PSP/TSP ACTIVITY IN TsAGI

V.E. MOSHAROV[c], V.N. RADCHENKO

Central Aero-Hydrodynamic Institute (TsAGI), Zhukovsky str. 1, Zhukovsky, Moscow reg., 140180 Russia

[c]Corresponding author: Tel.: +74955563733; Fax: +74957776332; Email: mosh@progtech.ru

KEYWORDS:

Main subjects: Pressure and heat transfer distribution measurements on the model surface
Fluid: air flows, hypersonic flows
Visualization method(s): Pressure Sensitive Paint (PSP), Temperature Sensitive Paint (TSP)
Other keywords: paint formulation, luminescent coatings

TsAGI was a pioneer of PSP technology in the world [1, 2]. Plenty of efforts were devoted to Pressure and Temperature Sensitive Paints (PSP and TSP) development. Pressure Sensitive Paints based on pyren derivative and silicon polymer (Py/Silicone) are the most utilized in our aerodynamic researches now. The advantages of this formulation are: large quantum yield, optimal sensitivity for 1 bar pressure, small response time, absence of hysteresis and internal temperature compensation. Temperature compensation is based on ability of pyren molecules to create excimers (exited dimers):

$$M_{S1} + M_{S0} \longrightarrow (MM)_{S1} \tag{1}$$

Excimer molecules emit light of differed spectral range in contrast to monomers:

$$(MM)_{S1} \longrightarrow M_{S0} + M_{S0} + h\nu_{ef} \tag{2}$$

Excimer molecules can be quenched by oxygen molecules similarly to monomers:

$$(MM)_{S1} + O_2 \xrightarrow{k_q} M_{S0} + M_{S0} + O_2 \tag{3}$$

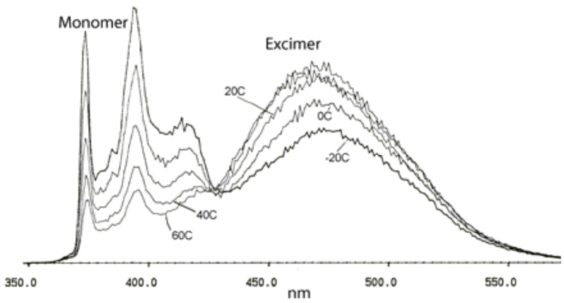


Fig.1 Luminescence spectra of pyren at different temperatures

PSP temperature sensitivity is determined by temperature dependence of diffusion coefficient of polymer binder. Reactions (1) and (3) are controlled by diffusion and can compensate effect of temperature variation on excimer luminescence intensity. Internal temperature compensation is illustrated in Fig 1, where luminescence spectra of pyren at different temperatures are shown.

Temperature sensitivity of Py/Silicone system does not exceed 0.3%/^{0}C.

The main disadvantage of Pyren based PSP is a short excitation wavelength (<340 nm) that requires the usage of quartz windows in wind tunnel for paint illumination.

PSP technology in TsAGI is widely used for three types of aerodynamic tasks:

1. Investigations of large scale aircraft models at transonic speeds.

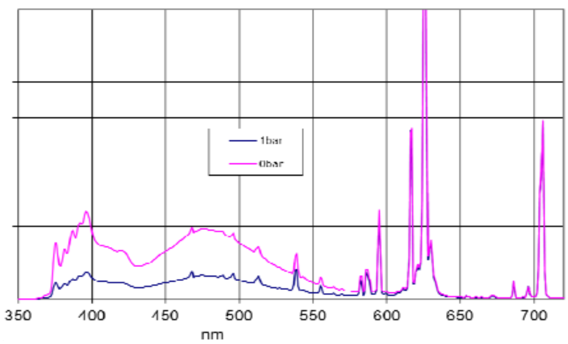


Fig. 2 Spectra of binary PSP at two pressures

PSP measurements are realized in two large transonic wind tunnels T-106 and T-128. Binary (two-color) PSP is used. The binary paint contains additional reference luminophor that is insensitive to pressure and emits light with intensity directly proportional to the excitation light intensity. Powder of europium doped crystal phosphor is used as a reference luminophor in combination with pyren derivative. Both luminophors (pressure sensitive and reference) are excited by the light of the same wavelength but emit in different spectral ranges, providing separate recording of sensitive and reference images, e.g. using two cameras with appropriate optical filters. Spectra of binary PSP at two pressures are shown in Fig.2.

Luminescence of reference luminophore is used for pixel-by-pixel correction of excitation light intensity variations during the test. Four CCD cameras and two flash lamps are used to measure pressure distribution on two model sides simultaneously.

Example of pressure fields on upper and lower surfaces of wing of training aircraft with deflected slat ($\delta=20^0$) at Mach number M=0.85 and angle-of-attack AoA=8^0 is presented in Fig.3.

Pressure distribution allows understanding flow physics and verifying CFD results. The integration of the pressure distribution over the surface of model elements yields the total loads and moments applied to these elements, for example allows determination of hinge moments of flaps, ailerons and slats.

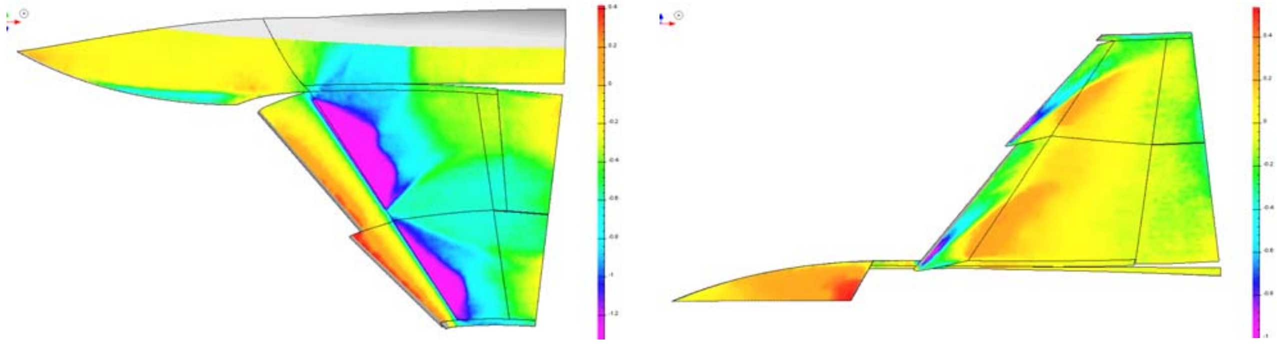
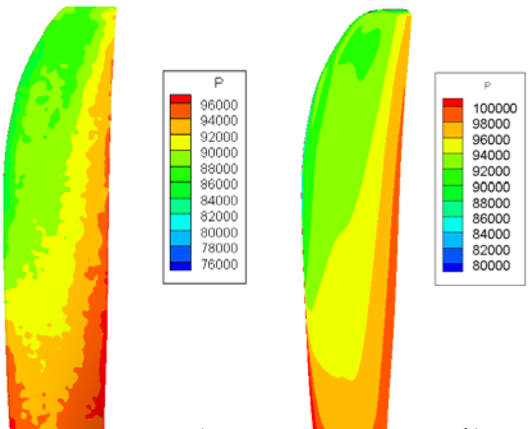


Fig. 3 Pressure distribution (C_P) on upper and lower surfaces of wing of training aircraft with deflected slat $\delta=20^0$, $\alpha=8^0$, M=0.85

2. Pressure field measurement on the propeller blade surface is an extremely complicated problem of experimental aerodynamics. Classical technique, i.e. creation of propeller model with vast amount of pressure taps, is quite time-consuming, complex and expensive. PSP provides alternative, quite rapid and economical method to obtain pressure distribution on the propellers. For the first time such measurements were performed in 1995 [3, 4]. Pressure measurements on the blades are important for CFD validation.



a) b)

Fig.4 Pressure field on propeller blade (5000 RPM V=30 m/s): PSP (a) and CFD (b)

Application of PSP technology to propellers has some specific features. The main problem is the image acquisition of moving blade. Linear speed of blade tip can reach up to 200÷300 m/sec. To eliminate blade displacement during image acquisition the measurement time must not exceed 1÷2 μsec that corresponds to blade tip displacement of 0.2÷0.5 mm. Longer measurement time will lead to unacceptable blur of blade image. The problem is solved by using the pulsed nitrogen laser operating in stroboscopic mode (light pulse duration is 6-8 nsec).

The other parameter affecting on the spatial resolution of pressure measurement on blades is luminescence decay time of PSP after excitation light pulse. Its effect on image blur is the same as an effect of illumination time. PSP formulations based on pyren derivative are optimal for the models moving with high speed since the lifetime of pyren derivative molecules is less than 400 nsec (lifetime in vacuum). Unfortunately, only single-component PSP can be used for pressure measurements on the blades. Reference component of our binary paint has too large lifetime (0.5 msec). For correction of excitation light intensity variation the spot of Luminescent Reference Paint (LRP) is applied on the model surface. Each image is divided by average LRP intensity.

Fig.4 shows pressure distribution on propeller blade in comparison with CFD prediction. Pressure fields are similar to each other, but PSP pressure level is lower by 4000 Pa that correspond to 4% of maximum pressure level on the blade. The reasons of discrepancies in the results are being investigated.

Under the project "DREAM" of European 7th FWP conducted research of pressure distribution measurements on the blades of coaxial rotors. The first rotor had 12 blades, and the second has 10. The problems of PSP measurements on this model are a shading of the blades by each other, light reflection from one rotor to another, as well as deformation of the blades. The blades were very thin. The deformation of the blade significantly affects on the intensity of luminescence at a grazing angle of illumination and observation, which was made to avoid overlaps of the blades. In these circumstances, obtaining reliable results is possible only with the binary paint.

3. PSP application in hypersonic flows is problematic because of significant PSP temperature sensitivity. Temperature problem is overcome by: a) executing the tests in short duration wind tunnel; b) model manufacturing from heat-conducting material (aluminum alloy) and c) application of PSP with fast response time.

Response time of PSP is determined by oxygen diffusion in the polymer layer and is directly proportional to the squared polymer layer thickness. Usage of permeable polymer applied as very thin layer (about 2 micrometers) allows getting response time less than 5 msec. Binary PSP for transonic applications contains crystal phosphor and is too thick for short duration facilities. To compensate excitation light variations in these tests we use a separate reference layer applied on the model surface before sensitive PSP layer.

PSP method is wildly used at Mach numbers M=5, 6 and 8 in Ludwieg wind tunnel UT-1 with flow duration 40 msec. One of the investigated problems is the interaction of the oblique shock waves, generated by a single fin or a fin pair, with boundary and entropy layers of blunted plate on which they are installed [5, 6]. These researches are supported by International Scientific and Technology Center (Project #3872) and Russian Foundation for Basic Research (Projects #04-01-00471-a, #05-01-00557-a, #08-01-00449-a, #11-01-00657-a). Model with single fin and flow scheme are shown in Fig.5. Pressure distributions on the plate and on the fin are presented in Fig.6. To exclude luminescent light re-reflection problem the pressure distributions on the plate and on the fin were measured in separate wind tunnel tests, tuning the investigated surface perpendicularly to illumination and observation direction.

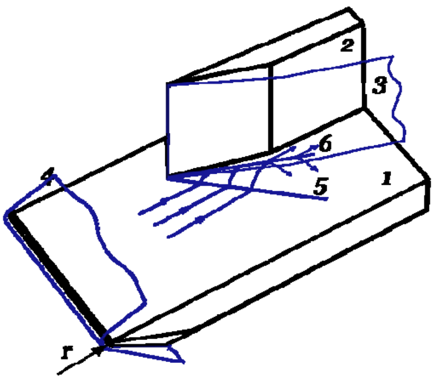


Fig.5 Investigated model and flow structure: 1 – plate, 2 – wedge, 3 - oblique shock wave, 4 – bow shock wave, 5 – separation line, 6 – reattachment line.

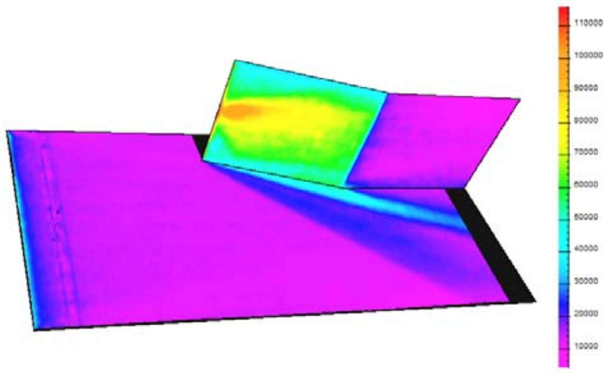


Fig.6 Pressure field (Pa) on a plate with blunting radius r=0.75mm and on a wedge with angle θ=20^{o} (M = 6, $Re_{\infty L}$ =4.3*10^{6})

Temperature Sensitive Paint is used for heat transfer measurements in short duration wind tunnels: Ludwieg wind tunnel UT-1 [5, 6] and pressure multiplier wind tunnel AT 303 (ITAM SB RAS) [7]. Both wind tunnels have time duration about 40 msec. For these applications the TSP method has advantages over other methods. The applicability of melting paints, as well as liquid-crystal coatings in pulsed wind tunnels is limited by the inertia of these coatings (large coating thickness – usually about 50 microns, and heat absorption for phase transition of melting paints). Additionally, the melting paints need image acquisition with the rate of several hundred frames per second; it complicates the experiment fulfillment and data processing. IR thermography needs special wind tunnel windows, is affected by thermal radiation from plenum chamber and has low spatial resolution.

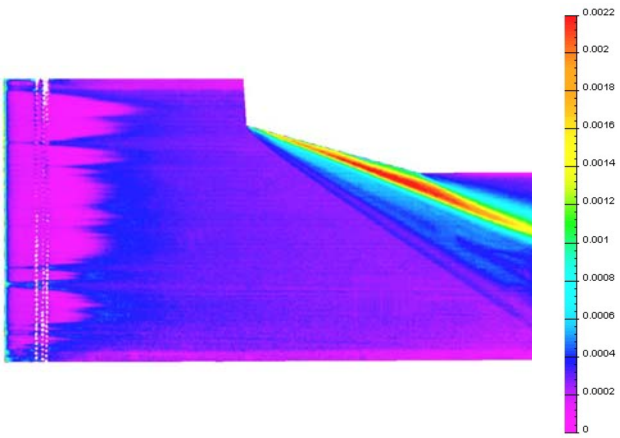


Fig.7 Distribution of Stanton number over the plate surface with sharp leading edge (*r=0)*. Mach number M = 5, Reynolds number $Re_{\infty L}$ = 27x10^{6} , total pressure P_o =70 bar, total temperature T_o = 500K.

Two-color TSP based on a complex of europium (temperature-sensitive luminophore), Coumarin (reference luminophore) and epoxy resin is used for the tests in short duration wind tunnels. Paint thickness is very small (3-5 μm) and usually can be neglected. Europium complex has luminescence of red spectral range while Coumarin emits in blue spectral range. Both luminophores are excited by UV light (<350 nm). The optimal temperature for this TSP is 20-

60°C. In this range the average sensitivity is about 3% /°C.

Field of heat transfer coefficient (Stanton number) on the plate with the fin (see model schematics in Fig.5) is presented in Fig.7

Natural laminar-turbulent boundary layer transition takes place (no trips are used). Turbulent wedges starting near the leading edge can be seen. They are joining at some distance from the leading edge and total transition takes place. The boundary layer separates from the plate surface far ahead the shock and reattaches between the shock and wedge. Heat transfer enlargement starts ahead the shock near the separation line. Heat flux increases dramatically in the narrow reattachment zone (red region near the wedge).

References

1. Pervushin G.E. et al. *Composition for Indicating Coating.* Patent of USSR - SU 1065452 A, 1981 (in Russian).
2. Mosharov V.E. et al. *Luminescent Coating for Pressure Distribution Investigation on the Models Surface in Wind Tunnels.* CIAM proceedings, N1232, 1988 (in Russian).
3. Bykov A.P. et al. *Application of Luminescent Pressure Sensor Technology to Propellers*., Preprint No.99, TsAGI, Moscow 1995
4. Bykov A.P. et al. *Pulsed Videoregistration of the Pressure on the Surface of Propellers with Luminescent Pressure Sensors. Proc. of ICHSPP'98* 1998, SPIE v.3516, part 1. - P.219.
5. Borovoy V. et al. *Laminar – turbulent flow around a wedge placed on sharp and blunted plates*. Flight Physics book of EUCASS, 2009. Torus Press, 2011, p. 145
6. Mosharov V.E. et al. *Hypersonic turbulent heating of sharp and blunt plates near a wedge.* Visualization of Mechanical Processes, Issue 1, 2011.
7. Borovoy V.Ya. et al. *Investigation of boundary layer transition by Temperature Sensitive Paint in impulse wind tunnel AT-303*, *Proceedings ICMAR 2010*, Novosibirsk, 2010