Advances in Pressure Sensitive Paints (PSPs): novel operating mechanisms and new opportunities in wind engineering

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SUMMARY

Pressure-Sensitive Paint (PSP) technology has recently gained significant momentum as researchers and engineers search for high-resolution, non-invasive methods for mapping pressure distributions in aerodynamic studies. The rapid development of this field stimulates the exploration of new polymer matrices and luminescent sensors capable of delivering precise, spatially continuous pressure data, particularly for complex geometries used in wind-tunnel testing. In response to these needs, this work investigates novel PSPs based on new, previously unimplemented mechanisms of action, including including SQ-PSP (Solvent-Quenched Pressure Sensitive Paints) and OSQ-PSP (Oxygen-Solvent-Quenched Pressure Sensitive Paints). The study focuses on understanding how the molecular structure of luminophores and the composition of the polymer matrix affect the photophysical behaviour, stability and pressure sensitivity of the resulting PSP coatings. A comprehensive spectroscopic characterization (UV-Vis and luminescence spectroscopy) was performed to determine excitation conditions and evaluate sensor performance, followed by preliminary pressure calibration and model-scale tests in the wind tunnel of the Wind Engineering Laboratory at the Cracow University of Technology. The results demonstrate that some of the tested PSPs exhibit strong luminescence after polymerization and respond effectively to pressure changes through combined solvent-quenching, thickness-variation and oxygen-quenching mechanisms. Notably, some of the tested PSPs show significantly enhanced sensitivity, indicating their suitability for aerodynamic screening tests in wind engineering. These findings highlight the potential of new type PSPs coatings as a new class of high-performance pressure sensors and point toward their prospective application in advanced measurement techniques.

Keywords: Pressure Sensitive Paints, wind tunnel tests, solvent and oxygen quenching

1. INTRODUCTION

The rapid evolution of advanced technologies across numerous industrial sectors has led to a dynamic surge in demand for novel, sophisticated measurement systems capable of determining thermodynamic state parameters of a system. Among the fundamental intensive state parameters frequently measured in industry are pressure and temperature [Jones, 1974; Willemsen and Wisse, 2007; Flaga, 2008]. Examples of such investigations include aerodynamic tests performed in wind tunnels on models of building structures (particularly high-rise buildings) and transportation vehicles (air, land and sea). During these aerodynamic tests, determining the pressure and temperature distribution on the surface of the tested models is often of critical importance. The nature of the distribution of these state parameters is influenced by factors such as the geometry of the tested models, their aerodynamic environment and their angle of attack relative to the direction of airflow in the wind tunnel. The pressure distribution on the models' surfaces is induced by the airflow interacting with them in the wind tunnel, which simulates the effects of wind or air momentum on real-world structures in their natural setting and on objects in motion (e.g., transportation vehicles), respectively.

Depending on the parameters, pushing pressure or suction pressure may be observed on specific parts of the models [McLachlan and Bell, 1995; Obata et al., 2016; Liu and Sullivan, 2005; Stich et al., 2008]. Determining the pressure distribution is crucial for assessing the wind resistance of building structures and the aerodynamic properties of transportation vehicles, such as air resistance (drag) and lift. Classical systems employed for mapping the distribution of thermodynamic state parameters like pressure or temperature on various object surfaces, particularly during wind tunnel tests, often consist of arrays of point sensors connected to multi-channel scanners or providing an analog current signal (each sensor separately). Specifically, for mapping the pressure distribution on object surfaces, especially during wind tunnel tests, techniques utilizing grid of point sensors connected to multi-channel pressure scanners are still frequently employed. Such systems, similar to point temperature sensors, often fail to provide sufficient spatial resolution of the results, particularly for testing models with complex three-dimensional geometry. Furthermore, their installation on the model surface is a highly time-consuming and labor-intensive task. In response to the demand, primarily from the aerospace and automotive industries, research into new systems for mapping surface pressure distribution—later termed Pressure Sensitive Paints (PSP) systems—began in the 1980s at Moscow State University in the former Soviet Union. It wasn't until 1990 that this technology was publicly disclosed in Aviation Week & Space Technology magazine, which subsequently drew the interest of other countries. In 1989, researchers at the NASA Ames Research Center demonstrated the feasibility of using PSP coatings developed at the University of Washington to map pressure distributions on model aircraft wing surfaces. Since then, research into PSP technology and its application to aerodynamic testing of aerospace transport vehicles has been conducted at NASA Ames, as well as at Boeing and McDonnell-Douglas Aerospace, NASA Langley Research Center and the Arnold Engineering Development Center (AEDC) of the United States Air Force. The operational principle of PSP systems used in high-pressure aerodynamic tests of transport vehicles is based on the phenomenon of oxygen quenching of molecular sensor luminescence [Vollmer and Möllmann, 2018]. PSP systems are typically formulated as thin, luminescent-labeled polymer coatings, often with a thickness not exceeding 30 μm. The luminescent sensor within such a coating undergoes the phenomenon of oxygen-induced luminescence quenching, which involves a decrease in the sensor's luminescence intensity due to collisions with oxygen molecules diffusing into the coating from the airflow in the wind tunnel (the collisional/dynamic quenching mechanism). [Russo, 2011; Gouterman, 1997; Troyanovsky et al., 1993; Stich et al., 2008].

2. METHODS

The SQ-PSP/OSQ-PSP composition consisted of several fundamental components: monomer or a mixture of co-monomers; solvent; polymerization initiating system; luminescent sensor. The fundamental characterization of the luminescent sensors, specifically the measurement of their UV-Vis absorption spectra, was performed in acetonitrile (Sigma Aldrich). All subsequent spectroscopic investigations, which included pressure calibration and sample thickness calibration, were conducted on cured polymer coatings. Samples of the SQ-PSP & OSQ-PSP systems, designated for preliminary pressure calibration in both Constant Thickness Mode (CTM) and Variable Thickness Mode (VTM), were fabricated in the form of cylinders with a diameter of 15 mm and a height of 2.5 mm. This shape was achieved by casting appropriately composed SQ-PSP mixtures into teflon molds. The cross-linking of the mixture was realized by photopolymerization (via exposure to UV light at a wavelength of 365 nm). The measurement setup for calibration in the Variable-Thickness Mode (VTM) is based on a specialized pressure chamber equipped with an aluminum piston. This chamber is used to apply controlled mechanical pressure to the sample, allowing for pressures exceeding 27 kPa to be achieved. Luminescence excitation is realized using a UV-LED and the emitted light is collected by an optical fiber positioned at an angle of 30 ° to the sample axis. The emission spectra are recorded in the UV-Vis range via the SilverNova fiber optic spectrometer. Loads below 27 kPa were applied directly to the coverslip covering the sample [Pilch et al., 2020]. The measurement setup for calibration in CTM mode was constructed in an analogous manner. However, in CTM measurement setup the pressure was applied using air or nitrogen compressed by a pump and the system ensured that a constant sample volume was maintained.

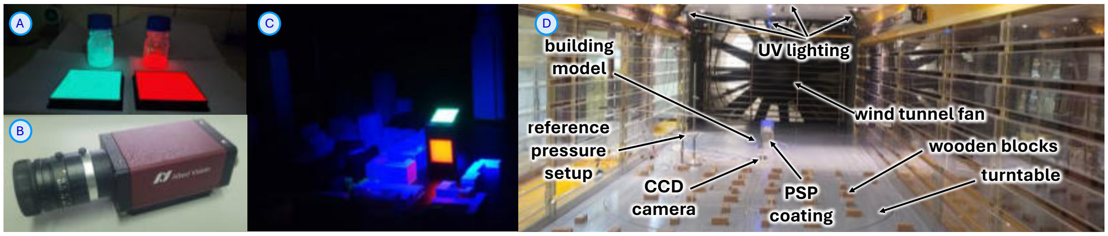

Fig.1. Photographs of the measurement setup for PSP testing in the wind tunnel: example of SQ-PSP coating samples (A), the CCD camera used (B), the test model with SQ-PSP coating in UV light, during comparative aerodynamic tests against point pressure sensors (C), the measurement section with the mounted camera and reference pressure measurement system (D).

The measurement setup for calibrating PSP systems in the wind tunnel against point pressure sensors consisted of a UV lighting system (8 × 3W 360 nm UV-LED diode), sample holder, CCD camera (Manta AllienVision Mg235B PoE 14 bit monochrome CCD camera) with UV filter (450 nm OD 2.0 Longpass Filter from EDMUND OPTICS), a device for archiving measurement data and controlling CCD camera and system for measuring the reference pressure (Fig. 1) [Pilch et al., 2024]. For these measurements, coating samples cast on square glass windows with a side length of 10 cm were used and mounted on the side walls of a model high-rise building, instead of cylindrical samples as in the VTM and CTM calibrations.

3. RESULTS & DISCUSSION

As a result of the conducted research, two main groups of new PSPs were developed:

1 - Solvent Quenched PSP (SQ-PSP): SQ-PSP systems consist of a polymer matrix labeled with a luminescent sensor and containing an absorbed solvent responsible for quenching the sensor's luminescence. The composition of these systems was optimized to enhance their sensitivity and reduce their response time during pressure measurements on model surfaces in aerodynamic tests within the field of wind engineering. Optimization involved selecting appropriate luminescent sensors and solvents, fine-tuning composition and optimizing coating thickness (Fig.2.)

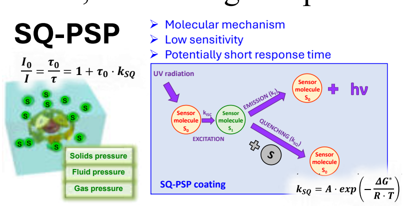

Fig.2. Visualization of the structure and mechanism of action of SQ-PSP systems with the computational model.

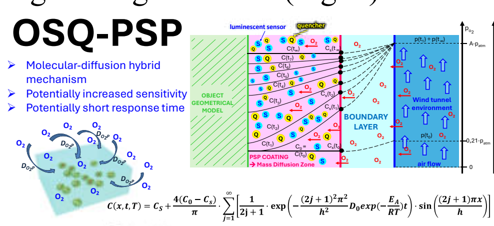

Fig. 3. Visualization of the structure and mechanism of action of OSQ-PSP systems with the computational model for oxygen quenching.

2 - Hybrid Oxygen-Solvent Quenched PSP (OSQ-PSP): These systems exhibitedvery high pressure sensitivity but relatively long response times. Preliminary observations revealed that certain luminescent sensors sensitive to oxygen quenching, such as noble metal porphyrin complexes and rare-earth metal complexes, also exhibit sensitivity to solvent quenching luminescence. The combined effects of these two phenomena synergistically enhance system sensitivity. These systems are

designed for mapping time-averaged pressure distributions and incorporate solvent-permeable polymers to balance sensitivity and response time (Fig.3.).

4. CONCLUSIONS

In summary, the results indicate that PSPs operating solely on the basis of solvent-induced luminescence quenching exhibit insufficient pressure sensitivity to be effectively used for measuring small pressure differences in aerodynamic model tests in wind engineering. However, systems of this type, due to their operating mechanism, may also find a range of other applications, such as measuring the pressure of liquids or the contact pressure of solid bodies, where the equivalent differential pressure values are typically much higher. In contrast, OSQ-PSPs appear significantly more promising. Their operation is based on the combination of up to three different mechanisms influencing luminescence intensity under pressure: solvent quenching, oxygen quenching and changes in luminescence intensity associated with variations in the thickness of the labeled gel coating. However, the interaction between these mechanisms makes the pressure response of such systems highly complex and difficult to describe quantitatively. Therefore, detailed spectroscopic–aerodynamic studies are required to establish a comprehensive characterization of these systems.

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