An Analysis of Pressure- and Temperature-Sensitive Paints: Principles, Methods, and Applications

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Pressure- and Temperature-Sensitive Paints (PSP and TSP) are thin, luminescent coatings applied to surfaces used to non-intrusively measure surface pressures and temperatures fields. With the use of oxygen and thermal quenching, PSP and TSP allow for quantitative, accurate measurements of complex areas and fluids without causing flow disturbances. This allows for significant advantages over traditional methods of observation, without the cost, complications, or error. This paper presents a summary of the fundamentals, mechanisms, and other aspects of this endlessly applicable technology.

Nomenclature

PSP	=	Pressure-Sensitive Paints
TSP	=	Temperature-Sensitive Paints
PTSP	=	Pressure/Temperature-Sensitive Paints
M	=	Mach number
Re	=	Reynolds Number
UV	=	Ultra Violet
CCD	=	Charge-Coupled Device (Camera)

I. Introduction

THESE Pressure- and Temperature-Sensitive paints are thin coat luminescent polymers that are able to react to the pressure and temperature forces applied on them, and can be measured accurately and quantitatively, and can be used as diagnostic tools for studying the phenomena in complex flows around any body. This technology allows for non-intrusive analysis of a number of areas of interest in aero and hydrodynamics, such as steady flow, shockwaves, transitional flow, and flow separation. With what would normally require complex machinery to study the specifics of flow around complex bodies, the application of PSP and TSP are simple, high-resolution, and quantitative means of mapping and analyzing.

The methodology applied to modern PTSPs goes back to 1980, in which Peterson and Fitzgerald demonstrated specific dyes that can be quenched by oxygen, and would emit light inversely correlated with local air pressure [1]. From then on, the importance of this discovery was quickly recognized, and polymer PTSPs began including more complex and sensitive elements. This need for better paint polymers is driven by the usefulness in detailed studies without the use of invasive complex machinery, and can now be used in conditions from low speed to hypersonic regimes.

The scope of this paper will be to define the capabilities of the technique, and describe the principles. Then, the paper will describe the procedure for implementing the technique, along with critical aspects needed to ensure success, as well as the advantages of this technique compared to equivalent and conventional measurement methods. Finally, the scope of this paper will also describe both applications and directions for future progress in this technology.

I. Capabilities

The primary capability of this technology is to use non-contact surface measurements for complex aerodynamic models, providing high resolution readings for heat and pressure distributions. The extent to which PTSP can perform is wide, being used anywhere from low-speed liquids to hypersonic air conditions. In 2002, researchers utilized TSP

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in test conditions ranging from 9.5 to 11.1 Mach, and Reynolds numbers of 140,000 to 300,000 per meter, covering a wide range [1].

These advanced experiments demonstrate the ability for TSP to measure quantitative heat transfer with appropriate insulation thickness, and short durations in hypersonic conditions. Beyond the extremes, it is useful for visualizing laminar-turbulent transitions, and can be used reliably without concern for error. A special case for this is the application in rotating machinery. Normally, to have rotating parts with recorded pressure and temperature, you would need complex additional machinery, and it would often have conflicting and intruding results, especially with models. By using PTSP, you can analyze moving parts with high accuracy without needing to attach complex sensors and machine parts [2].

II. Principles

The basic principle for PTSP is oxygen and thermal quenching, however the mechanisms between the two, and their resulting use are vastly different. This section aims to describe the two separately. PSP functions through oxygen quenching, in which oxygen interacts with luminescence within the dye, and the amount it reacts is related inversely to the amount of oxygen [2]. Therefore, a higher pressure means more oxygen, meaning a lower intensity of light. This principle is derived from Stern-Volmer relation, which relates the luminescence and its intensity to the partial pressure and temperature of the oxygen in the system. Because of this reliance on oxygen, there is a binder role in the fluid which should interact with the oxygen, and is the limiter of the response time of the dye. Porous binders, such as aluminum, significantly improve response time, which is handy for unsteady or turbulent flows. As mentioned, the oxygen inherently reacts to temperature, making PSP also TSP to an extent [2]. This can affect readings and may require corrections using TSP systems.

TSP relies on thermal quenching, which reacts inversely in terms of luminosity. Increased temperatures work to reduce the luminescence of these dyes. The binder that TSP functions best under is one that is oxygen-impermeable, in order to prevent pressure from interacting with the output of the dye [1]. The dependence of temperature from TSP dye is often Arrhenius, meaning the rate constant of a reaction between the fluid and the luminosity changes in relation to its temperature, this is proven with empirical data. Both PSP and TSP require calibration to relate the two together to minimize errors in the system, and careful considerations of the conditions are needed to avoid cross contamination of data points.

III. Implementation

The procedure behind PTSP starts with dissolving luminous chemicals and binders into a solvent, as stated in section two, PSP must have porous, oxygen-permeable solvent, whereas TSP bust be impermeable. Once mixed, apply the paint or dye to the surface of the test area using a spray gun, airbrush, or by simply dipping the object. PSPs work best with porous aluminum or ceramic binders [1]. Illumination is provided to the system with UV LED or lasers, and the emissions from the testing are detected with CCD cameras, which can detect these light frequencies with high resolution.

For longer, lifetime tests, pulsing light systems and cameras are synchronized to collect decay data over time, which can be used to monitor the loss of illumination independent of pressure levels, and vice versa. Processing data includes testing zero-conditions (wind off), as well as wind on, flat field (no test objects), dark current (lightless observations), and the aforementioned lifetime decay. With each of these tests in mind, researchers can gleam accurate data without interferences from separate parts. Heat flux measurements with TSP require insulation to ensure proper temperature rise during shorter runs, to avoid jumps in data that are hard to analyze [4].

IV. Critical Aspects

There are many critical points to this technology, and without following each one you might result in a failed experiment, which can be costly for experiments involving wind tunnels, especially high-speed wind tunnels. In PSP experiments, monitoring and controlling temperature is vital, since it is also temperature sensitive. Utilizing dual paint methods by combining PSP and TSP can be extremely helpful in minimizing temperature effects. Imaging alignment is also extremely useful, because without this, recordings between different tests may display alternative results, and can vastly change the outcome with the slightest error from deformation of imaging [1]. As mentioned in section three, system calibration must be performed before every experiment in order to relate the data between different aspects of the testing area, such as models, walls, speeds, and light effects.

In addition to previous checks, ensuring the pain is not contaminated and degraded is key in ensuring high quality observations – this is key in long duration experiments, or in tests with extreme conditions, such as high-speed tests. Mentioned in section two, certain materials and binders may increase bottle necking in the timing and exposure of the pressure and temperature [4]. This may further effect the frequency response of the measurements. Thicker paints and binders are a solution to this problem, allowing for faster response times without sacrificing the luminescence intensity in the dye.

V. Advantages

PTSP offers a number of advantages over the common methods of pressure and temperature analysis. The most obvious of these is the lack of point-based sensors, such as pressure taps, which take up space, and interrupt the environment around it. These paints act in real time without the need for electronic translation, meaning it has a high-frequency response and does not rely on electronic signals that can bottleneck the data. This technology is also highly useful for rotating parts, such as propellers, or turbomachinery blades, in which sensors that stick out or are built into thin parts are impractical, expensive, and far less accurate [2]. Naturally, since it changes in every place the paint is applied, it does not function the same as point based sensors, and can work across all of the control volume without limitation. In addition to its simplicity compared to mechanical sensors, it can function better at high speeds, and at extreme temperatures, with far less concern of failure [4]. The final major advantage is the dual-luminophore systems, which allow for both pressure and temperature to be measured in a combined map, something point based sensors fail to do.

VI. Applications Areas

As stated before, PTSP can be found in subsonic, transonic, supersonic, and hypersonic wind tunnels, all with extremely accurate and high-level observations. This also has been utilized in hydrodynamics, since TSP can be used to measure and identify skin friction fields. This application can help measure key aspects of the flow around cylinders and other bodies in complex underwater situations, such as crossflow [3]. Because this paint can enter small spaces and still be useful, it can model pressure and temperature in cavities and ducts, which is a major component of Aeroacoustics. Referenced in one paper, this paint can be used in rotating blades, and at operating speeds of up to 100,000 RPM, which can have high potential use for extreme performance planes.

Expanding on a point in section five, the ability to work in extreme temperatures, specifically cryogenic situations, allows for testing and validation for extreme atmospheres, like those found on mars for example. By testing in these extreme conditions, we can gain a better understanding of the atmosphere and the ability for our machines to function on other planets [2].

VII. Directions for Growth

With future development, we can see the paint being applied to unsteady pressure fields at even higher frequencies, and can identify dynamic points and their effects on larger systems. Changes to the formula will likely increase the brightness of the dyes, which can improve the response in high-speed environments [2]. Beyond that, general advancements to imaging technology will allow for better detection for long term observations. In addition, further changes to the paint can allow for longer lasting dye and higher durability use.

VIII. Conclusion

Pressure- and Temperature-Sensitive Paints are extremely powerful tools for measuring surface conditions in aerodynamic testing. This tool offers high resolution, and speedy analysis of control volumes, without intruding into the space itself. By detecting changes in oxygen levels and temperature, the luminescence adapts and can be measured through the use of cameras, allowing for high detailed readings in an entire space, as opposed to a single point. The paint can manage under extreme conditions, including hypersonic speeds, cryogenic temperatures, and high RPM spinning blades, all while reacting to the environments organically.

The modern applications are far reaching, with moving parts, futuristic testing for other planets, and hypersonic conditions all being simple for this miraculous paint. There are, however, some limitations, including PSP's sensitivity to temperature, despite research continuing to remove these side effects. This technique is new for the space industry, and while it is not widely used, it may be expected to be in the near future. In short, PTSP has countless applications, advantages, and fascinating properties, and while you may not want to have it coating all the walls in your house, it will certainly have a place in your at-home hypersonic wind tunnel!

References

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