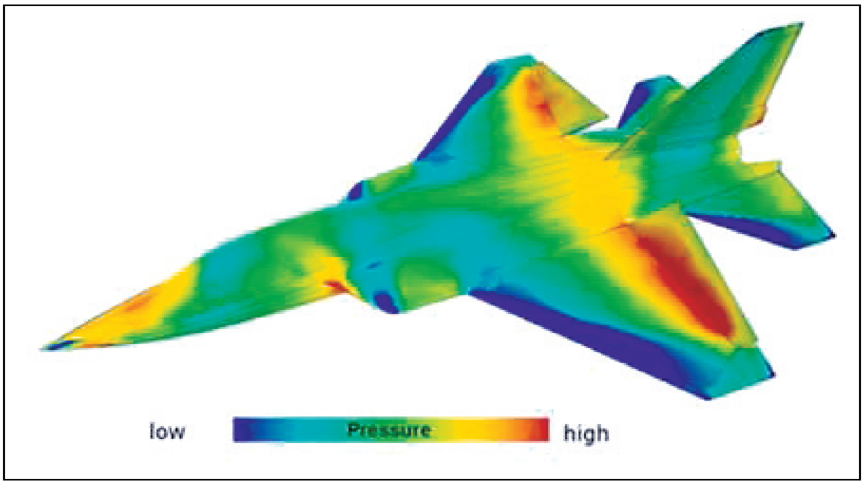


**Figure 6.** Surface pressure distribution of the PSP coated models of an aircraft [17].

pressure areas.

## 5. Other Applications of PSP

PSP measurement has also been used for acquiring film cooling effectiveness data in very complicated geometries. It is found to provide very high resolution contours of film cooling effectiveness, without being subject to the conduction error in high thermal gradient regions near the hole of the turbine blades.

Other than aircraft models, automobiles are also subjected to aerodynamic testing in wind tunnels. Automobile companies make use of the data collected in these tests to measure areas of high and low pressure [18, 19]. This helps engineers to improve designs to increase the performance of vehicles (reduce drag). Also, PSPs with very high response time can be used for measurements on unsteady flows [9, 20]. Unsteady or non-steady flow is one where the properties like velocity, pressure, etc., depends on time. They are undoubtedly difficult to analyze when compared to steady flow. PSP measurement has also been used for acquiring film cooling effectiveness data in very complicated geometries [21]. It is found to provide very high resolution contours of film cooling effectiveness, without being subject to the conduction error in high thermal gradient regions near the hole of the turbine blades.

## 6. Research on PSP Across the World and in India

Research on PSP development and improvement has been actively pursued by various aerodynamic communities all over the world in the last 25 years. Major US institutions like NASA Ames, NASA Langley, NASA Glenn, Boeing, Arnold Engineering Development Center, and US Air Force Wright–Patterson Laboratory have been involved in this study. Other research centres across the world, namely, British Aerospace, British Defence Evaluation and Research Agency in the United Kingdom, Deutsche Forschungsanstalt fur Lüft- und Raumfahrt in Germany, Office National d'Etudes et de Recherches Aerospatilaes in France, National Aerospace Laboratory in Japan, TsAGI in Russia, University of Florida, Purdue University, and the University of Washington are actively pursuing research on PSP [13]. Recently, the University of Manchester, Kyushu University of Japan, Agency for Defense Development in Korea, and few other research centres have also initiated research on PSP [20, 22].

In India, PSP development and implementation are being actively pursued at CSIR-NAL since the past few years. The mechanism of degradation of pyrene-based PSP coatings has been studied and found to be due to the diffusion and sublimation of pyrene from the coatings [14]. A novel and stable binary PSP formulation in which pyrene is covalently bonded to the polymer binder to prevent paint degradation has been indigenously developed [15]. The PSP formulation is found to be suitable for wind tunnel studies under transonic and supersonic flow conditions, and it has been used for mapping surface pressure distribution on wind tunnel models at NAL.

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## 7. Summary

Surface pressure measurements are of fundamental importance in aerodynamic testing. PSP technique is an optical method employed for mapping the surface pressure distribution on wind tunnel models. Based on the principle of luminescence quenching by oxygen, the luminescence of the PSP coating is inversely proportional to the local air pressure on the coated surface. This technique has a luminescent coating painted on a model surface as the key component. The luminescent molecules are excited in the ultraviolet or the visible range, and the emitted luminescence intensity is used to map the surface pressure distribution on the models. Thus, this technique provides pressure data over the entire model surface, and the flow anomalies at any point on the surface become immediately obvious. This is a major advantage of PSP over the discrete tap data obtained from the conventional method.

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