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Super-hydrophobic porous pressure-sensitive paint for global unsteady flow measurements

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ABSTRACT

Super-hydrophobic porous pressure-sensitive paint (hydrophobic PSP) is developed based on polytetrafluorethylene (PTFE) particle and platinum (II) *meso*-tetra(pentafluorophenyl) porphine. The former functions as the water repellent surface, and the latter gives luminescent output related to the pressures. From the luminescent image, global pressure measurements can be achieved in aerodynamic applications. The developed PSP is resistant to the change in the humidity of the test gas, which is one of the major issues for a PSP application in a practical use. The developed PSP shows contact angle more than 150° by the PTFE particle and a porous structure, which describes that the PSP surface is super-hydrophobic. It can be sprayed onto a testing object to open its applications for aerodynamic measurements. The change in the luminescent intensity by the relative humidity of 80% is 6%, and the change by the relative humidity of 60% is only 2% above the pressure at 40 kPa. The pressure sensitivity as well as the response time is independent of the humidity.

1. Introduction

Pressure-sensitive paint (PSP) measurement has been widely used in fluid dynamic experiments [1,2]. PSP is a chemical sensor, giving a luminescence related to the oxygen concentration and the partial pressure of oxygen in a test gas. The luminescence as an image can be acquired through a photo-sensitive device, such as a camera, and the image can be converted to the global information of oxygen concentration and the partial pressure of oxygen. For an aerodynamic application, the partial pressure of oxygen is related to the static pressure. PSP consists of a luminescent molecular probe (luminophore) and a supporting matrix. The former gives the luminescence under a photo excitation. The luminescent output from the PSP is related to the oxygen, a process called oxygen quenching [3]. The latter holds the luminophore onto a testing article. It also limits the oxygen permeation in the matrix, which is directly related to the response time of a PSP. To provide a fast response time, a porous matrix is used. An open structure of a porous material provides a high mass diffusion of a test gas freely interact with a luminophore on the porous surface. A conventional PSP, which uses a polymer as a supporting matrix, has its response time on the order of sub-second to second [4]. On the other hand, a PSP using a porous matrix gives the time response on the order of 10 μs [4,5]. Combined with a fast frame-rate camera, this type of PSP (porous PSP) has been used to capture an unsteady flow field and to apply for a short duration testing in the aerodynamic applications [6–11].

Because of a porous structure, a porous PSP absorbs unwanted gas molecule; major one is water molecule. By using the intensity-based method, a reference image is used to cancel the pressure-independent information, which is caused by a non-uniform illumination, camera–PSP distance, and a non-uniformity of a PSP [12,13]. These factors are the same between the reference- and the pressure-contained images. However, if the humidity changes during the measurement, it changes the luminescent pattern, which cannot be canceled by the rationing [6]. This would occur in flight testing, where the humidity would differ on the ground and at the flight altitude. When the test section of a wind tunnel should be opened between wind-tunnel measurements, the test gas is mixed with ambient gas that changes the humidity. Sakaue et al. reported a hydrocarbon-coated PSP [14]. A hydrocarbon, which was functioned as a hydrophobic surface to repel water molecule, was coated on an anodized aluminum surface by the self-assembled monolayer technique. They reported that the change in the luminescent intensity under a relative humidity of 60% was ranged from 8% to 18%. However, the application of this PSP is limited to an aluminum model, which is still an issue for an application purpose. To make a fast response and spray-able PSP, a polymer-ceramic PSP (PC-PSP) has been studied [15–20]. It uses

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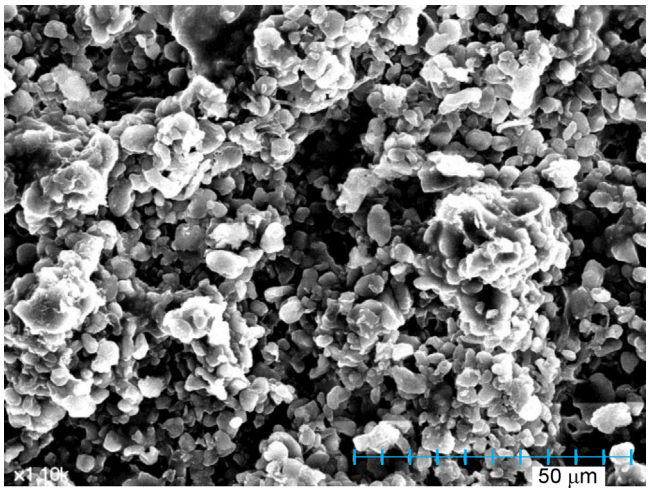

Fig. 1. Scanning-electron microscopic (SEM) photograph of the developed PSP surface.

a porous particle to enhance the response time and a polymer for spraying. An overall structure creates a micro-porous surface to enhance the mass diffusion in a PC-PSP layer. Shibuichi et al. [21] and Onda et al. [22] reported that a micro structure or a fractal surface enhances the hydrophobic feature, if the surface is chemically hydrophobic. These suggest that by using hydrophobic materials as components of PC-PSP, the resultant PSP would be fast response, spray-able, and water-repellant PSP.

We introduce a super-hydrophobic PSP that is spray-able, and provides a porous structure to enhance the response time. It can be an alternative for a conventional porous PSP with resistant to a humidity change. The development and characterizations of the PSP are included in the present paper. The characterizations include a contact angle, signal level, pressure sensitivity, and the response time related to the humidity.

2. Experimental

2.1. Materials

Platinum (II) *meso*-tetra(pentafluorophenyl) porphine (PtTFPP) from Frontier Scientific was used as a pressure-sensitive probe. This probe is protected by fluorine, which indicates that it is water repellant [23]. Polytetrafluorethylene (PTFE) particle from Kanto Chemical Co. Inc. was used as a hydrophobic material. Its surface shows hydrophobic and oleophobic characteristics. The water contact angle on a smooth PTFE surface is reported to between 98° and 112° [24]. The average diameter of PTFE particle was 5 μm. We used this particle combined with a silicone-based binding material (X40-2327, Shinetsu Chemical Co. Ltd.) to create a porous structure by spraying. These were mixed in a dispersant (HFE-7100) from Sumitomo 3M Ltd. The concentrations of these materials in the dispersant were 0.007 wt% (PtTFPP), 6 wt% (PTFE), and 6 wt% (X40-2327), respectively. The resultant mixture was sprayed onto the aluminum substrate (1 mm × 1 mm). The coating thickness was 30 ± 3 μm, measured by an eddy current apparatus (Kett LZ-300). Fig. 1 shows a scanning-electron microscopic (SEM) photograph of the developed PSP surface. We can see that PTFE particle ranged about 5 μm in diameter. The particle was distributed on the surface, creating a porous structure.

2.2. Water drop test

The hydrophobicity of the PSP surface in a macroscopic scale was determined by the contact angle. It was determined from the contact surface of the developed PSP and a water droplet of 2 μl. From the side-view photograph of the interacting surface, the angle can be determined.

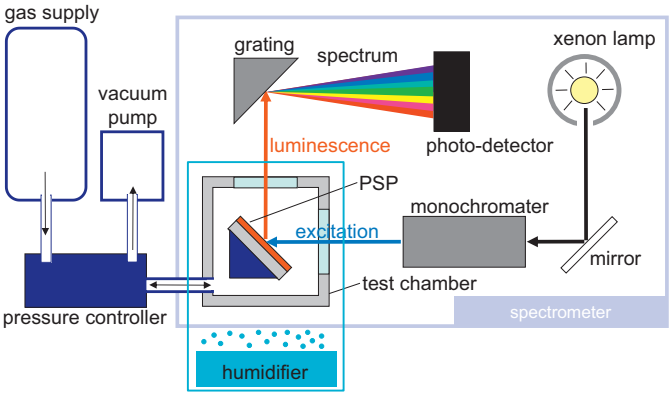

Fig. 2. Schematic of steady-state calibration setup.

2.3. Steady-state characterization

Fig. 2 schematically describes the steady-state calibration system, which consists of a spectrometer (Hitachi High Technologies, F-7000), pressure-controlled unit, and humidity unit. The system characterizes the signal level and pressure sensitivity under a set humidity as the steady-state characterizations of the developed PSP. A PSP sample was placed in the test chamber with varying pressures under a set humidity. The system measures the luminescent spectrum from the PSP. The excitation wavelength was 400 nm to illuminate the PSP. The chamber has optical windows that passed the excitation from the illumination unit and the luminescence from the PSP. The luminescence was measured from 550 nm to 750 nm. The luminescent intensity, I, was determined by integrating the spectrum from 630 nm to 670 nm. The chamber was filled with dry air to provide zero humidity. A humidifier was used to set the relative humidity of 60% and 80% outside the chamber. Under the reference pressure of 100 kPa, the chamber, which was filled with dry air, was replaced to the set humidity by opening the chamber lid. The lid was then closed to hold the humidity in the chamber. The chamber was de-pressurized from 100 kPa to 5 kPa to vary the pressures. Throughout the characterizations, the reference conditions were set at 100 kPa with a constant temperature of 25 °C.

For characterizing the signal level, η, all the PSP samples were measured with the same optical setup in the spectrometer but replacing samples in the chamber at the reference conditions with a set humidity. Based on Liu et al., I can be described by the gain of the photo-detector in our spectrometer, G, the emission from a PSP, I_{PSP}, the excitation in the spectrometer, I_{ex}, and the measurement setup component, f_{set} [25]:

$$I = GI_{PSP}I_{ex}f_{set} \tag{1}$$

In our characterization setup, G, I_{ex}, and f_{set} were the same for all PSP samples. We non-dimensionalized I by that of the PSP under the reference conditions with 0% humidity (refPSP). We call this value as the signal level, η, shown in Eq. (2):

$$\eta = \frac{I}{I_{refPSP}} \tag{2}$$

The change in η under a humid condition based on the η at 0% humidity, Δs, is defined as follows:

$$\Delta s = 1 - \frac{\eta_{humid}}{\eta_{dry}} \tag{3}$$