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.

Manuscript submitted to Sensors and Actuators B: Chemical

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 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 hours 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],

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

where I, p, and T are the luminescent intensity, pressure, and temperature, respectively. The subscript, ref, indicates a reference condition and $p_{\mathrm{ref}} = 100.0\ \mathrm{kPa}$ 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,

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

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,

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

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

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.

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 known that the emission peaks of fluorescein and PtTFPP are at 520 nm [34] and 650 nm [8], respectively. We observed the single emission peaks for each spectrum, indicating that PSP was successfully printed without any contamination by TSP and vice versa. The emission images were captured by a CCD camera (BU-52LN-F, Bitran, Japan, bit depth: 16 bit). Here, optical filters were attached to the lens of the CCD camera to detect the luminescence: the long-pass filter with a cut-on wavelength of 490 nm, a band-pass filter of 530 ± 60 nm (Asahi Spectra, Japan) for the TSP luminescence, and a band-pass filter of 670 ± 60 nm (Asahi Spectra, Japan) for the PSP luminescence. As shown in Fig. 3, the emission images can be separately detected by the optical filters. We confirmed that the isolated printing of PSP and TSP can be realized by a commercial inkjet printer as well as by a scientific grade inkjet printer.

4.2 Pressure- and temperature-sensitivity

The pressure- and temperature-sensitivities of the inkjet-printed PSP and TSP were investigated using the same pressure and temperature calibration system as our previous studies [35, 36], and are shown in Fig. 4. The temperature of the sample was kept at 293 K during the pressure calibration test, and the pressure in the chamber was kept at 100 kPa during the temperature calibration. The error bars show the standard deviations for five independent PSP and TSP samples. By fitting eq. (1) to each of the PSP and TSP data shown in Fig. 4(a) using the method of least squares, we obtained the pressure-sensitivities of $S_p^{\mathrm{PSP}} = 0.54 \pm 0.03\ \%/\mathrm{kPa}$ and $S_p^{\mathrm{TSP}} = 0.05 \pm 0.01\ \%/\mathrm{kPa}$ for the luminescent intensities in the PSP and TSP regions, where errors show the 95% confidence bounds obtained by considering the Student’s T cumulative distribution function. The pressure-sensitivity of the inkjet-printed PSP was similar to that of our previous study [24] or conventional PSPs [8]. On the other hands, the pressure-sensitivity of the inkjet-printed TSP was negligibly small. Fig. 4 (b) shows the results of temperature calibration and the temperature-sensitivities of the luminescent intensities in the PSP and TSP regions were respectively $S_T^{\mathrm{PSP}} = -0.96 \pm 0.06\ \%/\mathrm{K}$ and $S_T^{\mathrm{TSP}} = -0.28 \pm 0.05\ \%/\mathrm{K}$.

5. Demonstration of inkjet-printed dual dye PSP to pressure measurement

As an application of our inkjet-printed PSP and TSP to pressure measurement, we measured the pressure distribution induced by jet impingement. The luminescent intensity of PSP was low in the dot printed dual PSP and TSP proposed in our previous study [24], because the actual printed area of PSP was very small. In our printing method, the printing pattern of PSP and TSP can be easily designed and modified by an illustration software to adjust measurements. This is one of the advantages of our proposed method. Here, the grid pattern of PSP and TSP was prepared for the measurement as shown in Fig. 5a, because high spatial resolution for temperature distribution is not always required [37]. The grid bodies and the grooves were respectively printed by PSP and TSP, and the painted area of PSP was increased compared with that of our dot printed dual PSP and TSP. The TSP lines were placed on near jet impingement and along the centerline of the flow, because temperature considerably varied on these locations.

The experimental setup was the same as our previous study [24]. Figure 5b shows the schematic diagram of configuration of a convergent nozzle and the PSP and TSP plate. The nozzle diameter at the exit was 2.0 mm. The stagnation pressure and the ambient pressure were 230 kPa and 103 kPa, respectively. The reference conditions of pressure and temperature were $p_{\mathrm{ref}} = 103.0$ kPa and $T_{\mathrm{ref}} = 290$ K, respectively. The inkjet-printed PSP and TSP was illuminated by the LED light (wavelength: 395 nm), and the emission was captured by the CCD camera with the long-pass filter with cut-on wavelength of 490 nm. In this setup, the one pixel of the image corresponded to 0.118 mm. The exposure time of the camera was 0.1 s, and 32 images were captured and averaged to improve the signal to noise ratio of the image. Although the emissions from PSP and TSP were captured at the same time and in the same image, the emissions can be easily separated and analyzed by identifying the PSP and TSP portions due to the well-defined pattern of PSP and TSP. The pressures at the impingement surface were also measured by the pressure sensors through the pressure taps (tap diameter: 0.5 mm).

Figure 6 shows the results of the measurement. We interpolated the temperature ratio (T/T_{ref}) distribution between the TSP lines by thin-plate splines as shown in Fig. 6a. Then, the pressure distribution shown in Fig. 6b was corrected by the temperature distribution. The pressure profiles with/without temperature correction along the black line in Fig. 6b are shown in Fig. 6c. The main source of measurement uncertainty was the shot noise of the images, and the maximum uncertainty was estimated as 1 kPa (1% of p_{ref}). The temperature corrected pressure agreed well with those measured by the pressure taps. This result shows that our inkjet-printed PSP and TSP is promising method to measure pressure distribution with temperature variation.

6. Conclusion

We have proposed an instant PSP and TSP painting method using a commercial inkjet printer. The complex figure of PSP and TSP can be finely printed. By carefully adjusting the settings of the illustration software and the printer, PSP and TSP were separately printed without being mixed with each other, leading to prevent the interaction between PSP and TSP dyes. The pressure-sensitivity of inkjet-printed PSP was similar value to those of our previous study, dot printed PSP, and conventional PSPs. The pressure distribution induced by jet impingement was measured by the inkjet-printed PSP and TSP. The grid pattern sensor of PSP and TSP was prepared for the measurement. Although the emissions from PSP and TSP were captured at the same time and in the same image, the emissions can be easily separated and analyzed because of the well-defined pattern of PSP and TSP. The pressure distribution agreed well with the pressures measured by pressure taps. The printing pattern of PSP and TSP can be easily designed by an illustration software to adjust pressure distribution of interest. We consider this method is promising to measure pressure distribution with temperature variation.

Acknowledgments

This work is partially supported by Konica Minolta Science and Technology Foundation.

Table 1 Settings of Photoshop and the printer

Photoshop CS 5.1			
Color settings	Settings		Japan general purpose 2
	Working spaces	RGB	sRGB IEC61966-2.1
		CMYK	Japan color 2001 coated
		Gray	Dot gain 15 %
		Spot	Dot gain 15 %
	Color management policies	RGB	Preserve embedded profiles
		CMYK	Preserve embedded profiles
		Gray	Preserve embedded profiles
Print settings	Printer	Epson EP-306	
	Color management	Document (profile: sRGB IEC61966-2.1)	
	Color handling	Photoshop manages colors	
	Printer profile	EP-976A3 906F 806A 776A 706A 306 Series Photo Paper	
	Rendering Intent	Absolute colorimetric	

Epson EP-306

Paper options	Epson Photo paper
Quality options	Best photo
Color management	Off (No color adjustment)

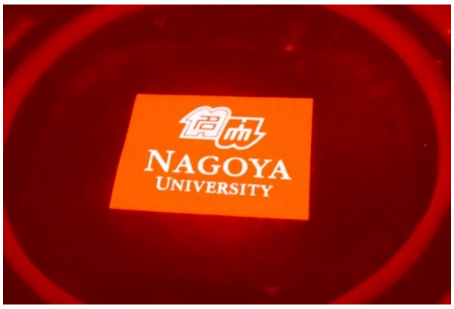

Fig. 1　Luminescence image of the inkjet printed PSP. The sheet of paper was 2.85 cm × 2.10 cm.

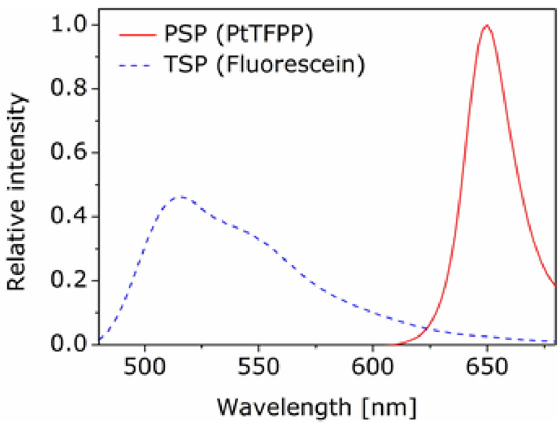

Fig. 2　Emission spectra of inkjet-printed PSP (PtTFPP) and TSP (Fluorescein)

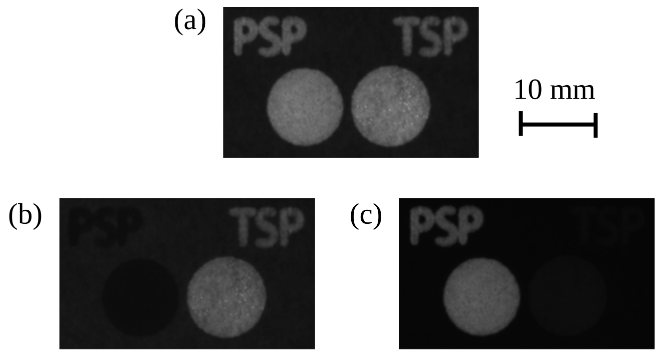

Fig. 3 Gray scale images of inkjet-printed PSP and TSP emission captured with (a) long-pass filter of 490 nm, (b) band-pass filter of 530 ± 60 nm, and (c) band-pass filter of 670 ± 60 nm.

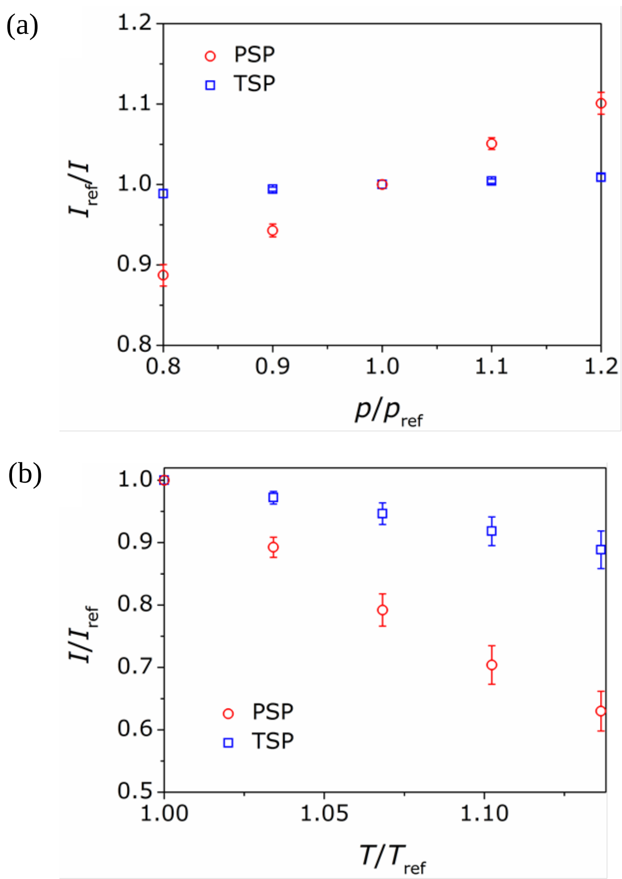

Fig. 4 Pressure and temperature calibrations for inkjet-printed PSP (PtTFPP) and TSP (Fluorescein). (a) Stern-Volmer plots for PSP and TSP, where p_{ref}=100 kPa. (b) Relation between luminescent intensity and temperature for PSP and TSP, where T_{ref}=293K

(a) (b)

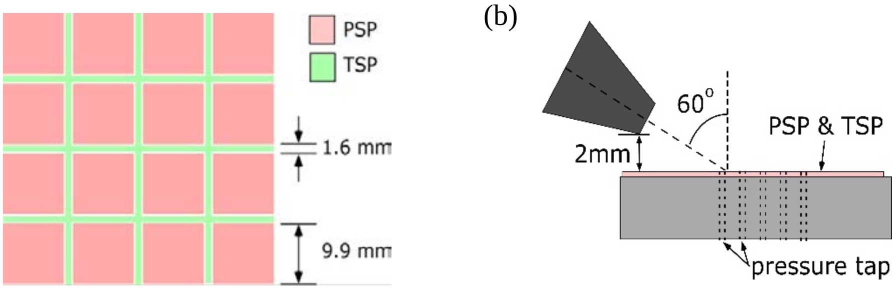

Fig. 5 Experimental setup for pressure measurement. (a) Grid pattern of PSP and TSP sample. (b) Setup of the convergent nozzle.

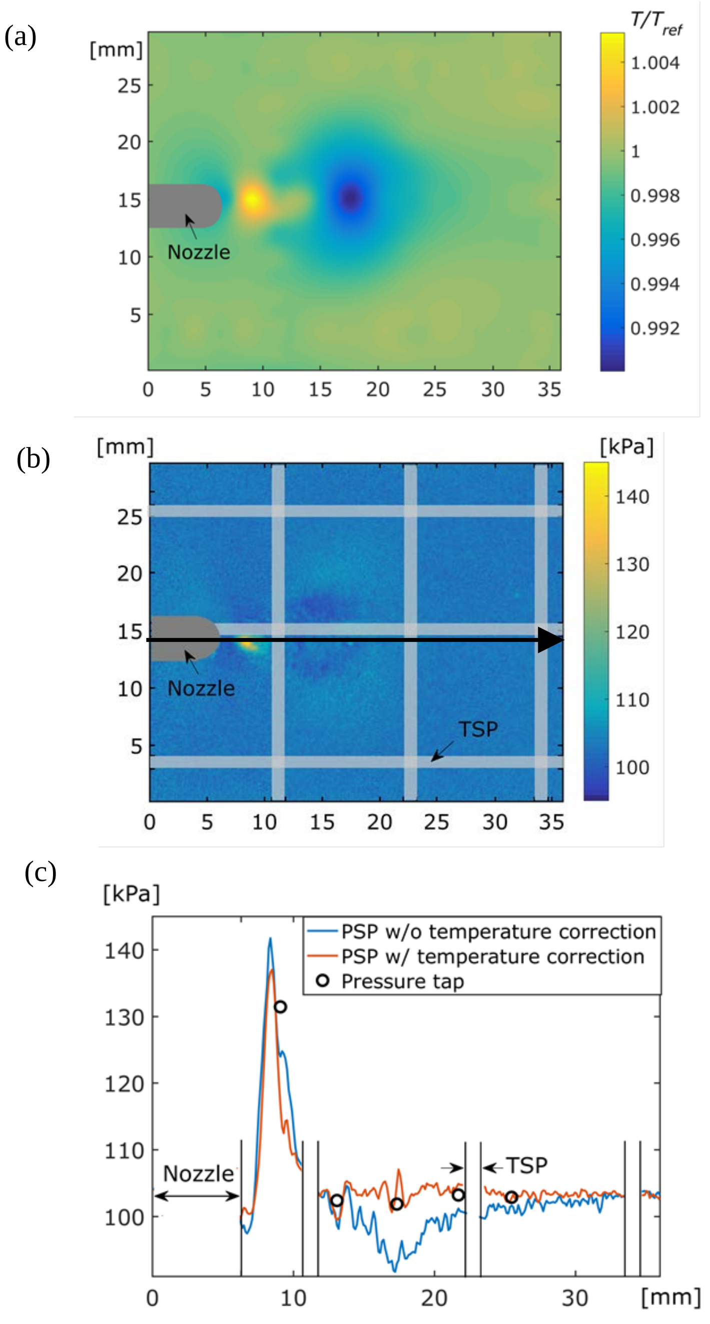

Fig. 6 Result of pressure measurement. (a) Temperature ratio distribution interpolated by thin-plate splines. (b) Pressure distribution with temperature correction. (c) Pressure profile along the black solid line in (b).

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