Application of Pressure-Sensitive Paint to Low-Speed Wind Tunnel Testing at Japan Aerospace Exploration Agency

Kazunori Mitsuo, Kazuyuki Nakakita and Mitsuru Kurita
Advanced Technology Team, Wind Tunnel Technology Center
Institute of Space Technology and Aeronautics, Japan Aerospace Exploration Agency

Keywords: *Pressure-Sensitive Paint, Temperature-Sensitive Paint, Low-Speed Wind tunnel*

Abstract

A new technique using Pressure-Sensitive Paint (PSP) has been developed for measuring the pressure field on wind tunnel models at Japan Aerospace Exploration Agency (JAXA). In this study, the PSP measurement system has been applied to low-speed testing. A-priori and in-situ method were applied to convert PSP images to pressure images, and the accuracy of PSP was evaluated comparing with pressure tap data. The result provided that the in-situ method (Case-B) using an after-run image as a reference image was most effective in correcting the temperature dependence of the PSP. Furthermore, pressure images of a supersonic transport-type model were examined varying the flow speed (20-50m/sec) and angle of attack (12-20º). The pressure images were clearly visualized, indicating that the present PSP system was applicable to low-speed testing and a useful tool for measuring pressure field on aerodynamic models.

1. Introduction

Recently, Pressure-Sensitive Paint (PSP) has been developed for measuring pressure field on an aerodynamic model surface [1], [2]. 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 on a model surface has been conducted using pressure taps arrays. This conventional measurement technique is very labor-intensive, and model preparation costs are high. 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.

JAXA has proceeded to apply PSP measurement system to practical wind tunnels at Wind Tunnel Technology Center (WINTEC) of ISTA/JAXA. So far, the PSP system has been applied to the 1m×1m supersonic wind tunnel (SWT1) and the 2m×2m transonic wind tunnel (TWT1) [3].

In this study, the PSP system has been applied to the 2m × 2m Low-Speed Wind Tunnel (LWT2) at WINTEC. In case of low-speed testing, there are some inconvenient problems in comparison with high-speed testing, i.e., transonic or supersonic speed testing. The accuracy of PSP at low-speed testing is strongly affected on variation and non-uniformity of temperature and illumination. This is because change of PSP luminescent intensity to pressure difference at low-speed is very small. For example, the dynamic pressure at the speed of 50 m/sec is approximately 1.5 kPa. Pressure sensitivity of a typical PSP is about 0.8 %/kPa. Therefore, the luminescent intensity of PSP changes only 1.2 % to the pressure variation of 1.5kPa.

Generally, the luminescent intensity of PSP depends not only on pressure, but also on temperature. The temperature dependence of PSP is approximately -1%/K. The variation of 1 K is corresponded to approximately 1 kPa in unit of pressure. On the other hand, even a scientific excitation light source is not completely stable. The stability of excitation light directly influenced on luminescent intensity of PSP. So, the light intensity must be corrected to improve measurement accuracy. These errors due to variation of temperature and illumination are fatal problem for low-speed PSP measurement.

In this study, temperature-Sensitive paint (TSP) was used for correcting temperature dependence of PSP. Each wing of a model was painted by PSP and TSP, respectively [4]. Here, we assumed that the flowfield on each wing was symmetric, that is, the pressure and temperature pattern on each wing was identical. The variation of illumination was monitored by a photo-diode (PD) and the PD data was applied to data reduction.

For PSP image processing, *a-priori* and *in-situ* method were applied to convert PSP image to pressure image. The previous study reported that an *in-situ* method using temperature-corrected PSP image improved measurement accuracy [5]. In this study, two methods to compensate temperature dependence of PSP were applied. The first method was to make use of TSP. Another is to use a wind-off image immediately after blowing over airflow (shutdown wind tunnel). The two methods were evaluated in this paper.

A model of Super-Sonic Transport (SST, 8.5% scale model), which has been developed at JAXA, was used to evaluate accuracy of PSP at low speed. The flow speed was varied from 20 to 50m/sec, and the angle of attack was set from 12 to 20deg. The PSP data was compared with pressure tap data, and the measurement accuracy was discussed.

2. PSP and TSP Characteristics

2.1 Formulation

PSP was composed of a pressure-sensitive dye, a binder and solvent. In this study, PtTFPP was used as a pressure-sensitive dye. A highly permeable fluoric polymer, Poly-IMB-co-TFEM was applied as a binder [6]. The dye concentration was adjusted for a low-speed testing.

Some researchers use Pyrene-based PSP for a low-speed testing, since the PSP has low temperature dependence and intense emission [7]-[9]. However, a Pyrene dye is not registrant to photo-degradation, and the absorption band is UV (350 nm). The UV light does not pass through a common optical window. On the other hand, PtTFPP has high pressure-sensitivity and resistant to photo-degradation. The dye can be excited at the wavelength of 380-550 nm. Therefore, we chose PtTFPP-based PSP.

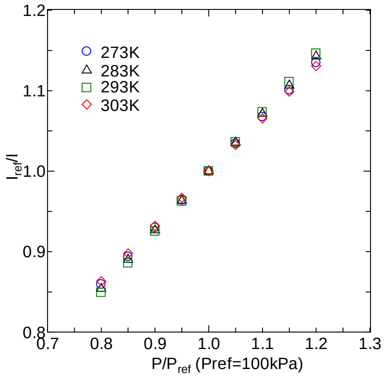
Ru(phen)-based TSP was used for temperature measurement. The dye was dissolved in thinner with urethane polymer. The TSP shows high temperature-sensitivity and can be excited by common wavelength with PtTFPP-based PSP.

PSP and TSP was painted on a model with a spray-gun. First of all, white basecoat was sprayed on a model surface as screen layer (white reflecting layer). The basecoat enhances PSP and TSP luminescence. After coating the basecoat, PSP and TSP was sprayed as an active layer.

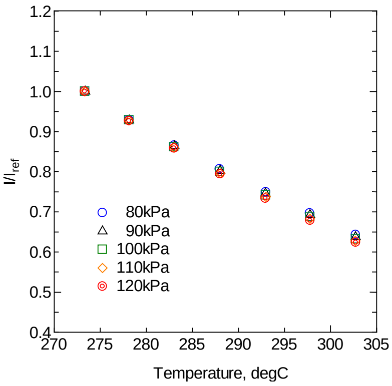
2.2 Characteristics

The calibration data of the PSP and TSP was obtained using a pressure and temperature controlled chamber. The optical setup was same as that of the low-speed testing. The characteristic of PSP is presented in Fig.1. The PSP demonstrated high-pressure sensitivity (0.75%/kPa). The sensitivity was independent of temperature. However, emission intensity of PSP depended on temperature. Therefore, the luminescence of PSP must be corrected, when temperature on a model surface is non-uniform.

The characteristics of TSP is illustrates in Fig.2. TSP showed high temperature sensitivity (2%/degC). In addition, the intensity ratio was insensitive to pressure. Therefore, the pressure sensitivity was not considered in the image processing.

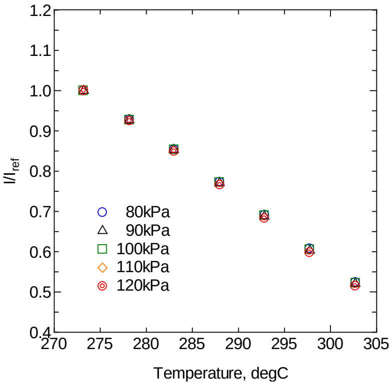


(a) Pressure Sensitivity.

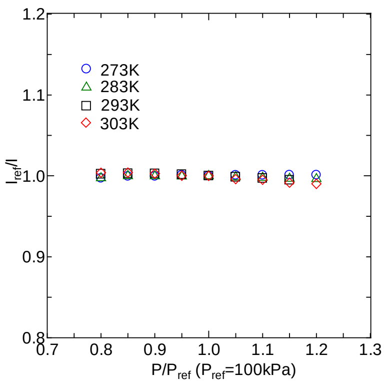


(b) Temperature Sensitivity.

Fig.1 Pressure and Temperature Sensitivity of PSP.



a) Temperature Sensitivity



(b) Pressure Sensitivity

Fig.2 Pressure and Temperature Sensitivity of TSP.

3. Experimental Setup

3.1 Wind Tunnel

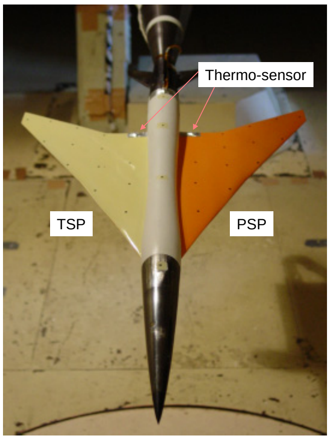
The PSP system has been applied to the 2m × 2m Low Speed Wind Tunnel (LWT2) at WINTEC of ISTA/JAXA. The LWT2 is a continuous wind tunnel, and the flow speed is capable to change up to 60 m/sec. The test section is 2m × 2m, and the length of the cart is 4 m. The optical wind on the roof of the cart is designed to set up an optical system for PSP and PIV. A model was supported by a robot arm, and the attitude can be controlled by it.

3.2 Optical Setup

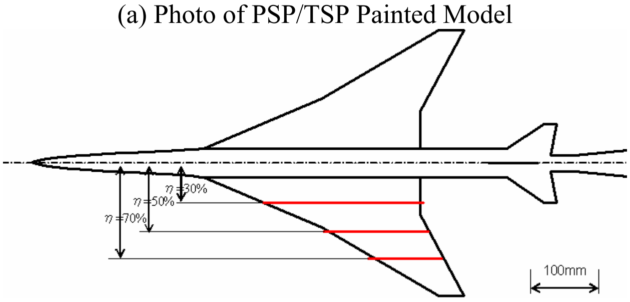
The model of SST (8.5% scale model) was used in this study. The photo of PSP/TSP painted model and the schematic view of the model are presented in Fig.3. Pressure taps were drilled at the location of 30% (S1 line), 50% (S2 Line) and 70% (S3 Line) of the wingspan (η=y/2b). Markers were installed on the wings for image resection between wind-on and wind-off image. A thermo-sensor (Platinum Thermo Resistance) was also mounted on both wings.

The photo and illustration of PSP system are presented in Fig.4. The illuminators and CCD camera (HAMAMATSU PHOTONICS: C4880-50-26W) were mounted on the roof of the LWT2. The CCD camera had a 16 bit intensity resolution, and size of CCD was 1024 × 1024 pixel. The Xe arc lamp (HAMAMATSU PHOTONICS C4338) was used as excitation light source. PSP was excited by the light at the wavelength of 380-550 nm through a band-pass filter. By using the filter, PSP and TSP was excited at the common wavelength. The luminescence from the PSP and TSP was simultaneously captured by the CCD camera with a band-pass filter of 590-710 nm.

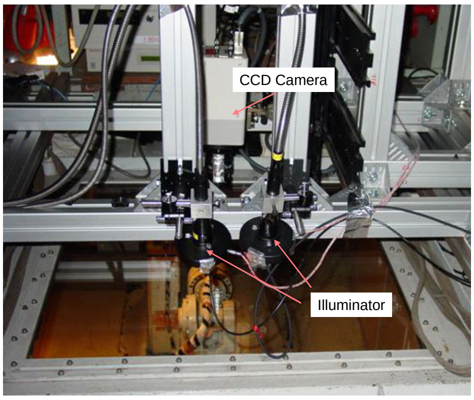
The instability of an excitation light intensity influences on measurement accuracy. So, the light intensity was monitored by a photo-diode (PD). The PD was mounted in front of an illuminator. As Figure 4 showed, two illuminators were set so as to uniformly irradiate the model.



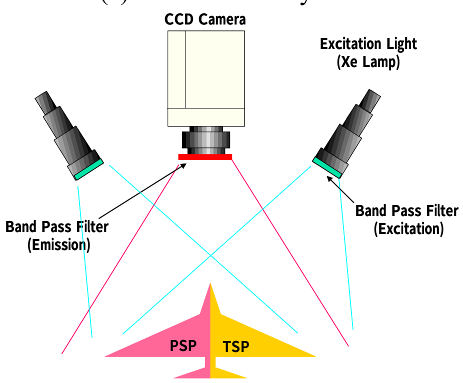
(a) Photo of PSP/TSP Painted Model



(b) Illustration of SST Model
Fig.3 SST Model.



(a) Photo of PSP System.



(b) Illustration of PSP System
Fig.4 PSP System at LWT2.

3. Principle of Image Processing

The data reduction method is described in this section. In this study, *a-priori* and *in-situ* method were applied to convert PSP image to pressure image.

To start with, *a-priori* method is described. The luminescent intensity of PSP depends on both pressure and temperature. Therefore, temperature dependence of PSP must be compensated. We made use of TSP for correcting. Here, we assumed that the symmetry of flow structure on each wings of the model was realized. At first, temperature distribution on the model was calculated from TSP image. The ratio image of wind-on TSP image to wind-off one was converted to temperature image using calibration curve in Fig.2. PSP image (wind-on image) was compensated by the temperature image and photo-diode data.

As a general, pressure-sensitivity of PSP is expressed by Stern-Volmer equation [1]. The equation was described as follows. It shows the relationship between pressure and the ratio of wind-on PSP image to wind-off image.

$$\frac{I_{ref}}{I} = A(T) + B(T)\frac{P}{P_{ref}} \qquad (1)$$

Where, I, P and T are luminescent intensity, pressure and temperature, respectively. A and B shows coefficients of Stern-Volmer equation. In practice, the equation is non-linear. Then, it was extended to quadratic expression in this study. The temperature-corrected PSP image was converted to pressure image by PSP calibration curve in Fig.1.

As another method, an *in-situ* method was applied. It referred to pressure tap data on a wing of a model. In order to precisely calculate pressure, temperature-corrected PSP image should be used before correlating pressure tap data with the ratioed PSP image. Two methods to compensate the temperature dependence were considered. The one method (case-A) is to use TSP for compensation. Another method (case-B) is to apply a wind-off image immediately after blowing over air-flow [10],[11].

Temperature distribution of the PSP image was fairly close to that of the wind-on one. So, temperature dependence of PSP could be corrected. After temperature correction, an *in-situ* calibration curve was determined referring to pressure tap data and the ratioed PSP image. This method assumed that pressure tap data was equal to ratioed PSP intensity around the tap location. For comparison, an *in-situ* method without temperature correction (Case-C) was also conducted.

Image processing procedure is as flows.

1. Averaging of PSP images
2. Marker detection for image registration.
3. Image registration between wind-on image and wind-off image.
4. Convert TSP image to temperature image.
5. Temperature correction of PSP image using temperature image.
6. *Case of *a-priori* method: PSP image was calculated with PSP calibration curve.
   *Case of *in-situ* method: PSP image was calculated with *in-situ* calibration curve.

When a wind-off image immediately after shutdown wind tunnel was applied, the temperature correction of PSP was not carried out.

4. Experimental Results

4.1 Temperature Correction of PSP

A-priori and *in-situ* method were applied to process PSP images, and the accuracy of PSP was evaluated. The one hundred and twenty-eight PSP images were processed. First, the result processed by *a-priori* method is presented. The experimental condition was the flow speed of 50 m/sec and an angle of attack (α) of 20˚. The pressure and temperature image is illustrated in Fig.5. Temperature distribution on the wing was not uniform, while it took 10 minutes after start of measurement. Pressure image showed that low pressure region induced by primary vortex was visualized along the leading edge. However, pressure image was so unevenness. Figure 5(c) indicated that the PSP dada was discrepant with pressure tap data. It was inferred that temperature image on the PSP was different from that on the TSP. The problem would be caused by difference of body structure between each wing. Besides, the error might result from accuracy of the TSP.

The results processed by an *in-situ* method are presented in Fig.6. As remarked in the previous section, PSP image was converted to pressure image by three methods. In case of Case-A method, the wind-on PSP image was compensated with TSP image. For Case-B method, the PSP image was processed by wind-off image immediately after blowing over airflow. For comparison, the wind-off PSP images before testing were used without temperature correction (Case-C method).

Pressure image obtained by Case-A method was uneven as the result by *a-priori* method predicted. The result by Case-C method was also not clear as might be expected, since the image was converted without temperature correction. On the other hand, the image processed by Case-B method was clearly visualized in comparison with other two cases.

The in-situ calibration curves for three methods are presented in Fig.7. Because of low-speed testing, the plotted data was somewhat scattering to the fitting curve. RMS (Root-mean Square) difference between the pressure tap data and PSP data was estimated for comparing the measurement accuracy. The RMS differences for the three methods were 0.0658kPa for Case-A, 0.0450kPa for Case-B and 0.0652 kPa for Case-C. The degree of scattering for Case-B method was smallest among three methods, indicating that the method was most effective in temperature correction.

Figure 8 shows the comparison of PSP data with pressure tap data. Although the results processed by three methods were agree with pressure tap data at the location of taps, the PSP data by Case-A and Case-C method fluctuated except their points. This would be due to inadequate temperature correction. On the other hand, the result by Case-B method showed smooth profile. As a result, the Case-B method was the best method to convert PSP image to pressure image among three methods.

However, small differences between PSP data and pressure tap data were still seen. These would be due to incomplete temperature correction of PSP, since the temperature pattern for wind-on PSP image was not exactly same as that for wind-off image. By directly measuring temperature of PSP with IR camera or biluminophor paint [12], the measurement accuracy might be improved.

4.2 Measurement Accuracy of PSP

In order to understand the relation between accuracy of PSP and flow speed, pressure images were acquired varying flow speed from 20 to 50 m/sec. PSP data was processed by Case-B method. The result is presented in Fig.9. For the speed of 30, 50m/sec, pressure pattern was clearly recognized. However, in case of 20 m/sec, pressure image seems to be somewhat rough. This is because the dynamic pressure decreases with decreasing the speed. The lower speed condition is crucial for the PSP measurement, since PSP is an absolute pressure sensor.

Figure 10 shows comparison of PSP data with pressure tap data. For the speed of 30, 50 m/sec, PSP agreed with pressure tap data. PSP data at 20 m/sec was fluctuating and partially difference from pressure tap data. Therefore, the lower speed-limitation for the present PSP system was 20 m/sec.

The quality of the pressure image is sensitive to averaging number of PSP images. At the experiment, one hundred and twenty-eight PSP images were acquired during a test. Pressure image at the flow speed of 50 m/sec and angle of attack of 20º was investigated. As Figure 11 showed, the result indicated that sixteen PSP images were enough to clearly visualize pressure image. Besides, the measurement accuracy was slightly improved by decreasing number of PSP images, since the temperature difference between the wind-on and wind-off image decreased. The total time to measure sixteen images was shortened by approximately two and half minutes, although the total acquisition time of one hundred and twenty-eight PSP images was about twenty minutes.

Figure 12 shows the dependence of pressure pattern on α. In this case, sixteen PSP images were processed. The flow speed was fixed at 50 m/sec. The pressure images were clearly visualized and showed that the strength of vortex became strong with increasing α. Figure 13 presents comparison of PSP data with pressure tap data. The result provided that PSP data agreed with pressure tap data.

Consequently, these results indicated that the present system was applicable to low-speed wind tunnel testing and a useful tool to measure pressure field on an aerodynamic model surface.

3 Conclusions

The PSP measurement system was applied to low-speed testing at the 2m × 2m Low Speed Wind Tunnel/WINTEC of JAXA. In this study, the methods to compensate temperature dependence of PSP were evaluated. The result provided that the *in-situ* method (Case-B method) using an after-run image as a reference image was most effective in correcting the temperature dependence of the PSP in comparison with *a-priori* method and the other *in-situ* method. The accuracy (RMS difference) of the in-situ calibration was 0.0450 kPa at the flow speed of 50 m/sec and angle of attack of 20º. The pressure patterns on the SST model could be visualized varying flow speed (20-50 m/sec) and an angle of attack (12-20º). Pressure distributions were quantitatively measured by the PSP system except a speed range less than 20 m/sec. In addition, the correlation between image quality and averaging number of PSP image was investigated. It was found that the sixteen PSP images were enough to clearly visualize pressure images at the flow speed of 50 m/sec. These results indicated that the present system was applicable to low-speed wind tunnel testing and a useful tool to measure pressure field on an aerodynamic model surface.

Acknowledgements

The authors would like to gratefully thank Mr. Shigeya Watanabe, Mr. Toshimi Fujita, Mr. Masatake Ito and Mr. Takuro Hashimoto for constructing the PSP system at LWT2 and their valuable discussion. In addition, a special thank goes to Dr. Kenji Yoshida and Mr. Masayoshi Noguchi for giving us the opportunity to use the SST model.

References

[1] 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, pp 227-246, 1997.

[2] Bell, H. J., Schairer, T. E, Hand, A. L and Mehta, R. D. Surface Pressure Measurements Using Luminescent Coatings. Annu. Rev. Fluid Mech., 33, pp 115-206, 2001.

[3] Nakakita, K., Kurita, M. and Mitsuo, K. Development of the Pressure-Sensitive Paint Measurement for Large Wind Tunnels at Japan Aerospace Exploration Agency. *24th Congress of the International Council of the Aeronautical Sciences*, Yokohama, ICAS2004-3.2.2, 2004.

[4] Shimbo, Y., Asai, K., Kanda, H., Iijima Y., Komatsu, M, Kita, S and Ishiguro, M. Evaluation of Several Calibration Techniques for Pressure-Sensitive Paint in Transonic Testing. *20th AIAA Advanced Measurement and Ground Testing Technology Conference*, Albuquerque, NM, AIAA Paper 98-2502, 1998.

[5] Kurita, M., Nakakita, K., Mitsuo, K. and Watanabe, S. Data Processing of Pressure-Sensitive Paint for Industrial Wind Tunnel Testing. *24th Aerodynamic Measurement Technology and Ground Testing Conference*, Portland, OR, AIAA-2004-2189, 2004.

[6] 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, 1267-1296, 1999.

[7] Rolf H. Engler, Marie-Claire Mérienne, Christian Klein and Yves Le Sant. Application of PSP in low speed flows. *Aerospace Science and Technology*, 6, pp 313-322, 2002.

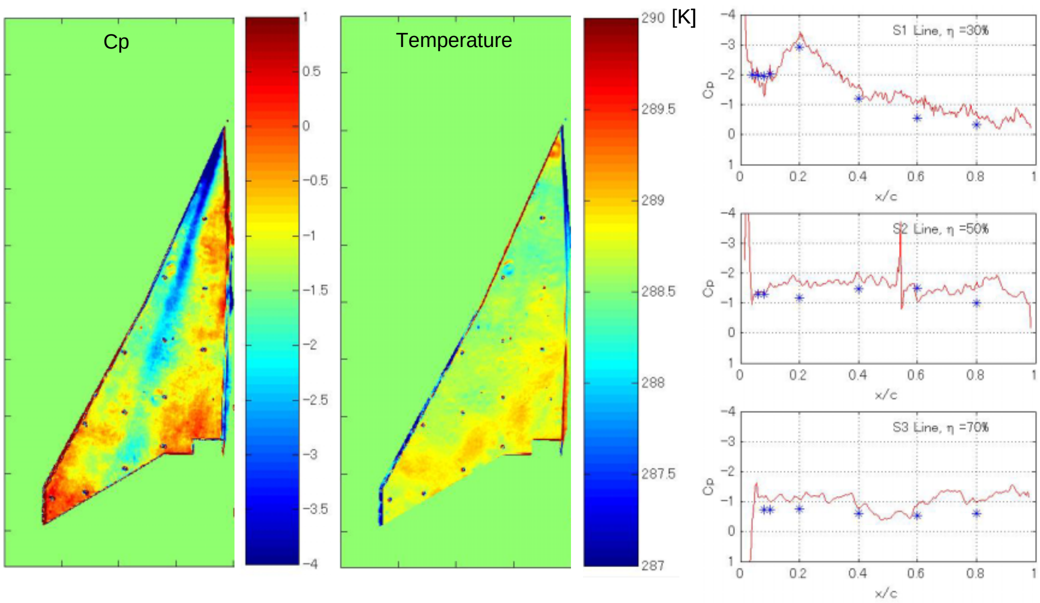
[8] Le Sant, Y., Bouvier, F., Mérienne, M-C and Peron, J-L. Low Speed Tests using PSP at ONERA. *39th AIAA Aerospace Sciences Meeting & Exhibit*, Reno, NV, AIAA 2001-0555, January, 2001.

[9] Lyonnet, M., Deléglise, B. and Lesant, Y. Application of Pressure Sensitive Paint Technique un the S1MA Wind Tunnel. *40th AIAA Aerospace Sciences Meeting & Exhibit*, Reno, NV, AIAA 2002-0744, January, 2002.

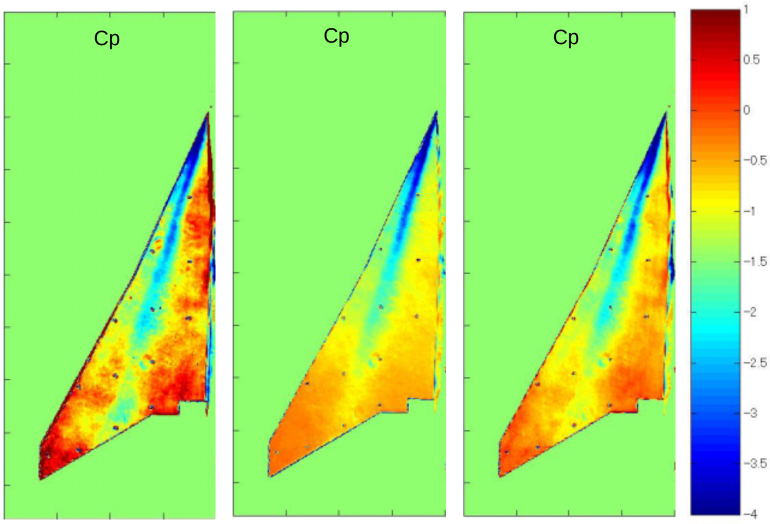
[10] Mitsuo, K., Hayasaka, M., Kameda, M. and Asai, K., Pressure-Sensitive Paint Measurement of Multi-Jet Impingement Flow. *Proceedings of 23rd International Symposium on Space Technology and Science*, Iwate, ISTS-02-e-52, 2002.

[11] Bell, James H. Applications of Pressure sensitive Paint to Testing at Very Low Flow Speeds. *42nd AIAA Aerospace Sciences Meeting & Exhibit*, Reno, NV, AIAA-2004-0878, 2004.

[12] Mitsuo, K., Asai, K., Hayasaka, M. and Kameda, M. Temperature Correction of PSP Measurement Using Dual-Luminophor Coating. *Journal of Visualization*, Vol.6, No.3, pp 321-331, 2003.

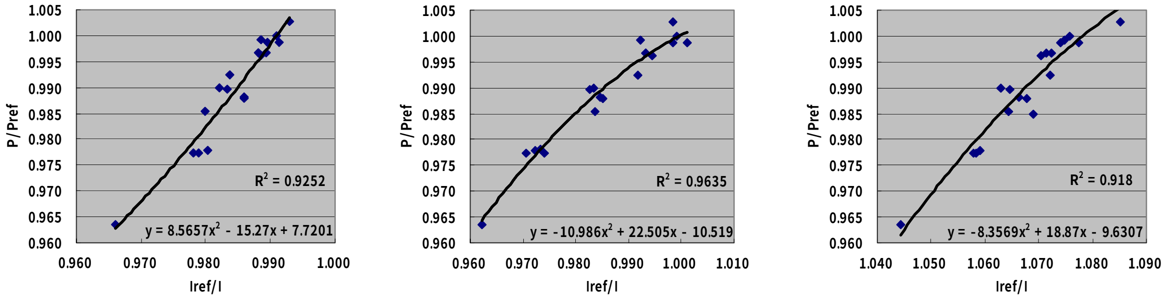


(a) Pressure Image (b) Temperature Image (c) Comparison of PSP Data with Pressure tap Data
Fig.5 Results Processed by *A-priori* Method. (V=50 m/sec, α=20˚, 128 PSP Images)



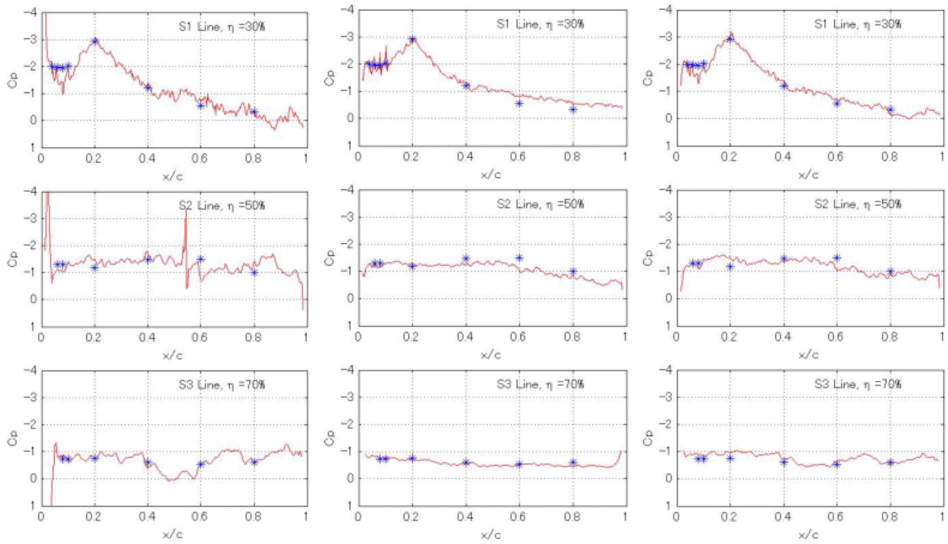
(a) Case-A. (b) Case-B (c) Case-C

Fig.6 PSP Images Processed by *In-situ* Method. (V=50 m/sec, α=20˚, 128 PSP Images)



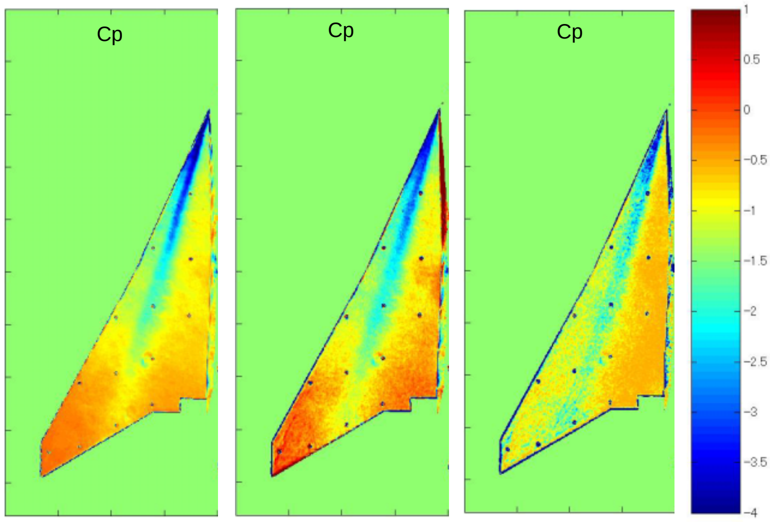
(a) Case-A (b) Case-B (c) Case-C

Fig.7 *In-situ* Calibration Curves. (V=50 m/sec, α=20˚, 128 PSP Images)



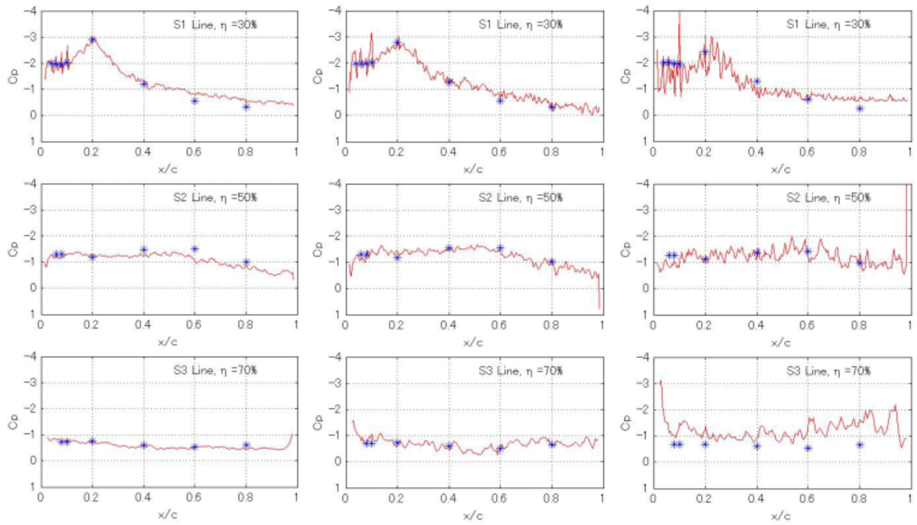
(a) Case-A. (b) Case-B (c) Case-C

Fig.8 Comparison of PSP Data with Pressure Tap Data (V=50 m/sec, α=20˚, 128 PSP Images)



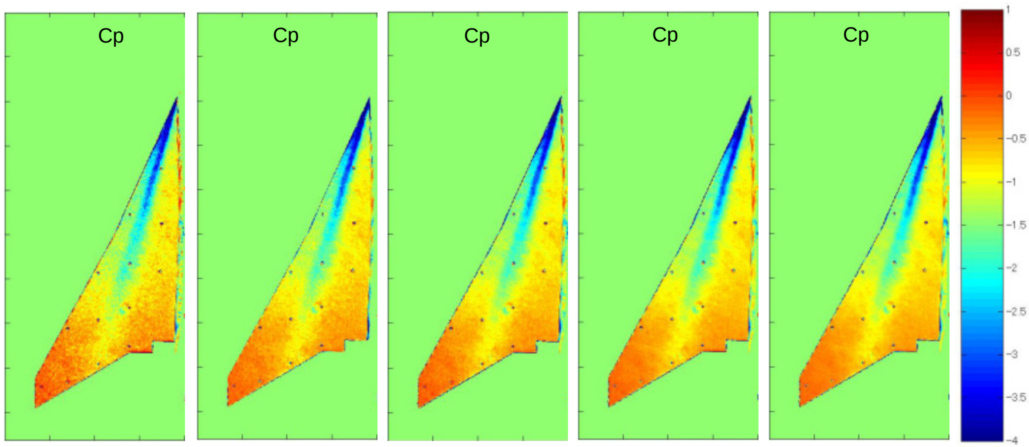
(a) V=50m/sec (b) V=30m/sec (c) V=20m/sec

Fig.9 Pressure Images Processed by *In-situ* Method. (Flow Speed was set at 20, 30 and 50 m/sec. α=20˚, 128 PSP Images)



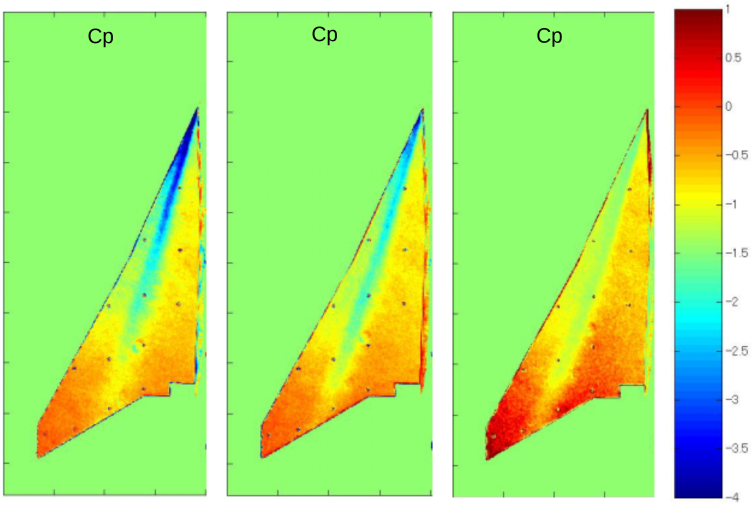
(a) V=50m/sec (b) V=30m/sec (c) V=20m/sec

Fig.10 Comparison of PSP data with Pressure Tap Data.
(Flow Speed was set at 20, 30 and 50 m/sec. α=20˚, 128 PSP Images)



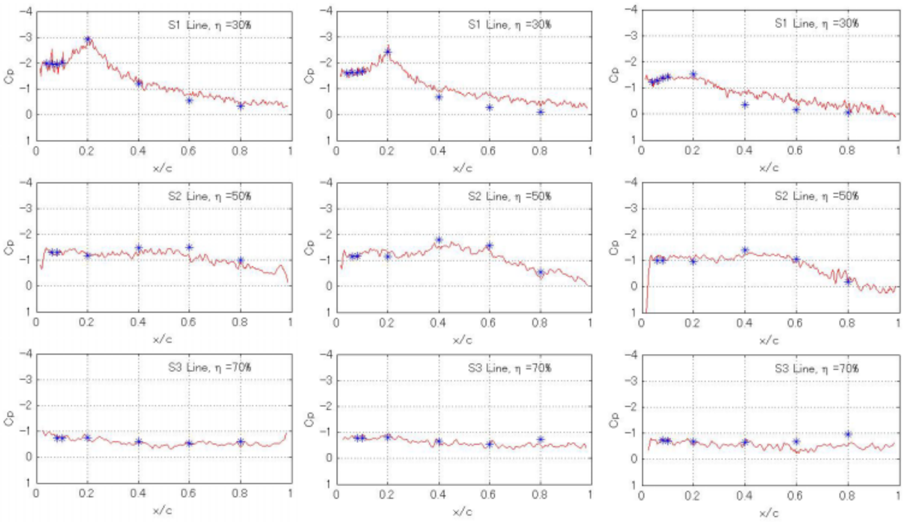
(a) 4 image (b) 8image (c) 16image (d) 32image (e) 64image

Fig.11 Pressure Images. (Number of Averaging Image: 4, 8, 16, 32, 64. V=50m/sec, α=20˚)



(a) α=20˚ (b) α=16˚ (c) α=12˚

Fig.12 Pressure Images by *In-situ* Method. (α was set at 12˚, 16˚ and 20˚. V=50 m/sec, 16 PSP images)



(a) α=20˚ (b) α=16˚ (c) α=12˚

Fig.13 Comparison of PSP Data with Pressure Tap Data. (α was set at 12˚, 16˚ and 20˚. V=50 m/sec, 16 PSP images)