Journal of Visualization, Vol. 6, No. 3 (2003) 213-223

Temperature Correction of PSP Measurement Using Dual-Luminophor Coating

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Received 8 November 2002
Revised 14 Januany 2003

Abstract : We developed a dual-luminophor pressure/temperature sensitive paint (DPTSP) to correct the temperature dependence of pressure-sensitive paint. The DPTSP is composed of two sensor molecules, PtTFPP and Rhodamine B (RhB), and Poly-IBM-co-TFEM as a binder. Temperature was determined from the image of RhB, and the temperature dependence of PtTFPP was corrected using the calculated temperature. To validate the capability of DPTSP for temperature correction, the pressure field on a delta wing model was measured by the DPTSP measurement system. The pressure values obtained with DPTSP were in good quantitative agreement with pressure tap data. It has been validated that DPTSP is effective in correcting the temperature dependence of PSP.

Keywords **:** PSP, TSP, Dual-luminophor coating, Delta wing.

1. Introduction

Recently, a new technique using Pressure-Sensitive Paint (PSP) has been developed for measuring the pressure field on wind tunnel models (Liu et al., 1997; Bell et al., 2001). PSP measurement makes use of a sensor that is based on a photochemical reaction known as oxygen quenching of luminescent molecules. Through the photo-physical process of oxygen quenching, the luminescent intensity of PSP is related to air pressure. Previously, pressure field measurement to determine the pressure distribution on a model surface has been conducted using pressure taps. This conventional measurement technique is very labor-intensive, and model preparation costs are high when a detailed pressure map is desired. In contrast, PSP measurement provides a simple and inexpensive way to obtain a full-field image of the pressure distribution on an aerodynamic model surface with high spatial resolution.

The emission intensity of PSP depends on temperature as well as pressure. Therefore, it is necessary to compensate for the temperature dependence of PSP in order to obtain accurate pressure measurement. In previous studies, the temperature dependence of PSP has been corrected using either a Temperature-Sensitive Paint (TSP) image (Shimbo et al., 1999) or thermocouples

(Egami et al., 2001).

In this study, we use a dual-luminophor pressure/temperature sensitive paint (DPTSP) to solve this problem. This paint is composed of a temperature sensitive dye, a pressure sensitive dye and a polymer. Using the DPTSP, we can simultaneously measure the pressure and temperature distribution on a model surface. Hence, we can remove the error due to the temperature dependence of PSP and accurately measure the pressure distributions on the model surface. There have been several studies on DPTSP, but their characteristic have not been well documented (Crafton et al., 1999; Jordan et al., 1999). In this paper, we present a general strategy for developing DPTSP and a working DPTSP formulation.

In our DPTSP, PtTFPP, RhB (Rhodamine B) and Poly-IBM-co-TFEM (Poly- isobutylmethacr–ylate-co-trifluoroethylmethacrylate) were used as a pressure sensitive dye, a temperature sensitive dye and a polymer, respectively. We have investigated the basic characteristic of this paint to evaluate the capability of dual-luminophor paint. Furthermore, a verification test was conducted to evaluate the performance of the DPTSP at the 0.2-m Supersonic Wind Tunnel (SWT) at the National Aerospace Laboratory of Japan. A pressure map on the surface of a simple delta wing was visualized using the DPTSP measurement system.

2. Basis for DPTSP Design

To realize dual-luminophor pressure/temperature sensitive paint, the following conditions must be satisfied:

- Pressure- and temperature-sensitive dyes must be excited with common illumination light.
- Emission wavelength of the pressure-sensitive dye must be clearly separated from that of the temperature sensitive dye.

Phosphorescence and fluorescence materials were considered for use as pressure- and temperature-sensitive dyes, respectively, for DPTSP. For fluorescent materials, the Stokes' shift is short and the emission spectrum is the mirror image of excitation. Fluorescence emits when an excited molecule relaxes from singlet state S_1 to singlet state S_0, as illustrated in Fig. 1. An excited molecule in the S_1 state is mainly thermally quenched, since the lifetime is very short. On the other hand, in the case of a phosphorescent material, the Stokes' shift is large and the emission peak is far from the excitation. An excited molecule in the T_1 state is subject to oxygen quenching due to its long phosphorescence lifetime. Therefore, by choosing a fluorescent dye that emits fluorescence at wavelengths between the phosphorescent-dye excitation and emission, a common exciting light can provide two clearly separated emissions, as Fig. 2 shows.

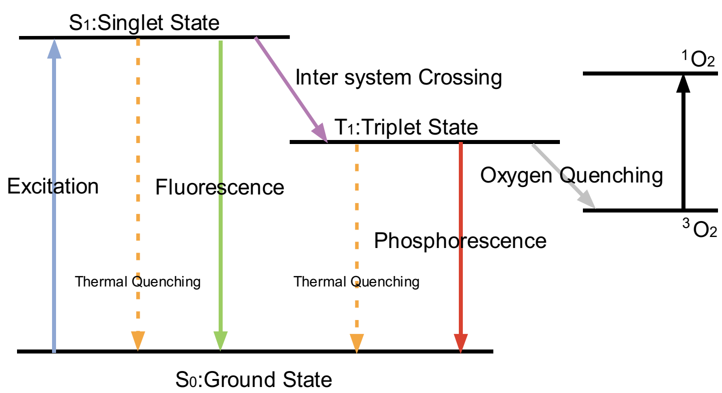


Fig. 1. Jablonski energy level diagram.

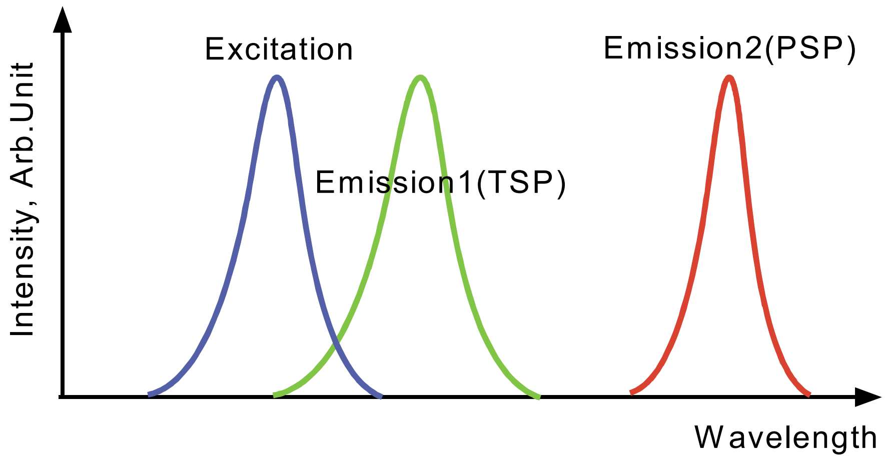


Fig. 2. Diagram of excitation and emission for DPTSP.

Another consideration in the DPTSP design is the solubility of the dyes and polymer in the same solvent. Furthermore, the characteristics of DPTSP should be spatially uniform over the model surface. In addition, these luminescent materials must be resistant to photodegradation caused by excitation light.

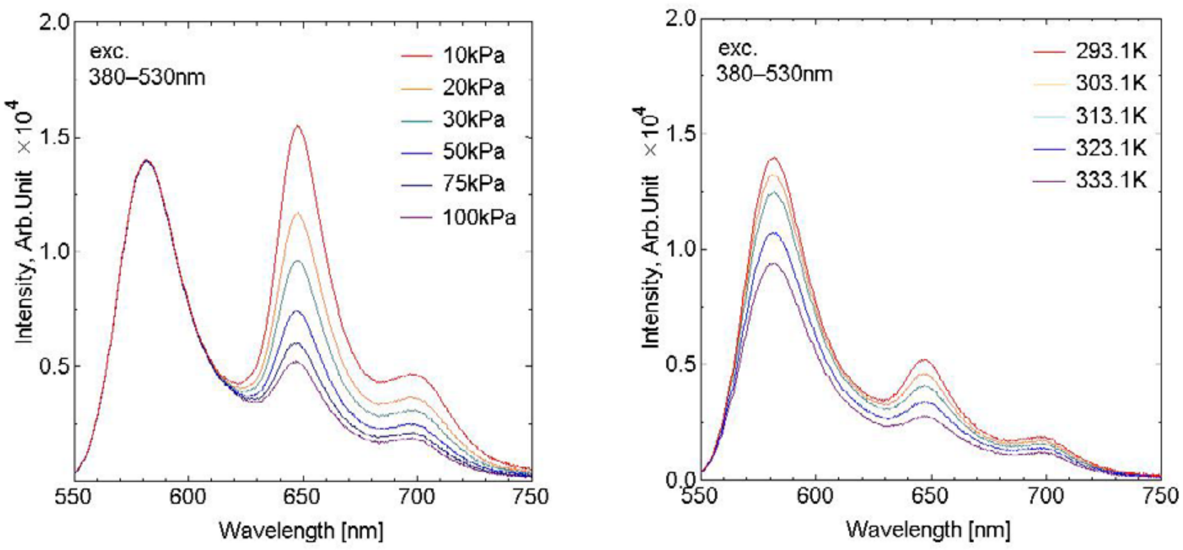
According to the DPTSP design strategy mentioned above, we have selected PtTFPP and RhB as the pressure-sensitive and temperature-sensitive dyes, respectively. Furthermore, a highly permeable fluoric polymer, Poly-IMB-co-TFEM was used as the binder to reduce the temperature dependence of the pressure sensitivity of the PSP (Amao et al., 1999). These materials were solved in dichloromethane as the common solvent. The characteristics of the DPTSP are reported in the following section.

3. Characteristics of DPTSP

3.1 Characteristics of Luminescence of DPTSP

Spectroscopic measurement was conducted to examine the characteristics of the luminescence of DPTSP. The PSP painted sample was set in a temperature and pressure controlled chamber, and the dependence of emission spectra on pressure and temperature was investigated. The experimental results are shown in Fig. 3. Three peaks are seen in Fig. 3.

The left peak is the emission of RhB, and the other two peaks are the emission of PtTFPP. In the present paper, the emission peaks of 580 nm and 650 nm are designated as Peak 1 and Peak 2, respectively. As Fig. 3 shows, Peak 1 is clearly separated from Peak 2. The intensity of Peak 2 decreases with increasing pressure. However, the intensity of Peak 1 is independent of pressure. Both emission intensities are dependent on temperature, indicating that the temperature can be determined from the emission intensity of Peak 1, and that the temperature dependence of Peak 2 can be corrected using the temperature estimated from the emission intensity of Peak 1.



(a) Pressure dependence (b) Temperature dependence

Fig. 3. Dependence of DPTSP spectra on pressure and temperature.

3.2 Pressure- and Temperature-sensitivity of DPTSP

In order to examine the pressure and temperature sensitivities of DPTSP, a calibration test was conducted. The sample was illuminated by the excitation light provided by a 300-W Xenon arc lamp (HAMAMATSU PHOTONICS C4338) with a band pass filter of 380-530 nm. The emission from the sample was detected by a cooled CCD camera (HAMAMATSU PHOTONICS C4880) with an emission filter. This CCD camera has a 1000×1018 pixel resolution and a 14-bit intensity resolution. Band pass filters of 580±20 nm and 650±20 nm were used as the emission filters for Peak 1 and Peak 2, respectively. We used a filter wheel (ISI SYSTEMS, FW-1) to exchange two emission band-pass filters.

Figure 4 shows the temperature dependence of emission intensity ratio (I/I_{ref}) for Peak 1 in DPTSP. The I/I_{ref} of Peak 1 remains almost constant from 293 K to 308 K and monotonically decreases above 308 K. The temperature sensitivity for Peak 1 is about 1%/℃ between 308 K and 323 K. This trend of Peak 1 is almost the same as that for RhB alone, indicating that the emission of PtTFPP does not interfere with that of RhB.

A Stern-Volmer plot for Peak 2 is shown in Fig. 5. The emission intensity ratios I_{ref}/I increase with increasing pressure, and the pressure sensitivity is not dependent on temperature. The pressure sensitivity for Peak 2 in DPTSP is smaller than that for PtTFPP alone due to the overlap of PtTFPP emission and the tail of the RhB emission spectrum.

3.3 Uniformity of Sensitivity of DPTSP

For accurate pressure measurement, it is important to achieve uniformity of sensitivity of the DPTSP over a model surface. In order to investigate this uniformity, the emission images of RhB and PtTFPP were acquired using a CCD camera. Fig. 6(a) and (b) illustrate the ratios between two images obtained under two different conditions for RhB and PtTFPP, respectively. The sample size was 25 mm x 25 mm.

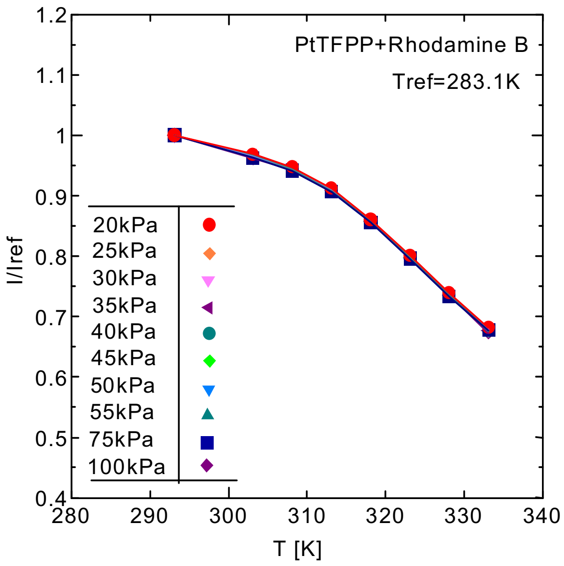


Fig. 4. Temperature dependence of I/I_{ref} at Peak 1.

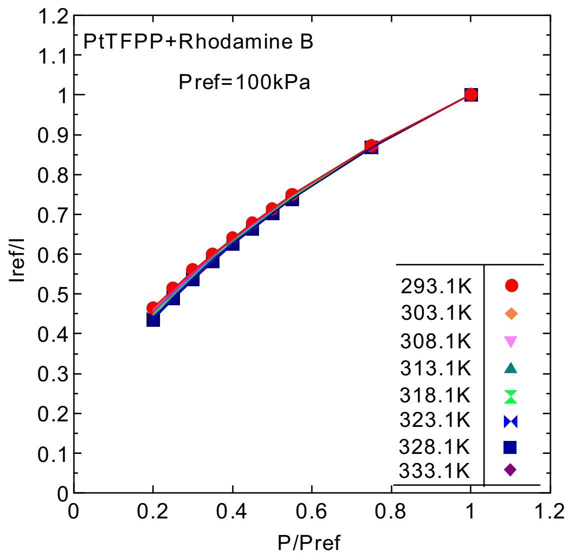
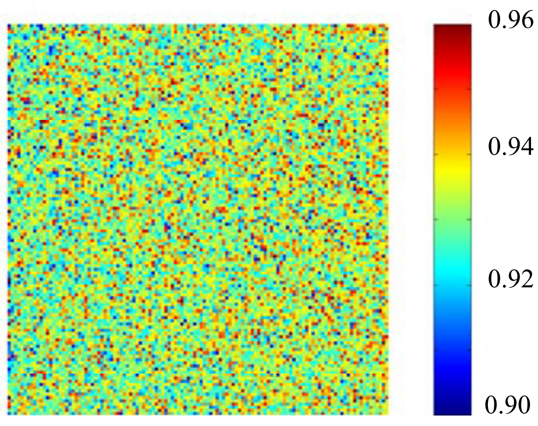
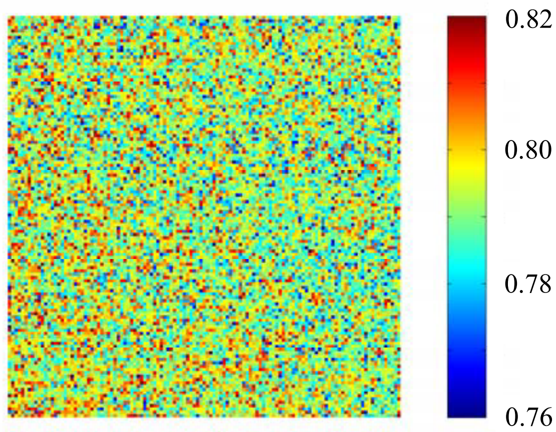


Fig. 5. Stern-Volmer plot at Peak 2.



(a) Ratio image of RhB ($I_{T=323.1\ K}/I_{T=318.1\ K}$ at 55 kPa)



(b) Ratio image of PtTFPP ($I_{p=55\ kPa}/I_{p=35\ kPa}$ at 318.1 K)

Fig. 6. Uniformity of sensitivity of DPTSP.

If the sensitivity is uniform over the coating, the intensity ratio is constant on the image. However, both RhB and PtTFPP ratios display random errors, which are thought to be due to the optical interference between the two dyes. The emission of RhB overlaps the excitation spectrum of PtTFPP. Hence, a part of the energy emitted by RhB can be absorbed by PtTFPP. Furthermore, the relationship between excitation and emission spectra for RhB is that of a mirror image, and a part of the emission spectrum overlaps the excitation spectrum. Thus, the inner filter effect may not be negligible. Here, the inner filter effect indicates the phenomenon whereby RhB can absorb the photon-energy of its own emission. On the other hand, the tail of the RhB emission spectrum overlaps the emission peak of PtTFPP. Therefore, the emission intensity of RhB influences that of PtTFPP. In addition, PtTFPP can absorb some of the energy emitted by RhB. These effects are sensitive to the film thickness of DPTSP.

The film thickness of DPTSP can not be perfectly uniform, since the solvent evaporates immediately due to the relatively low boiling point of dichloromethane. In other words, the sensitivity depends on the location of the PSP sample.

The error due to the non-uniform film thickness was estimated from the images. Data points for more than 10000 pixels in the image were calculated. The pressure error was approximately ±2 kPa (twice standard deviation) at the pressure of 35 kPa and, the temperature error was approximately ±1.5 K at 318.1 K. The dependence of characteristics on the film thickness can be minimized by maintaining the coating thickness to be as uniform as possible. Thus, for the verification test, DPTSP was painted on the model surface with great care to achieve a uniformly thick DPTSP coating.

3.4 Photodegradation

Luminescence material is degraded by excitation light. In the PSP measurement system, photodegradation cannot be ignored, since we measure the emission intensity of the PSP. For DPTSP this is further complicated because DPTSP contains two luminescent sensor dyes in one matrix. If the photodegradation rate differs between the two dyes, the measurement error will be increased.

In this study, the photodegradation for DPTSP was investigated. The sample plate was set in the calibration chamber and illuminated by excitation light for one hour. Pressure and temperature in the calibration chamber were set at 60 kPa and 318.1 K, respectively. The optical setup was identical to that used in the calibration test. The emission intensity of the sample was measured with a CCD camera at 10-minute intervals.

Figure 7 shows the time history of the emission intensity for PtTFPP, RhB and DPTSP samples. After one hour, the emission intensities of PtTFPP and RhB decreased by approximately 1% and 2% of the maximum intensity ratio, respectively. The photodegradation rates for RhB and PtTFPP in DPTSP are similar. As a result, it is concluded that these dyes in DPTSP are resistant to photodegradation at this operational excitation condition, showing that the measurement accuracy should not be affected by photodegradation.

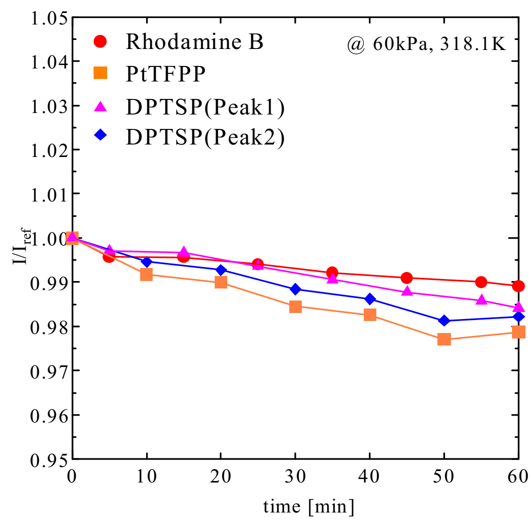


Fig. 7. Temporal variation of emission intensity under continuous illumination.

4. Data Reduction

The data reduction process for DPTSP is described in this section. First, the temperature distribution is estimated with the image of the RhB. According to the calibration data, the intensity ratio of RhB emission is independent of pressure. Therefore, the calibration curve can be fitted with the following equation:

$$\frac{T}{T_{ref}} = \sum_{i=1}^{5} A_i \left(\frac{I}{I_{ref}} \right)^{i-1} \tag{1}$$

where A_i are the calibration coefficients obtained from the calibration data. Using this equation, the temperature distribution on a model surface is evaluated based on RhB images.

On the other hand, the emission intensity of PtTFPP in DPTSP is a function of both pressure and temperature. As mentioned in the previous section, the pressure sensitivity of PtTFPP is independent of temperature. Therefore, we need only compensate for the emission intensity. The temperature dependence of the emission intensity can be corrected with the wind-on temperature obtained from the RhB image, since the characteristics of the temperature sensitivity of PtTFPP are known from the calibration data. By applying the temperature correction to the reference image, the pressure can be expressed as a function of only the ratio of the corrected reference image to the wind-on image, as in the following equation:

$$\frac{p}{p_{ref}} = \sum_{i=1}^{4} B_i \left(\frac{I_{ref}}{I} \right)^{i-1} \tag{2}$$

where B_i are the calibration coefficients obtained from the calibration data, and their values are independent of the temperature. The PtTFPP images can be converted to pressure images using this formulation (the Stern-Volmer equation).

5. Verification Test

5.1 Experimental Apparatus

A verification test was conducted to evaluate the performance of DPTSP in wind tunnel testing. A pressure map on the surface of a simple delta wing was visualized using DPTSP. The test was conducted at subsonic speeds in the 0.2-m Supersonic Wind Tunnel at the National Aerospace Laboratory of Japan.

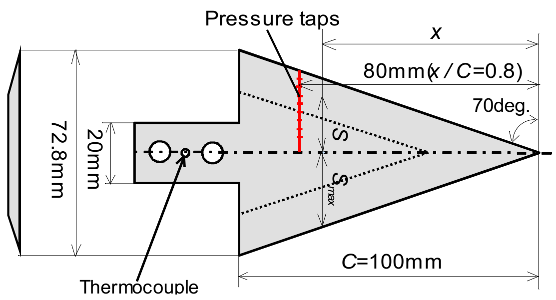


Fig. 8. Schematic diagram of the delta wing model.

Figure 8 shows the delta wing model used in this experiment. The model is made of aluminum and has a centerline chord, C, of 100 mm. The wing leading edge is sharp and has a 70° sweep angle. The top surface of the model was coated with a white optical undercoat (AKZO NOBEL, Aerodex Finish Matt White (lead free)) and DPTSP topcoat using an airbrush. Eight pressure taps were provided at the chordwise location of $x/C = 0.8$ and at spanwise locations S/S_{max} of 0.2 to 0.9 at intervals of $0.1S_{max}$. The model was strut-mounted in the center of the test section at an angle-of-attack of 20°.

The optical setup for this experiment is shown in Fig. 9. The delta wing painted with DPTSP was irradiated with an excitation light of the 300 W Xenon lamp through an optical fiber, and the emission image from the model was detected with a cooled CCD camera with 14 bit pixel resolution. We used a filter wheel to change between the two emission band-pass filters, one for PtTFPP and the other for RhB. In the experiment, an *a priori* calibration technique which does not require pressure tap data, was used to convert the measured luminescent intensity into pressure.

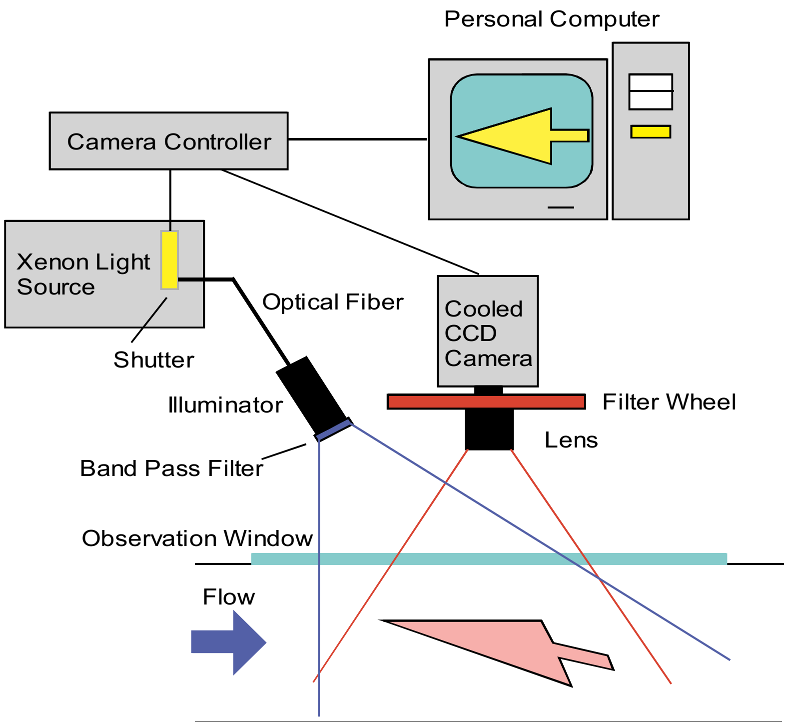


Fig. 9. Experimental setup for the verification test.

5.2 Experimental results

Figure 10 shows the pressure field on the surface of the delta wing measured with DPTSP for Mach numbers from 0.55 to 0.70 and a total pressure of 60 kPa. In the flowfield over a delta wing at an angle-of-attack of 20°, the strength of the primary separation vortices is increased significantly. In addition, secondary separation vortices near the leading edge are induced by the primary separation vortices. Their separation vortices generate the low-pressure regions on a delta wing. Therefore, we can determine the locations of separation vortices from the pressure distribution (Egami et al., 2001). As Fig. 10 shows, the flowfields including primary and secondary leading-edge separation vortices are visualized. As the Mach number increases, the location of the secondary vortex breakdown moves downstream, and the pressure along the leading edge decreases. These results indicate that the primary vortices become stronger with increasing Mach number.

Figure 11 shows the temperature distribution on the delta wing. The Mach number, total pressure and total temperature are 0.55, 60 kPa and 324.1 K, respectively. The temperature on the model surface is almost constant. This is reasonable because the experiment was conducted in a continuous wind tunnel, and sufficient time was allowed for the model to reach thermal equilibrium. The temperature profile over the delta wing is slightly non-uniform, most likely due to the influence of the film thickness.

The pressure distribution measured with DPTSP at the location (x/C = 0.8) and the corresponding tap data are presented in Fig. 12. The PSP data (Peak 2) corrected using the total temperature (*Tt*) is also shown in Fig. 12 for comparison, assuming that the temperature on the delta wing is constant and equal to *Tt*. There is a significant difference between the pressure tap data and the PSP data that was corrected with *Tt*. On the other hand, the DPTSP data agrees approximately with the tap data, revealing that this technique is effective in correcting the temperature dependence of PSP. An error on the order of 2-3 kPa remains which, based on the sample test, may be due primarily to the inherent error of DTSP, as discussed in Section 3.3. Another error source for DPTSP is the image registration. We need to process four images in order to calculate pressure and temperature, and thus a slight misalignment may result in a measurement error. The accuracy of DPTSP measurement would be greatly enhanced if the uniformity of the DPTSP thickness could be improved.

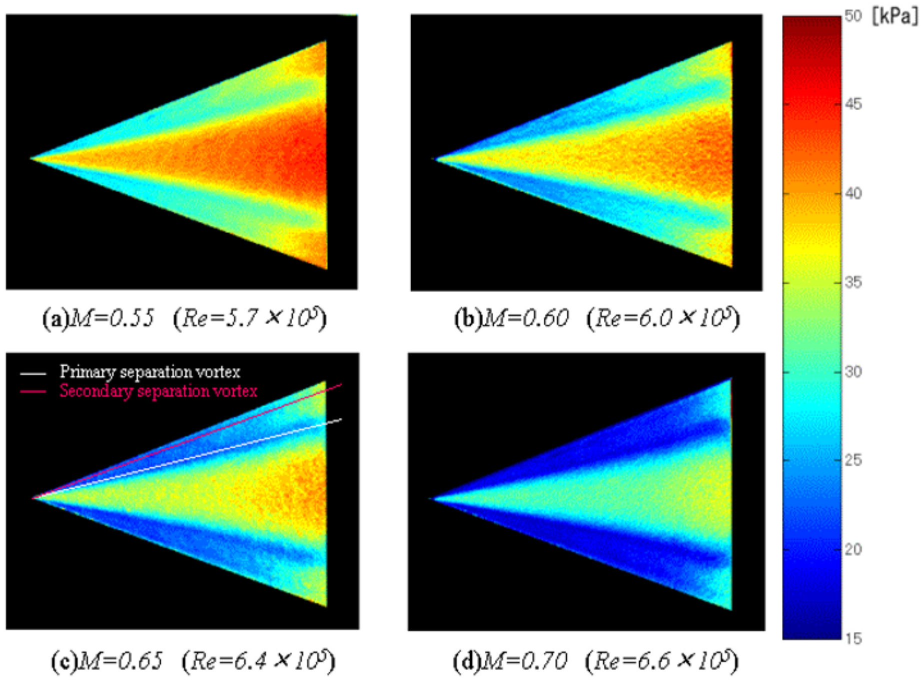


Fig. 10. Pressure field on the surface of a delta wing measured using DPTSP.

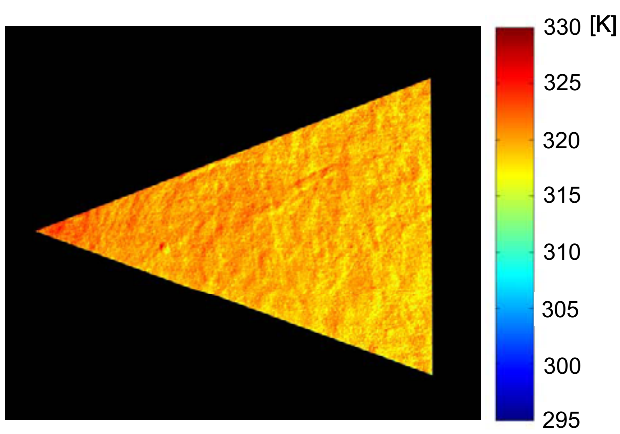


Fig. 11. Temperature field on the surface of a delta wing measured with DPTSP.
(*Pt* = 60 kPa, *M* = 0.55)

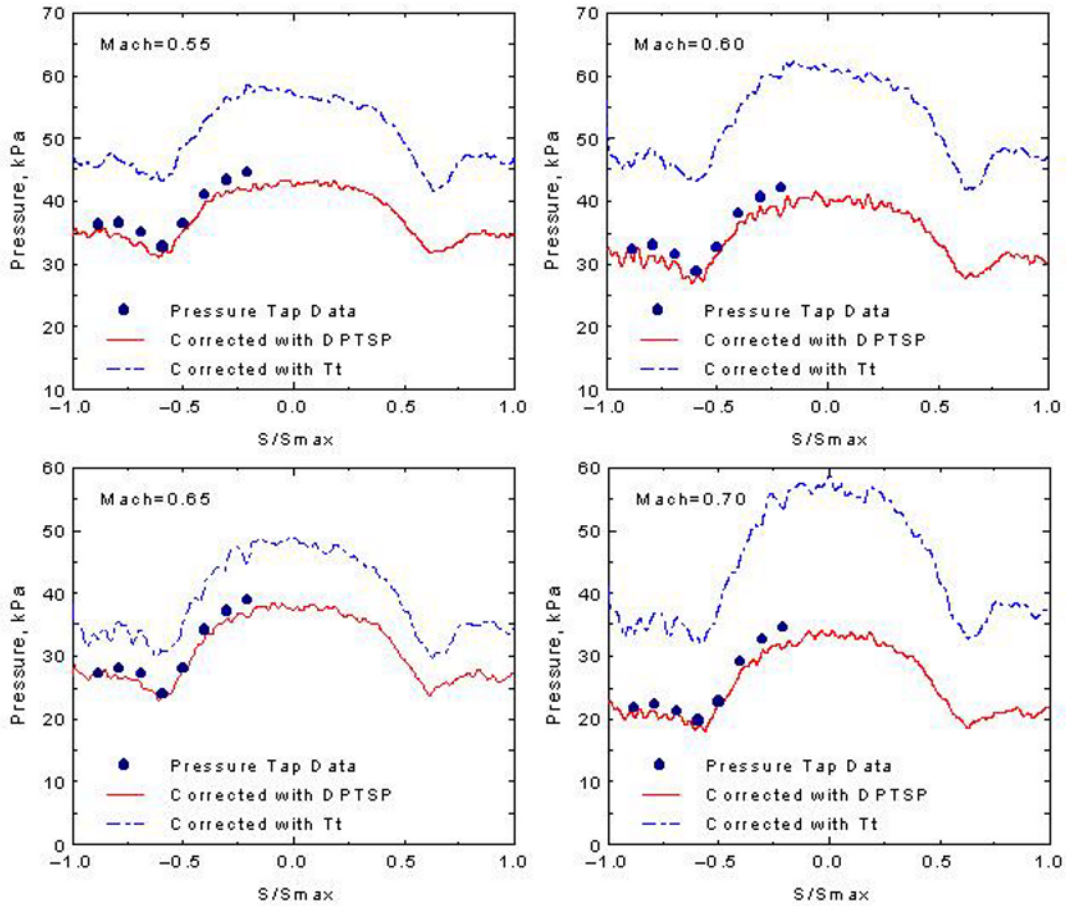


Fig. 12. Comparison of PSP data and pressure tap data.

6. Conclusions

We have developed a dual-luminophor pressure/temperature sensitive paint (DPTSP) for correcting the temperature dependence of PSP. The capability of DPTSP for temperature compensation was examined and evaluated through sample calibrations and a wind-tunnel experiment. The results obtained in this study can be summarized as follows:

(1) A DPTSP, which is composed of two sensor dyes, PtTFPP and Rhodamine B, and Poly-IBM-co-TFEM as a binder, has been developed to correct the temperature dependence of PSP. Temperature was determined from the image of RhB, and the temperature dependence of PtTFPP was corrected using the calculated temperature.

(2) A measurable error attributed to the optical interference between two molecules could be minimized by maintaining the uniformity of the coating thickness.

(3) The intensities of RhB and PtTFPP in DPTSP were not degraded by continuous excitation. The measurement accuracy of DPTSP can be considered not to be affected by photodegradation.

(4) Using the DPTSP measurement system, the complex pressure field on a delta wing including primary and secondary leading-edge separation vortices was clearly visualized.

(5) The pressure values obtained with DPTSP were in good quantitative agreement with the

pressure tap data. It has been verified that DPTSP is effective in correcting the temperature dependence of PSP.

Acknowledgements

This work is supported in part by Special Coordination Funds under the Molecular Sensors for Aero-Thermodynamic Research (MOSAIC) project of the Ministry of Education, Culture, Sports, Science and Technology, Japan

References

Amao, Y., Asai, K., Miyasita, T. and Okura, I., Photophysical and Photochemical Properties of Optical Oxygen Pressure Sensor of Platinum Porphyrin-Isobutylmethacrylate-Trifluoroethylmethacrylate Copolymer Film, Polymer Journal, 31-12 (1999), 1267-1296.

Bell, J. H., Schairer, E. T., Hand, L. A. and Mehta, R. D., Surface Pressure Measurements Using Luminescent Coatings, Annu. Rev. Fluid Mech., 33 (2001), 155-206.

Crafton, J., Goss, L., Jones, G., Davis, J. and Carter, C., Bi-Luminophor Pressure-Sensitive Paint Development, 7th PSP Workshop (1999).

Egami, Y., Iijima, Y., Amao, Y., Asai, K., Fuji, A., Teduka, N. and Kameda, M., Quantitative Visualization of the Leading-edge Vortices on a Delta Wing by Using Pressure-sensitive Paint, Journal of Visualization, 4-2 (2001), 139-150.

Jordan, J. D., Watkins, A. N., Davis, J. C. P. N. and Dale, G. A., Development and Application of Biluminophore Paint Systems, 7th PSP Workshop (1999).

Liu, T., Campbell, B. T., Burns, S. P. and Sullivan, J. P., Temperature and Pressure-Sensitive Luminescent Paints in Aerodynamics, Apl. Mech. Rev., 50-4 (1997), 227-246.

Shimbo, Y., Noguchi, M. and Makino, Y., Blowdown Tunnel Application of Pressure Sensitive Paint, AIAA Paper 99-3169 (1999).

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