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Appendix A. Calibration Apparatus

For PSP, the relationship between the luminescent intensity (or lifetime) and air pressure is determined by calibration. Figure A1 shows a simple apparatus for calibration of PSP (Burns 1995). A PSP coating is applied to an aluminum block (1.5×1.5×0.625 cm) that is thermally anchored using high thermal conductivity grease to a Peltier heater/cooler controlling the surface temperature of the block. A thermometer inserted in the aluminum block near the painted surface is used to measure the temperature of the paint sample. The PSP sample on the block is placed inside a pressure chamber with an optical access window. Pressure inside the chamber is controlled and measured using a pressure transducer. An illumination light, typically from a UV lamp, LED array or laser, passes into the chamber through the window and excites the paint sample. The luminescent emission from the paint sample is collected with a lens, filtered by a long-pass or band-pass optical filter, and projected onto a photodetector like a photodiode, photomultiplier tube (PMT) or CCD camera. The photodetector output over a range of pressures and temperatures is acquired with a PC, where the dark current is subtracted from the intensity output. Therefore, a relation between the luminescent intensity and pressure is determined over a range of temperatures; the calibration data are typically fit using the Stern-Volmer equation for different temperatures. For lifetime or phase calibrations, a pulsed or modulated excitation light should be used.

The set-up in Fig. A1 can be used for TSP calibration when the surface temperature of a TSP coating on the aluminum block is varied over a range of -15 to 150°C by controlling the Peltier heater/cooler while the chamber pressure is kept constant. Thus, a calibrated relation between the luminescence intensity and temperature is obtained, which is typically represented by the Arrhenius plot over a certain temperature range. Note that an oven for calibrating fluorescent temperature sensors was described by Crovini and Fernicola (1992). This simple apparatus can be adapted for TSP calibration down to cryogenic temperatures (Campbell et al. 1994). In this case, a TSP sample is thermally anchored to a copper bar cut at an angle of 45° at its top that rests in a container filled with liquid nitrogen. The sample temperature near the temperature of liquid nitrogen can be achieved due to heat conduction from liquid nitrogen to the sample through the copper bar. To prevent condensation of moisture from forming on the paint sample, the sample is purged with dry nitrogen gas. Using this apparatus, Campbell et al. (1994) examined the temperature dependencies of the luminescent intensity for many TSP formulations.

Figure A2 shows a cryostat device designed by Erausquin (1998) specially for calibrating PSP at cryogenic temperatures. Liquid nitrogen contained in the buffer volume is used to cool the device to cryogenic temperatures. A bellows is introduced between the buffer volume area of the cryostat and the test chamber area where a PSP sample is placed. Thus, the liquid nitrogen storage portion is separated from the actual test chamber into which the test gas (a mixture of oxygen and nitrogen) is introduced. Two valves are added to the lower portion to allow for filling and evacuating the test gas. There is one window on the lower portion of the test chamber allowing optical access to the PSP sample mounted on a copper sample holder. The sample holder is attached to the base of the lower tube leading from the buffer volume, allowing liquid nitrogen to directly contact with the sample holder. An aluminum sample block with a PSP coating on one surface is attached to the sample holder with an aluminum bracket and screws. The sample temperature, which is controlled by a temperature controller, is measured using a temperature sensor located above the sample holder. Absolute pressure in the test chamber is measured with an absolute pressure transducer. The luminescent emission from the paint is collected by a large lens and projected onto a PMT through a long-pass glass/interference optical filter; then, the PMT output signal is acquired with a PC. Clearly, this device can also be used for calibrating cryogenic TSP.

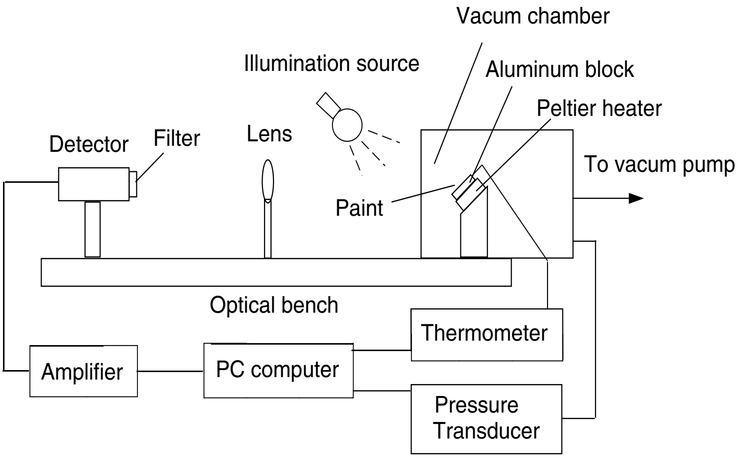


Fig. A1. Simple apparatus for calibration of PSP and TSP. From Burns (1995)

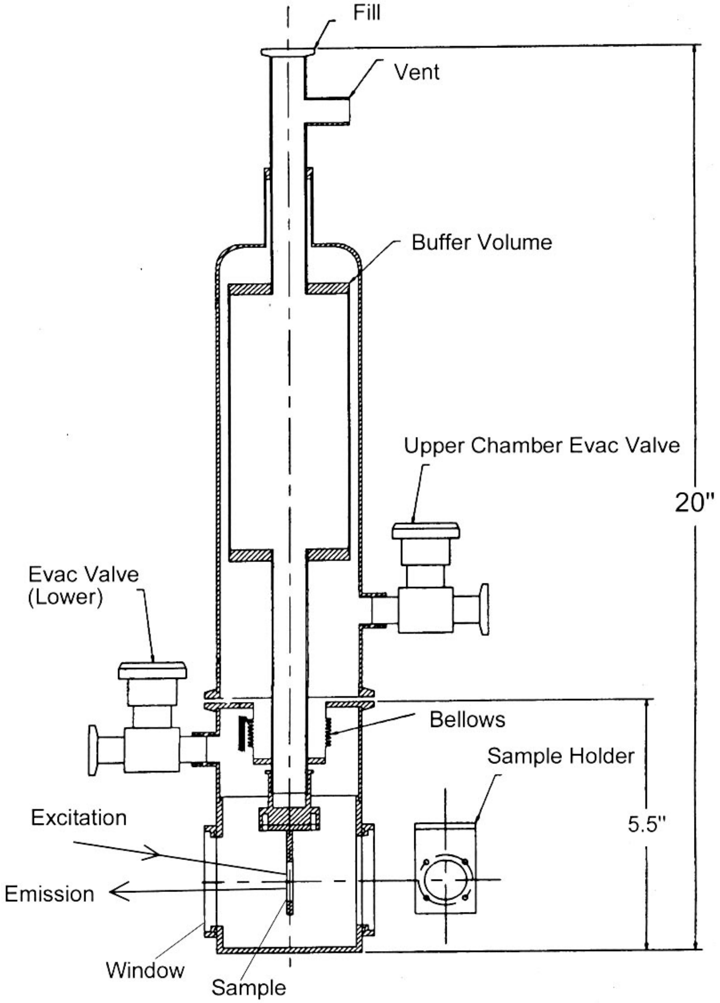


Fig. A2. Calibration chamber for cryogenic PSP and TSP. From Erausquin (1998)

Appendix B. Recipes of Typical Pressure and Temperature Sensitive Paints

Recipes of Three PSP Formulations

(1) Ru(ph_2-phen) or Ru(dpp) in RTV

Ingredients: 4 mg of Bathophen Ruthenium Chloride [Ru(ph_2-phen) or Ru(dpp)], 25 ml of dichloromethane, 7.5 ml of GE RTV 118, 2 g silica gel particles.

Directions: Dissolve Ru(ph_2-phen) in the solvent dichloromethane, add silica gel particles and then GE RTV 118, and stir until fully dissolved.

(2) PtTFPP in RTV

Ingredients: 6 mg of platinum meso-tetra(pentafluorophenyl)porphyrin (PtTFPP), 25 ml of dichloromethane, 7.5 ml of GE RTV 118, 2 g silica gel particles.

Directions: Dissolve PtTFPP in the solvent dichloromethane, add silica gel particles and then GE RTV 118, and stir until fully dissolved.

(3) PtTFPP in FEM (NASA Langley)

Ingredients: 5.3 mg platinum meso-tetra(pentafluorophenyl)porphyrin (PtTFPP) (120 ppm), 12 g Polytrifluorethyl-co-isobutyl methacrylate (TFEM/IBM), 37.5 g Solvent DuPont 3602S, 3.6 g Solvent DuPont 3979S or 3696S.

Directions: Dissolve the TFEM/IBM in the DuPont solvents, add PtTFPP, and stir until dissolved, and adjust the viscosity of the solution to 10.5 cp with the 3602S solvent. Allow the paint to cure at the room temperature for about 20 minutes before heating to 65°C for one hour.

Recipes of Two TSP Formulations

(1) Ru(bpy) in Clear Coat

Ingredients: 6 mg of tris(2,2'-bipyridyl) ruthenium [Ru(bpy)], 20 ml of automobile Urethane Clear Coat (DuPont ChromaClear), 5 ml of activator, 10 ml dichloromethane.

Directions: Dissolve Ru(bpy) in the solvent dichloromethane, sonicate for 5 minutes, add urethane clear, shake and sonicate. Just before painting (within 5 minuets) add the activator, shake and sonicate for 1 minute. Acetone is used as a solvent to clean up the paint.

(2) EuTTA in Dope

Ingredients: 12 mg Europium (III) Thenoyltrifluoroacetonate (EuTTA), 20 ml model airplane dope, 20 ml dope thinner.

Directions: Mix EuTTA with the dope thinner, shake and then sonicate for a few minutes. Add the dope, shake and sonicate. Acetone is used as a solvent to clean up the paint.

Appendix C. Vendors

Chemicals

(1) Frontier Scientific, Inc. (former Porphyrins Products)
P.O. Box 31, Logan, Utah 84323-0031, USA
Tel: (435) 753-6731, E-mail: sales@frontiersci.com, Web: www.frontiersci.com
Products: Pt(III) meso-tetra(Pentafluorophenyl)porphine (PtTFPP) (PSP probe), Pt(II) Octaethylporphine (PtOEP) (PSP probe)

(2) Sigma-Aldrich
3050 Spruce St., St. Louis, MO 63103, USA
Tel: 800-325-3010, Web: www.sigmaaldrich.com
Products: Tris(2,2’-bipyridyl)ruthenium(II) chloride hexahydrate [Ru(bpy)] (TSP probe), Dichlorotris(1,10-phenanthroline)ruthenium(II) [Re(ddp)] (PSP probe), Pyrene (PSP probe)

(3) Gelest, Inc.
11 East Steel Road, Morrisville, PA 19067, USA
Tel: (215)-547-1015, E-mail: info@gelest.com, Web: www.gelest.com
Products: Europium III Thenoyltrifluoroacetonate (EuTTA) (TSP probe)

(4) GFS Chemicals, Inc.
P.O. Box 245, Powell, OH 43065, USA
Tel: (877)-534-0795, E-mail: sales@gsfchemicals.com, Web: www.gfschemicals.com
Products: Terpyridine ruthenous dichloride [Ru(trpy)] (TSP probe), Ruthenium bis(4,4’,5,5’-tetramethyl-2,2-bipyridine)(2,2’:6’,2”-terpyridine) [$Ru(tmb)_2(trpy)$] (TSP probe), Ruthenium bis(2,2’-bipyridine)(2,2’:6,2”-terpyridine) [$Ru(bypy)_2(trpy)$] (TSP probe), 1,10-phenanthroline ruthenous chloride [$Ru(phen)_3Cl_2$] (TSP probe), Tris(2,2’-bipyridine) ruthenous dichloride, hydrate [Ru(bypy)] (TSP probe), Tris(bathophenanthroline) ruthenium dichloride [Ru(bath)] (PSP probe)

(5) Innovative Scientific Solutions, Inc.
2766 Indian Ripple Road, Dayton, OH 45440-3638, USA
Tel: (937)-429-4980, E-mail: solutions@innssi.com, Web: www.innssi.com
Products: Unicoat PSP, FIB-based PSP top coat and base coat, PtTFPP sol-gel PSP, and Ru sol-gel PSP

Cameras

(1) Roper Scientific, Inc.
3660 Quakerbridge Road, Trenton, NJ 08619, USA
Tel: (609)-587-9797, E-mail: info@roperscientific.com, Web: www.roperscientific.com
Products: high-performance CCD cameras for scientific and technical applications

(2) PixelVision
10500 SW Nimbus Avenue, Tigard, OR 97223-4310, USA
Tel: (503)-431-3210, E-mail: info@pvinc.com, Web: www.pvinc.com
Products: high-performance CCD cameras for scientific and technical applications

(3) Hamamatsu Corporation (USA)
360 Foothill Road, Bridgewater, NJ 08807-0910, USA
Tel: (908)-231-0960, E-mail: usa@hamamatsu.com, Web: www.hamamatsu.com
Products: digital CCD cameras and other photonics equipment

Color Plates

The following pages contain color plates of figures that are shown in black and white in the text to reduce the cost of reproduction.

Fig. 1.6. PSP image for the F-16C model at Mach 0.9 and the angle-of-attack of 4 degrees. From Sellers (2000).

Fig. 7.11. Typical pressure distribution obtained from PSP on a Cessna Citation model. From Kammeyer et al. (2002a).

Fig. 9.8. Calibrated PSP image in Case III for 30 m/s and $\alpha = 5^{\circ}$. From Brown (2000).

Fig. 9.13. Raw blue image obtained using two separate CCD cameras and a 308-nm lamp for excitation, where the integration time for 16 images was 32 seconds. From Engler et al. (2001a).

Fig. 9.16. Pressure image mapped onto a surface grid of the Daimler Benz model with arrangement of pressure taps at 60 m/s. From Engler et al. (2001a).

Fig. 9.24. Typical pressure distribution mapped onto a surface grid of the AerMacchi M-346 advanced trainer model. From Engler et al. (2001b).

Fig. 9.27. The distributions of the pressure coefficient C_p on the wing upper surface obtained with the FIB PSP and the corresponding temperature distributions obtained using an infrared camera at $M = 0.74$, $Re_c = 3.8\times10^6$, and AoA = 0, 1, 3 and 5 degrees. From Mebarki and Le Sant (2001).

Fig. 9.28. Typical pressure fields on the Mitsubishi MU-300 business jet model obtained using a combination of PSP and TSP at Mach 0.73 and $\alpha = 2.3$ and 4.7 degrees. From Shimbo et al. (2000).

Fig. 9.32. Normalized surface pressure map P/P_s on the control panel with a standard multiple 90° bleed hole configuration, where P_s is the wall static pressure measured upstream of the fenced porous plate insert. Tunnel flow is from left to right. From Bencic (2002).

Fig. 9.33. Normalized surface pressure map P/P_s on the control panel with a multiple pre-conditioned 90° bleed hole configuration, where P_s is the wall static pressure measured upstream of the fenced porous plate insert. Tunnel flow is from left to right. From Bencic (2002).

Fig. 9.34. Normalized surface pressure map P/P_s on the control panel with a multiple 20° inclined bleed hole configuration, where P_s is the wall static pressure measured upstream of the fenced porous plate insert. Tunnel flow is from left to right. From Bencic (2002).

Fig.9.37. PSP image on the expansion corner model at Mach 10 and the angle of attack of 40^o. From Nakakita et al. (2000).

Fig.9.38. PSP image on the compression corner model at Mach 10 and the angle of attack of 30^o. From Nakakita et al. (2000).

Fig. 9.53. Pressure and temperature distributions on compressor blades at the speed of 17800 rpm. From Torgerson et al. (1998).

Fig. 9.55. Temperature fields on the TSP-coated blade at four rig speeds of 4950, 5800, 7450 and 7875 rpm. From Bencic (1997).

Fig. 9.56. Normalized pressure fields on the PSP-ccoated blade at four rig speeds of 4950, 5800, 7450 and 7875 rpm. From Bencic (1997).

Fig. 9.63. The distribution of C_p obtained using (a) the intensity-based CCD camera system and (b) the FLIM system. From Guille (2000).

Fig. 9.72. Pressure distribution in a micronozzle at the total pressure of 11.45 psi. From Huang et al. (2002).

Fig. 10.4. Heat transfer rate results for the sharp-nose indented cone model in LENS I with an 8 ms delay from flow onset at Mach 9.6 and Re = 270,000 per meter. Color scale ranges from violet = 0 W/cm^2 to red = 100 W/cm^2. From Hubner et al. (2002).

Fig. 10.17. Surface temperature distribution of the impinging multiple-micro-jet at H/D = 19.05. From Huang et al. (2002).

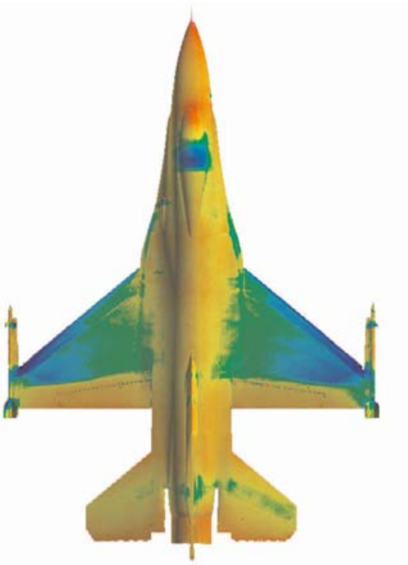
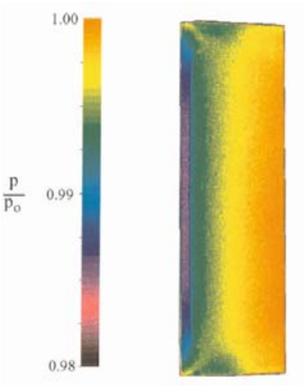


Fig. 1.6.



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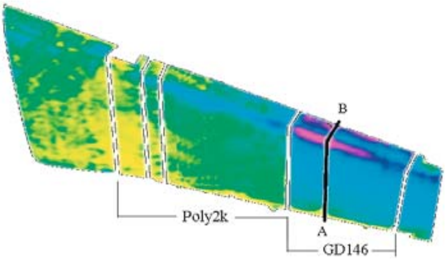


Fig. 9.13.

Fig. 7.11.

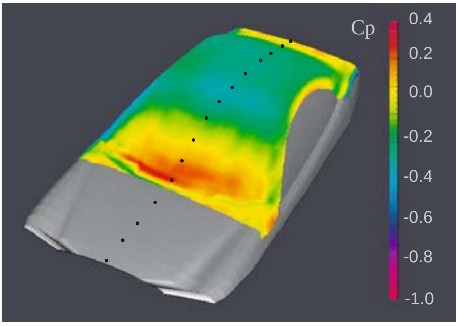
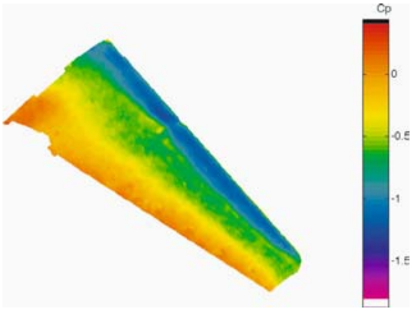


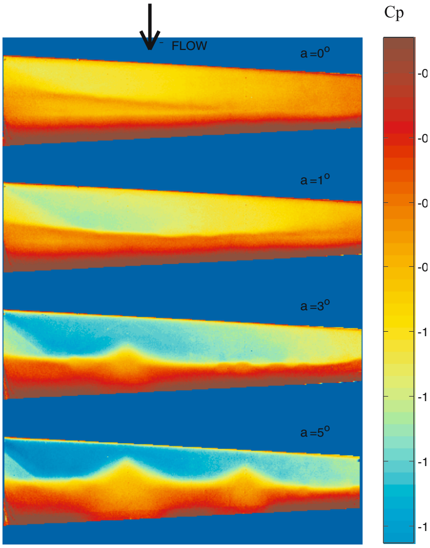
Fig. 9.16.

Fig. 9.24.



(a) M = 0.73, AoA = 2.3 deg.

Fig. 9.28.



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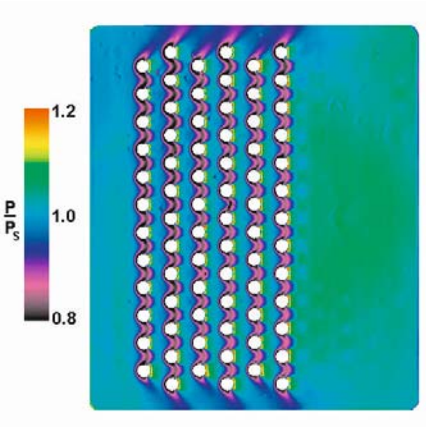

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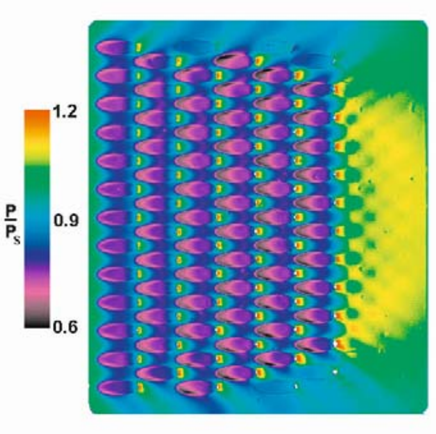

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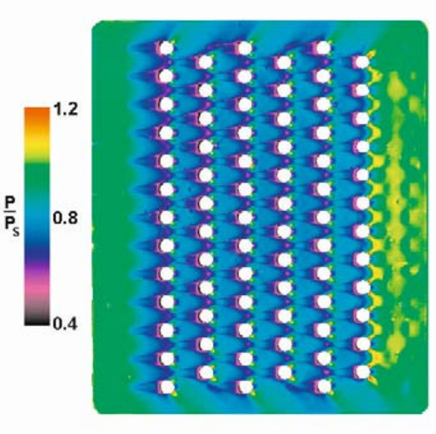

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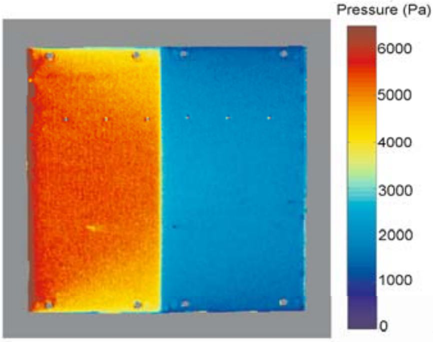
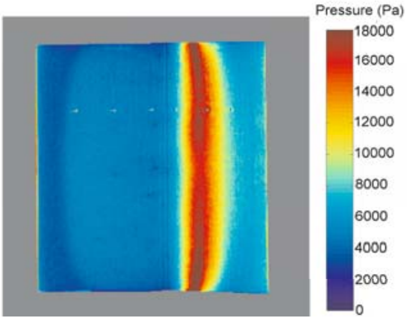


Fig.9.37



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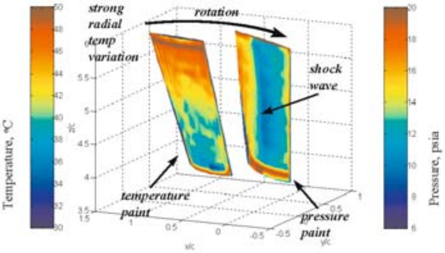

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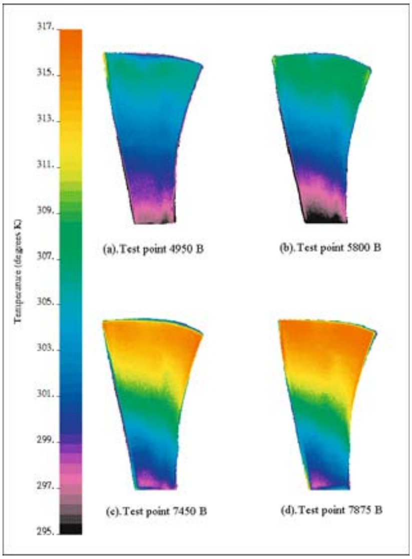

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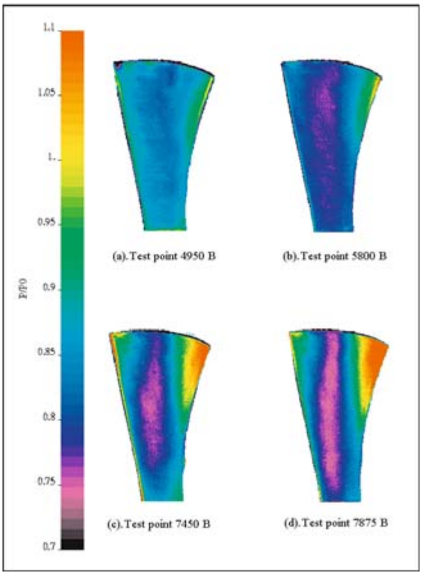

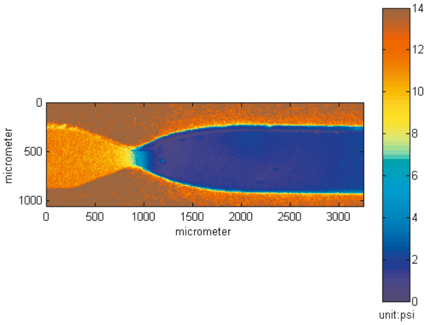

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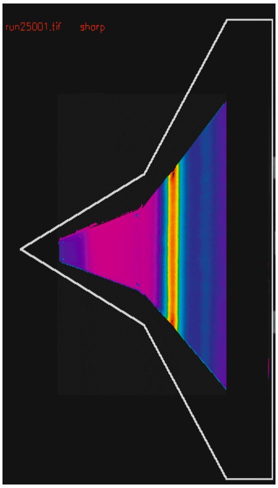

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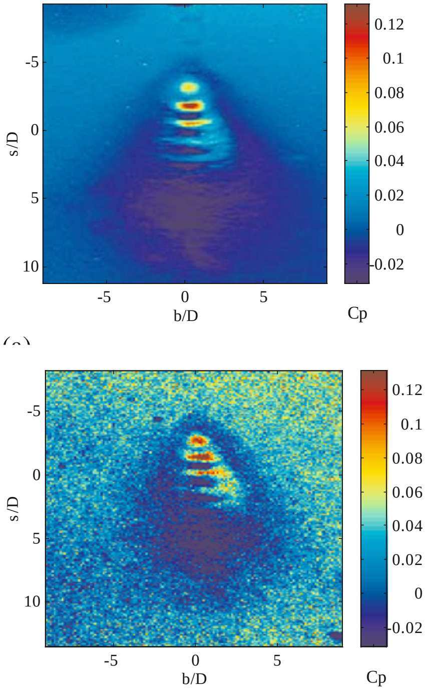

(a)

(b)

Fig. 9.63.

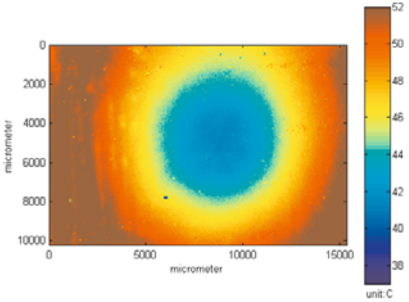

Fig. 10.17.

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