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Fine printing of pressure- and temperature-sensitive paints using commercial inkjet printer

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ABSTRACT

We have proposed an instant method for painting of pressure- and temperature-sensitive paints (PSP and TSP) using a commercial inkjet printer. This method enables us to finely and separately paint PSP and TSP to prevent them from being mixed and the interaction between PSP and TSP dyes. Moreover, the pressure-sensitivity of inkjet-printed PSP was similar to those of conventional PSPs. We consider this method is promising to measure pressure distribution with temperature variation, because the printing pattern of PSP and TSP is easily designed by an illustration software to adjust pressure distribution of interest. The pressure distribution induced by jet impingement was measured by the grid pattern of PSP and TSP as a demonstration. The pattern of PSP and TSP was well-defined; thus, the emissions from PSP and TSP can be easily separated and analyzed even when the emissions were captured by a CCD camera at the same time. This is also an advantage of our method. The pressure distribution agreed well with the pressures measured by pressure taps.

1. Introduction

In recent years, the optical pressure measurement technique by pressure-sensitive paint (PSP) has been applied to various fields of fluid dynamic researches such as wind tunnel testing [1–8], fluid machinery [9–11], micro-gas flow [12–15], and dissolved oxygen measurement [16]. The pressure distribution on a surface of interest can be obtained by measuring the variation of the luminescent intensity/lifetime emitted from PSP, because the luminescent intensity/lifetime depends on the partial pressure of oxygen in air due to oxygen quenching; i.e., the intensity decreases with increasing the pressure, and vice versa [1,2]. However, the intensity/lifetime also varies depending on temperature variation; i.e., the intensity decreases with increasing the temperature. Therefore, the pressure distribution measured by PSP should be corrected with the temperature distribution to improve an accuracy of the measurement. The temperature distribution for the correction can be measured by an IR camera [17] or temperature-sensitive paint (TSP). Though high temperature resolution measurement can be achieved by an IR camera, the measured temperature has to be corrected with the emissivity of the object of interest and with the IR radiation from the surroundings, and the measurement procedure is complex (ex. matching between pressure and temperature distributions is required. an IR transmissive window is required in a wind tunnel). It is considered that TSP is the most promising way to measure the temperature distribution, because the measurement by TSP can be conducted using the same equipment as that by PSP. There are many studies on trying to develop a dual sensor of PSP and TSP. For example, dual sensors by mixing dye molecules for pressure and temperature sensing have been proposed [18–23]. The pressure and temperature on the surface of interest can be obtained by dichroism measurement. However, these sensors are suffered from the reduction in photo-stability and the sensitivities due to the interaction between the dye molecules [23,24]. A multi-layer of PSP and TSP sensors have also been proposed by some research groups [25,26]. Since the PSP layer is painted on the TSP layer, the temperature of the PSP layer is different from that of the TSP layer due to the low heat conductivity of polymer binder of TSP, resulting in the large temperature difference between the top and bottom layers [27,28] and in low accuracy of pressure measurement. A new

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approach to develop a dual PSP and TSP sensor has been strongly desired.

In our previous study, we proposed a dual PSP and TSP array sensor fabricated by a scientific grade inkjet printer [24,29]. Since the inkjet-printed PSP and TSP are spatially separated, the interaction does not occur; thus, this method overcomes the above-mentioned drawbacks. However, the scientific grade inkjet printer is time consuming for printing (about 10 h is required to fabricate a sensor of 10 × 10 cm), and is very expensive (>$20,000 USD). In recent years, a commercial inkjet printer is applied to fabricate an electronic circuit [30–33]. Complex figures are easily, rapidly, and less-costly (∼$100 USD) printed by a commercial inkjet printer. Therefore, we propose a PSP and TSP printing technique by a commercial inkjet printer in this study.

2. Characteristics of PSP and TSP

The pressure/temperature measurement technique using PSP/TSP is based on the oxygen/thermal quenching of luminescence. PSP and TSP are composed of dye molecules and a binder material to fix the dye molecules to a surface. When the PSP/TSP layer applied to the surface is illuminated by a violet light (∼400 nm), the dye molecules are excited and emit luminescence (phosphorescence or fluorescence). The luminescence of PSP is quenched by oxygen; thus, the luminescent intensity decreases with an increase in partial pressure of oxygen. The pressure on the surface is deduced by measuring the variation of the luminescent intensity using the following Stern-Volmer relation [1,2],

$$\frac{I_{\mathrm{ref}}(p_{\mathrm{ref}}, T_{\mathrm{ref}})}{I(p, T)} = A(T) + B(T)\frac{p}{p_{\mathrm{ref}}} \tag{1}$$

where I, p, and T are the luminescent intensity, pressure, and temperature, respectively. The subscript, ref, indicates a reference condition and $p_{\mathrm{ref}} = 100.0$ kPa in this study. The constants A and B are the Stern-Volmer constants satisfying the constraint condition of $A(T_{\mathrm{ref}}) + B(T_{\mathrm{ref}}) = 1$. On the other hand, the luminescence of TSP is thermally quenched, and the relation between the temperature and the luminescent intensity is described by the following equation in this study,

$$\frac{I(p, T)}{I_{\mathrm{ref}}(p_{\mathrm{ref}}, T_{\mathrm{ref}})} = C + D\frac{T}{T_{\mathrm{ref}}} \tag{2}$$

where C and D are constants. As mentioned in Sec. 1, PSP is sensitive not only to pressure but also to temperature, and the dependency of the luminescent intensity of PSP on temperature is also represented by Eq. (2). Throughout the paper, the pressure sensitivity S_p and the temperature sensitivity S_T are defined by the following equations,

$$S_p = \frac{\partial}{\partial p}\frac{I_{\mathrm{ref}}(p_{\mathrm{ref}}, T_{\mathrm{ref}})}{I(p, T)} = \frac{B}{p_{\mathrm{ref}}}\left[1/\mathrm{kPa}\right] \tag{3}$$

$$S_T = \frac{\partial}{\partial T}\frac{I(p, T)}{I_{\mathrm{ref}}(p_{\mathrm{ref}}, T_{\mathrm{ref}})} = \frac{D}{T_{\mathrm{ref}}}\left[1/\mathrm{K}\right] \tag{4}$$

3. Inkjet printing of PSP and TSP by commercial printer

We adopted PtTFPP (platinum (II) *meso*-tetra(pentafluorophenyl)porphine, Frontier Scientific, USA) and fluorescein (Wako Pure Chemical Industries, Japan) as a dye molecule for PSP and TSP, respectively. The PSP and TSP solutions were prepared by dissolving each dye in ethanol (Wako Pure Chemical Industries, Japan) with concentrations of 0.90 g/L and 0.20 g/L, respectively. We prepared filter paper (Whatman grade 1 filter paper, pore size 11 μm, GE healthcare, USA) as a typical paper sample, because it is easily available and shows no autofluorescence. The filter paper was coated with the poly(4tBS) (poly(4-*tert*-butyl styrene), Sigma Aldrich, USA) layer sprayed by its toluene solution with a concentration of 40 g/L, where the volume of the solution was 20 mL/m^2. Here, PtTFPP, fluorescein, poly(4tBS), ethanol, and toluene were used without further purification.

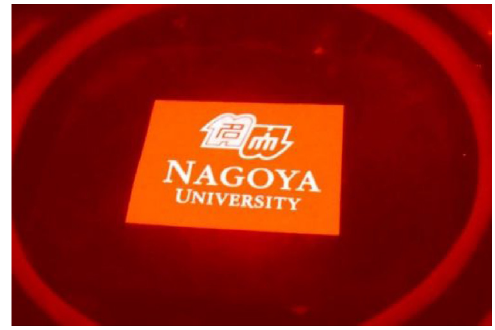

Fig. 1. Luminescence image of the inkjet printed PSP. The sheet of paper was 2.85 cm × 2.10 cm.

The both PSP and TSP solutions were printed on the polymer coated filter paper using a commercial inkjet printer (EP-306, dye ink printer, Seiko Epson, Japan). The specifications of the inkjet printer were as follows: minimum dot spacing was 1/5760 in, minimum ink droplet size was 3 pL, and maximum print resolution was 5760 × 1440 dpi. The inkjet printer had six independent color cartridges, black, cyan, magenta, yellow, light cyan, and light magenta. The inkjet printer was carefully cleaned before use by filling all the cartridges with ethanol, which was then printed on paper to rinse the nozzles and tubes of the printer. This cleaning procedure is important as there is residual ink in the nozzles and tubes even when a printer is a brand new one. Then, the PSP and TSP solutions were filled into the cyan and magenta cartridges, respectively. The print patterns of PSP and TSP were prepared and printed by Photoshop CS 5.1 (Adobe systems, USA). Since a general commercial inkjet printer is not a postscript printer, the settings of Photoshop and the printer were carefully set as shown in Table 1. In these settings, we can obtain the shapes filled with only PSP (TSP) by printing ones filled with the color of C:M:Y:K = 100:0:0:0 (0:100:0:0) in Photoshop CS5.1. When the settings are inappropriate, the printed PSP contains TSP even when C:M:Y:K = 100:0:0:0, resulting in poor properties due to the interactions of PSP and TSP dye molecules. It also should be noted that the color management mode cannot be controlled by a user in some commercial inkjet printers. The inkjet-printed PSP and TSP samples were dried for an hour at 80 °C in an incubator (FS-30W, TGK, Japan) to remove any remaining ethanol from the samples.

As a simple demonstration, we printed the logo of Nagoya University in cyan (PSP) on high-quality paper and the luminescence under an illumination light of 395 nm (LEDH294-395, Hamamatsu Photonics, Japan) was captured by the auto capture mode of a color CMOS camera (Nikon 1 S2, Nikon, Japan) with an optical filter (long-pass filter with a cut-on wavelength of 490 nm, Asahi Spectra, Japan) as shown in Fig. 1. The complex figure of the logo, which is difficult to print by conventional PSP/TSP painting methods by a sprayer or a spin coater, was finely printed on the sheet of the high-quality paper of 2.85 cm × 2.10 cm.

4. Properties of inkjet-printed PSP and TSP

4.1. Emission spectra of inkjet

The circles of PSP and TSP with a diameter of 10 mm with the characters of "PSP" and "TSP" were printed on the filter paper. The emission spectra of each of PSP and TSP measured by a spectrometer (CT-25C, Bunkoukeiki, Japan) are shown in Fig. 2. It is well