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TRANSACTIONS OF THE INSTITUTE OF AVIATION
3 (252) 2018, pp. 37–48
DOI: 10.2478/tar-2018-0021

TEMPERATURE MEASUREMENTS USING THERMAL SENSITIVE PAINT

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Abstract

Article highlights practical issues concerning temperature measurements using thermal sensitive paint (abbrev. TSP). TSP paint after blue light excitation emits red light with intensity dependent on its temperature. Temperature measurements are preceded with paint calibration, according to exact experiment conditions. Purpose of calibration is to find transfer function between intensity of emitted radiation and surface temperature. To achieve this goal, special computational procedure is implemented. Devices and methodology used for paint calibration are briefly described as well as measuring sample preparation process. Short description is devoted to the procedure for calculation temperature using recorded intensity. Results obtained during calibration are presented. Final conclusions about perspective of using thermal sensitive paint in laboratory are presented, as well as advantages and disadvantages of TSP method versus other methods currently used in temperature measurements.

Keywords: Thermal sensitive paint, TSP, temperature measurement.

1. INTRODUCTION

Development of temperature field measurement using thermal sensitive paint (abbrev. TSP) began at the end of the last century [1]. One of the first applications for luminescent paint was research of pressure field in supersonic wind tunnels (pressure sensitive paints) [2]. This new method eliminates the need of using grid of pressure sensors and offered at the same time unprecedented ability to measure pressure over the whole surface of wing [3].

Application of thermal sensitive paint made possible to visualize the temperature field on the surface of investigated object [4, 5]. One of the main advantages of this method is, that those measurements are made without need of using thermocouples [6, 7, 8]. Because of its non-invasiveness, this method is particularly valuable during research of laminar-turbulent transition. Heat transfer coefficient is changing rapidly in the transition zone, which is well seen on the temperature maps [9, 10, 11].

Using of thermal sensitive paint can be also helpful during the test of ducted fan drives. Investigation of aerodynamic phenomena occurring in the gap between the fan blade and duct wall is very important to estimate the minimum gap size and thus increase the efficiency of drive unit [12, 13].

Application of thermal sensitive paint is limited to 80^{o}C, due to chemical properties of paint. The range of application for thermal sensitive paint can be extended by using theory of flows similarity. This allows to research of heat flows between fluid flow and fan blades, veins and duct walls in turbomachinery applications [14], where phenomena occur in environment much warmer than thermal sensitive paint limit [15]. Temperature distribution on the surface of solid body depends on heat transfer intensity with interacting flow. Exact measurement of entire surface temperature field allows to determine surface heat transfer coefficient distribution [16]. Two different methods can be involved: steady state and unsteady state heat transfer approach [17, 18].

Steady state heat transfer approach relies on constant heat supply to the outer surface of solid object. This can be made by covering the surface with metal foil layer, having high electrical resistance and connecting to constant voltage. In equilibrium, electrical heat flux is equal to heat flux transferred to the flow and is directly dependent from surface temperature field.

Unsteady state approach assume that investigated object has ambient temperature. Next, the object interacts with hot air flow, where hot air temperature is known. Surface temperature is measured in certain time intervals to estimate heat transfer coefficient.

Preliminary studies for TSP measurement method in Warsaw Institute of Aviation had a main goal to familiarize with this particular methodology and to research thermal sensitive paint properties. Result was the exact transfer function between intensity of radiation emitted by thermal sensitive paint and paint temperature.

2. TEMPERATUR MEASUREMENT WITH TSP

2.1. Thermal sensitive paint properties

Thermal sensitive paint consists of luminescent particles and oxygen impermeable binder. Luminous particles can reach the excitation state by photon absorption. Excited particles can go back into unexcited state by emission of a photon or by vibrational relaxation. Parameter, that has major impact on whether particle will return to unexcited state with or without light emission is temperature. This phenomenon, called “thermal quenching” is a working principle for thermal sensitive paint. The higher paint temperature, the less particles return to unexcited state with light emission, so recorded image is darker the surface temperature is higher [19]. Typical thermal sensitive paint is excited using radiation of wavelength 460 nm (blue light). Emitted radiation is then recorded by RGB camera equipped with low pass optical filter, which removes whole radiation of wavelength below 550 nm from the spectrum. Excited paint emits light with wavelength longer than 590 nm (red light). This process is schematically shown in Fig. 1.

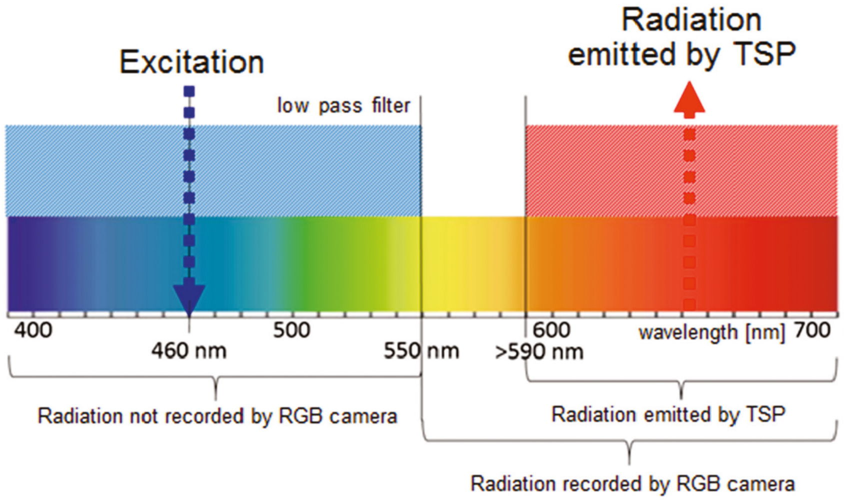

Fig. 1. Radiation emitted by excited thermal sensitive paint [20]

2.2. Recording of radiation intensity

Recording of radiational response of thermal sensitive paint are made using RGB camera, which records visible light spectrum. The camera should be of good quality with CCD matrix of linear dependency between incident radiation power and recorded signal. Basic property of image recording system is the ability to take pictures while lamp is exciting the paint. Recording of data by the camera must be ripped in time with light impulse generated by the lamp.

The lamp and RGB camera are controlled by computer and trigger. The lamp receives information about start and end of exciting light emission while the camera receives information about image capturing and image integration time. Captured images are transmitted to the computer memory via network switch.

Lamp radiation and image capturing process are set by voltage impulse (+5V) generated by the trigger. Impulse duration determines the time of lamp radiation and RGB camera integration time. Connection diagram of RGB camera, lamp with driver, trigger, network switch and computer is presented in Fig.2.

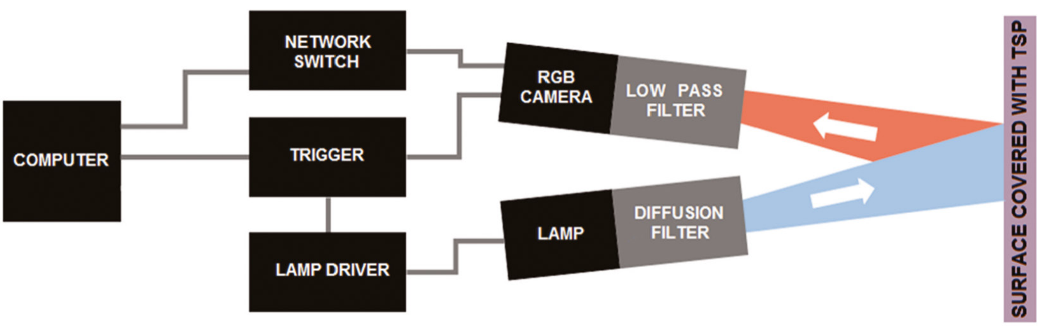

Fig. 2. Scheme of radiation recording system used in thermal sensitive paint experiments [10]

2.3. Estimation of paint temperature

During TSP test, a radiation intensity is measured. Its value depends from ambient conditions and therefore for proper temperature estimation it is necessary to take a reference photo at given and known sample temperature. For every picture taken during the test, ratio of measured intensity to reference intensity at each image point (pixel) is calculated. Dimensionless intensity ratio is then converted to surface temperature. By using intensity ratio, all influences of the environment and the photo recording system are subtracted. Manufacturer of thermal sensitive paint provides calibration curve for its product in the form of a 3rd degree polynomial [21].

$$\frac{I}{I_{ref}} = 1.2086 \cdot 10^{5} \cdot T^{3} - 0.0002 \cdot T^{2} - 0.0019 \cdot T + 1.1016 \quad 1)$$

where: T [^{o}C] – surface temperature
I [cts] – measured radiation intensity
Iref [cts] – reference radiation intensity

Reference temperature for manufacturer's data is Tref = 20^{o}C. For this temperature, a ratio I/Iref = 1. Function given by the manufacturer can also be represented as a function of temperature ratio instead of temperature (by dividing the temperature coordinate by the reference temperature):

$$\frac{I}{I_{ref}} = 0.00967 \cdot \left(\frac{T}{T_{ref}}\right)^{3} - 0.08 \cdot \left(\frac{T}{T_{ref}}\right)^{2} - 0.038 \cdot \left(\frac{T}{T_{ref}}\right) + 1.1016 \quad 2)$$

where: Tref [^{o}C] – surface reference temperature

Reverse function can be used to determine temperature ratio T/Tref for measured intensity ratio I/Iref, assuming the same reference temperature Tref, for which I/Iref = 1.

3. TSP CALIBRATION

3.1. TSP calibration stand

To determine transition function between recorded radiation intensity and surface temperature, it is necessary to have a device which ensures a steady and uniform temperature of test sample over a long period of time. For this purpose, we have designed and constructed a calibration chamber. Basic feature of this device is to provide constant temperature over time and the possibility of temperature setting. Working principle of the chamber is heat transfer between sample and surrounding hot air flow. A TSP sample immersed in constant temperature flow for a sufficiently long time will warm up to the temperature of the flow. Temperature of hot air was controlled by setting constant mass flow and constant and known heat power. To ensure temperature stability and to reach possible wide temperature range (up to 80^{o}C), it was necessary to minimize thermal losses in the chamber.

A constant mass flow was provided by lab's pressure installation and controlled by a flow meter integrated with valve. Constant heat output is provided by a high precision DC power supply. Heat losses were minimized by using low connectivity materials in calibration chamber structure and application of additional thermal insulation as well.

The calibrator is built in the form of rectangular tunnel. Hot air leaving heater is supplied to its front part. At the hot air outlet, a thermocouple No. 1 is installed. Its indications are the basis for setting of maximum allowable heating power and estimation of heat losses across the chamber. In chamber's front part, the flow is decelerated and become uniform. Then the hot air flow is directed to further part of calibrator containing TSP sample. Sample is in form of rectangular plate, fitted parallel to the flow. In samples nearest vicinity, two thermocouples No. 2 and No. 3 are placed, upstream and downstream respectively. Their indication is used for calculation of sample average temperature. The calibration stand diagram is shown in Fig. 3.

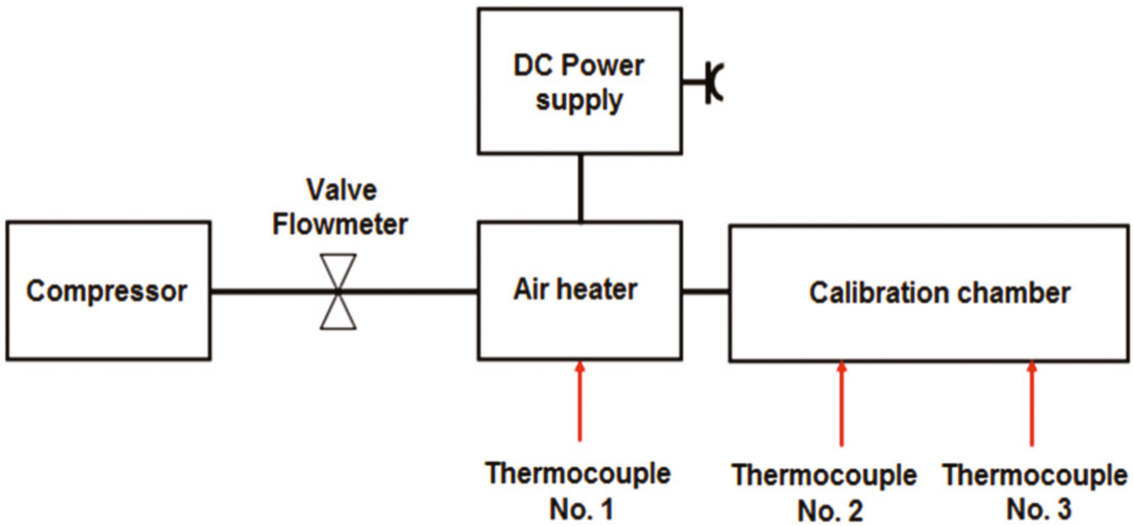

Fig. 3. Scheme of TSP calibration stand [20]

To check accuracy of the calibrator, the main chamber is equipped with two replaceable screens, that allow an observation of a sample. One of them is made of acrylic glass (Plexiglas), the other is made of thin polyethylene foil. The first screen provides very high visible light transparency (up to 92%), while the last one allows infrared observation. Using IR imaging, it is possible to estimate temperature inequality across the sample during its warming up process. Hardware implementation of calibration chamber is presented in photo 1.

The main issue was to obtain a constant temperature in the surroundings of TSP sample. To verify the temperature homogeneity on sample surface, IR pictures were taken, as well as temperature profile across the channel was investigated using thermocouples. Two locations were checked: sample upstream and downstream position. The cross section of the main chamber channel is a 120 mm x 50 mm rectangle. According to the diagram shown in Fig. 4, temperature changes significantly within 25 mm range from the wall. In the middle of the duct temperature remain constant, in approx. 7 cm wide zone. The temperature gradient in chamber's axial direction was within acceptable limits, under condition of applying adequate hot air mass flow. Size of the sample was adjusted to the size of constant temperature zone.

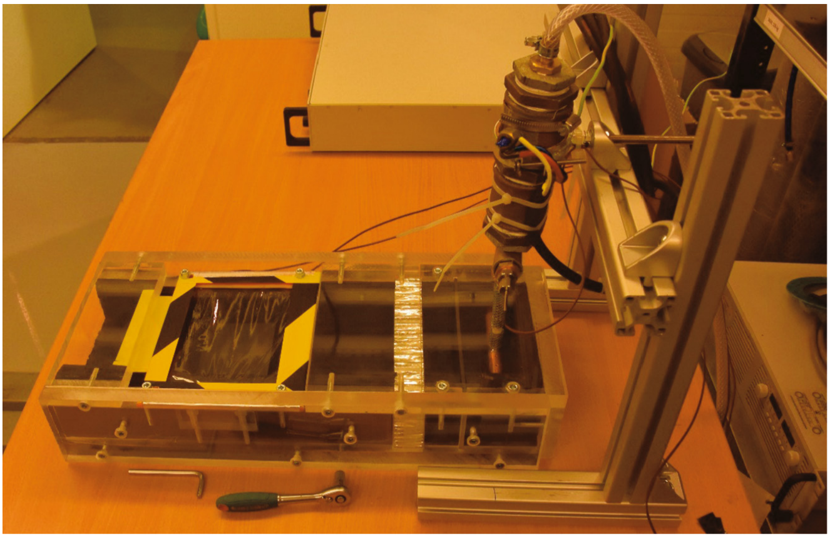

Photo 1. Calibration chamber attached to air heater [20].

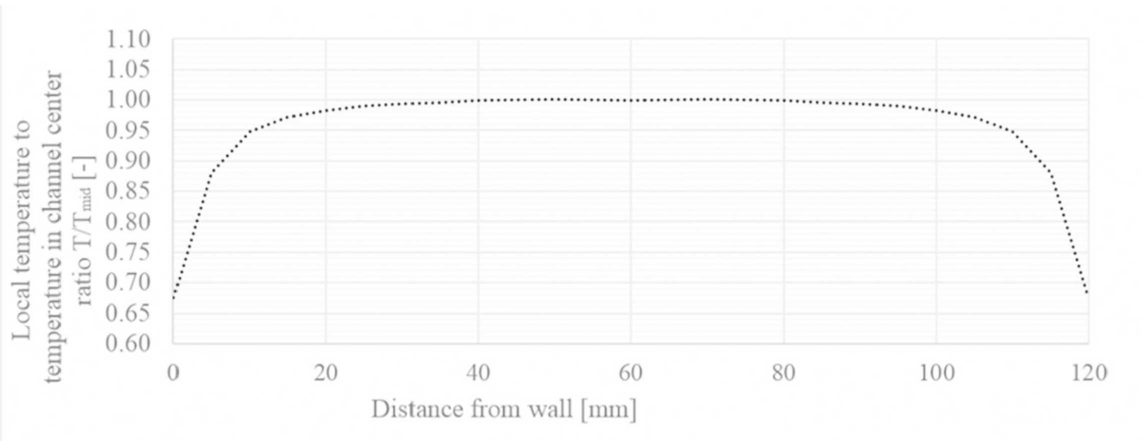

Fig. 4. Temperature profile measured in horizontal plane, in the middle of test cell [20].

Pictures taken with infrared camera showed constant temperature on the sample within ±0.25°C range in its central part of size approx. 4 x 4 cm (photo No 2). Such accuracy is completely sufficient in further temperature measurements and in eventual heat transfer coefficient estimations.

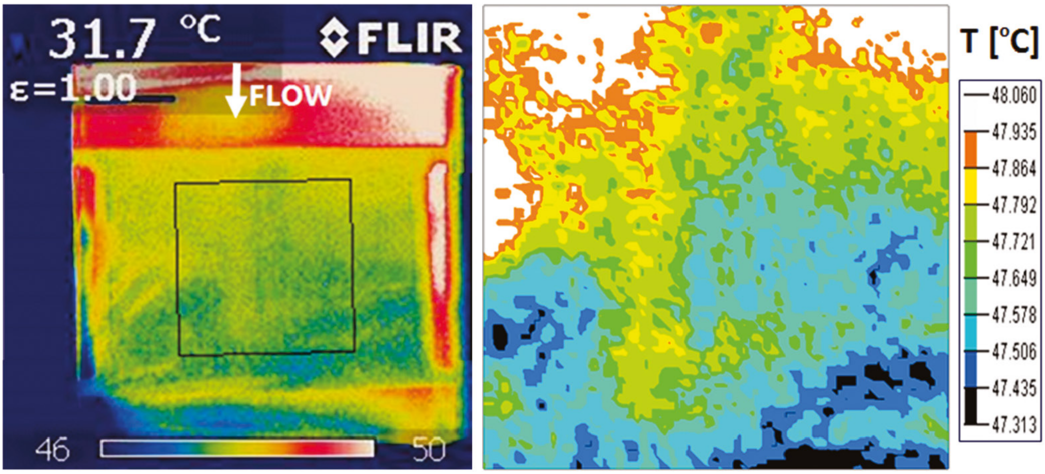

Photo 2. IR view of test sample for constant temperature area estimation (left) and 4x4 cm center field temperature with ±0.25 °C limits (white and black) on the right.

3.2. TSP sample preparation

Sample temperature determination rely on dimensionless intensity ratio, calculated as quotient of test picture intensity and reference picture intensity, so the unevenness of paint coverage is abolished. Despite this, painting of each surface with thermal sensitive paint should be carried out with due diligence, guaranteeing uniformity of paint coverage of the entire surface and maintaining its proper roughness after painting. During painting process, proper precautions were taken to protect personnel and to dispose of the resting waste due to paint toxicity.

Thermal sensitive paint was sprayed on the sample surface using an airbrush. The sample was made of a thin metal foil, which ensures rapid and even warming in the calibration chamber. No primer was used, because of sufficient surface adhesion between paint layer and metal. Thickness of paint layer was several microns. Method of spray coating is illustrated on the photo No 3.

Photo 3. Thermal sensitive paint sample spray painting [20].

3.3. Results

Calibration is carried out using a test bench described in Chapter 1.4. Ambient temperature at the time of paint calibration was 22.7°C. This temperature was recognized as a reference condition and a reference picture was taken. Then the air flow in the chamber was set to 8.5 g/s. Before reaching the calibration chamber, whole air flew thru air heater and warmed up, then it passed to chamber with TSP sample inside and heated it up. Maximum heat output, supplied to the heater was 500W. Power was increased by 50 W in each test point. 50 W power difference caused the sample temperature rise for approx. 5.5°C. A 20mm thick plexiglass screen was used for sample observation. Whole calibration bench, including RGB camera was placed in the darkroom.

The test campaign included 11 test points, ranging from reference temperature (ambient temperature) to 80°C. The center part of the sample was selected and its average intensity estimated for all images. Then average sample temperature was calculated using upstream and downstream thermocouple indications. Pairs of intensity ratio and corresponding temperature were obtained by dividing average intensity by average reference intensity. This pairs were plotted, creating experimental calibration curve for the test bench. Comparison of the calibration curve points with data supplied by paint manufacturer is shown in Fig. 5.

Temperature was measured using type T thermocouples. The accuracy of this thermocouples, according to DIN EN 60584-2 norm for class 1 is designated for ±0.5°C. The maximum deviation from steady state temperature during the TC measurement was ±0.35°C. Considering the temperature field nonuniformity in field of view as ±0.30°C, the final temperature accuracy during thermocouples measurement can be estimated for ±1.15°C.

The accuracy of captured image was estimated by making series of 50 images for each test point. For each pixel in area of interest, the maximum error was calculated using formula:

$$\delta I = 2 \cdot \frac{\sqrt{\sum_{i=1}^{n}\left(I_i - \bar{I}\right)^2}}{\sqrt{n}} \qquad 3)$$

where: n – number of samples
Ii [cts]– pixel intensity for i-th image
$\bar{I}$ [cts] – average pixel intensity

The calculated intensity error is in the range from 0.5% for power-off conditions to 1.0% for full power conditions.

The calibration curve is usually given in polynomial form. For this calibration 4th degree polynomial form was used to obtain good alignment between the calibration curve and test point set:

$$T = T_{ref} \cdot \left[a \cdot \left(\frac{I}{I_{ref}}\right)^4 + b \cdot \left(\frac{I}{I_{ref}}\right)^3 + c \cdot \left(\frac{I}{I_{ref}}\right)^2 + d \cdot \left(\frac{I}{I_{ref}}\right) + e \right] \qquad 4)$$

where: T [°C] – measured temperature
Tref [°C] – reference temperature

I [cts] – measured intensity
Iref [cts] – reference intensity
a, b, c, d, e [-] – polynomial coefficients

The measurement error for temperature is expressed as follows:

$$dT = \sqrt{\left(\frac{\partial T}{\partial T_{ref}} \cdot dT_{ref}\right)^2 + \left(\frac{\partial T}{\partial I} \cdot dI\right)^2 + \left(\frac{\partial T}{\partial I_{ref}} \cdot dI_{ref}\right)^2} \qquad 5)$$

where: dTref [°C] – reference temperature error
dI [cts] – intensity error
dIref [cts] – reference intemperature error

By substituting partial differences and applying intensity errors indicated in area of interest, a calibration curve is obtained:

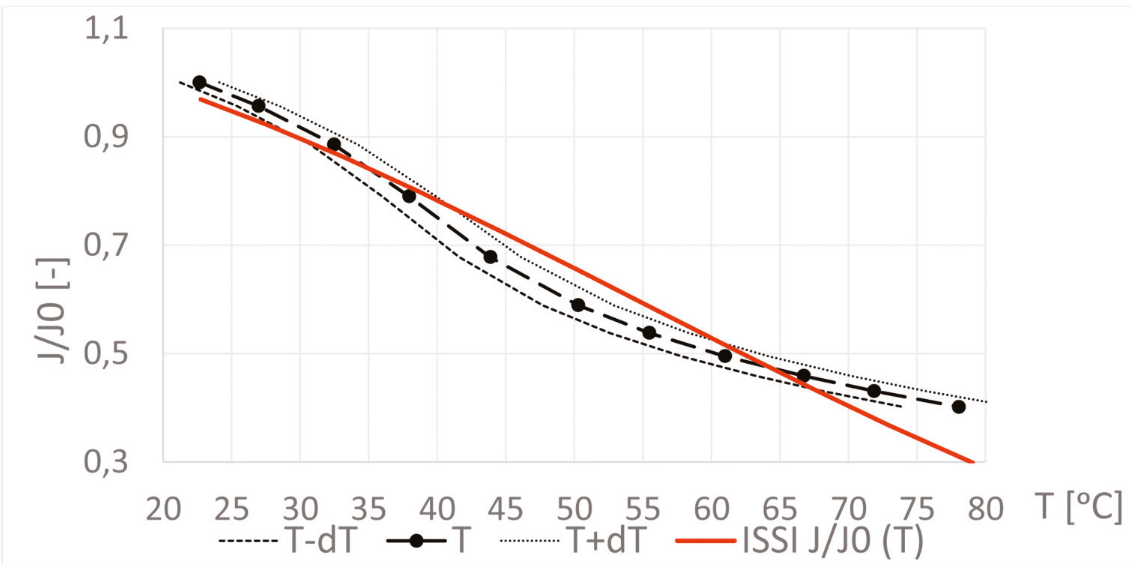

Fig 5. Manufacturer's calibration curve for thermal sensitive paint (red line). in comparison with calibration test points (dots). Doted lines present calculated measurement uncertainty.

Obtained results show slightly higher intensity at both ends of operating temperature range and slightly lower in the middle of this range in comparison to data provided by paint manufacturer. Differences in both calibration curves are probably related to the presence of acrylic glass screen and using of non-dedicated camera and lamp (manufacturer of thermal sensitive paint offers also a complete set of imaging equipment). The manufacturer's calibration curve shows high linearity between recorded intensity and temperature, while obtained data shows remarkable non-linearity.

Manufacturer calibration curve has a 3rd degree polynomial form:

$$T = -6.0824 \cdot 10^1 \cdot \left(\frac{I}{I_{ref}}\right)^3 + 1.0731 \cdot 10^2 \cdot \left(\frac{I}{I_{ref}}\right)^2 - 1.3978 \cdot 10^2 \cdot \left(\frac{I}{I_{ref}}\right) + 1.1287 \cdot 10^2 \qquad 6)$$

While test calibration curve form has a 4th degree polynomial point to obtain good fit with test data:

$$T = -5.2826 \cdot \left(\frac{I}{I_{ref}}\right)^4 - 3.3106 \cdot 10^1 \cdot \left(\frac{I}{I_{ref}}\right)^3 + 5.7393 \cdot 10^1 \cdot \left(\frac{I}{I_{ref}}\right)^2 - 4.1375 \cdot 10^1 \cdot \left(\frac{I}{I_{ref}}\right) + 1.2804 \cdot 10^1 \qquad 7)$$

Using the experimental calibration curve, all images were post-processed and surface temperature field was calculated. Results showed very good correspondence between sample temperature calculated from TSP images and thermocouples (photo No. 4). Temperature measured in 4x4 cm middle part of the sample is within ±0.3°C range in comparison with thermocouples time averaged indication.

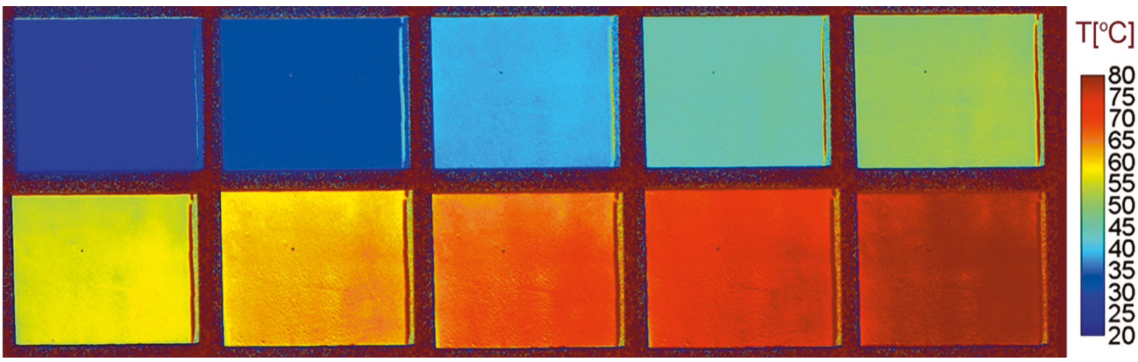

Photo 4. TSP post-processed images of the sample submergerd in flow having different temperature [20].

CONCLUSIONS

Obtained results show good conformity of the TSP measured temperature with the thermocouples indication. With appropriate care and accuracy in the preparation of test samples and a proper data post-processing, the TSP method can be used for temperature and heat transfer coefficient measurements. Obtained precision is comparable with this provided by commonly used thermocouples. Nevertheless, using non-standard data capturing devices requires calibration of thermal sensitive paint. The presence of screen between the sample and the RGB camera, as well as different camera sensitivity in comparison to this provided by paint manufacturer may lead to significant temperature error.

Measuring device does not distort the structure of test object (there are no thermocouples installed neither inside of test object nor outside of the test object, where interacting flow could be influenced). TSP provides also huge resolution unattainable for thermocouples as well. Each pixel on camera CCD matrix acts like a temperature sensor, e.g. for 1024 x 1012 pixels camera we obtain over one million sensors. Such a huge resolution allows an exact temperature field measurement as well as a surface temperature gradient estimation.

In contrast with the measuring surface temperature using infrared camera, the measurements with TSP does not require a precise determination of surface emissivity and its angular dependency. For infrared measurements, an inaccurate determination of the emissivity lead to a large temperature error, while TSP method does not have such restrictions and therefore its results are more certain. This means, that TSP is more suitable for complex geometry testing than IR (surface emissivity necessary in IR method depends on the angle of observation).

Disadvantages of the TSP method are: paint toxicity, requiring preservation of necessary safety measures during sample preparation, degradation of paint caused by an ambient UV light and an excitation light, relatively short time of paint suitability (one year from the date of manufacture) and maximum temperature limit of 80^{o}C.

REFERENCES

[1] Liu, T. and Sullivan, J.P., 2005, Pressure and Temperature Sensitive Paints, Springer, New York.

[2] Jahanmiri, M., 2011, "Pressure Sensitive Paints: The Basics & Applications," 2011:07, Chalmers University of Technology, Göteborg, Sweden.

[3] Bell, J.H., 2004, "Applications of Pressure-sensitive Paint to Testing at Very Low Flow Speeds," AIAA-2004-0878.

[4] Rosłowicz, A. and Bednarczyk, P., 2017, "Analysis of Heat Transfer in a Supersonic Rocket Head," Transactions of the Institute of Aviation, No. 1 (246), pp.79-94.

[5] Fonov, S., Crafton, J., Goss, L., Jones, G., Fonov, S. and Tyler, C., 2005, "Multi-Aspect Solutions for Moving Vehicle Testing," RTO-MP-AVT-124-5, NATO Science and Technology Organisation.

[6] Crafton, J.W., 2004, "The Impingement of Sonic and Sub-Sonic Jets onto a Flat Plate at Inclined Angles," Ph.D. Thesis, Purdue University.

[7] Kurits, I. and Norris, J. D., 2011, "Temperature-Sensitive Paint Calibration Methodology Developed at AEDC Tunnel 9," AIAA 2011-851.

[8] Schramm, J.M., Hannemann, K., Ozawa, H., Beck, W. and Klein, Ch., 2014, "Development of Temperature Sensitive Paints for the High Enthalpy Shock Tunnel Goettingen," 8th European Symposium on Aerothermodynamics for Space Vehicles, Lissabon.

[9] Stokes, N., Patel, S. and Hahn, M., 2012, "Boundary Layer Transition Detection Using Temperature Sensitive Paint in the ARA Transonic Wind Tunnel," ICAS 2012-3.4.2, 28th International Congress of the Aeronautical Sciences, Brisbane, Australia.

[10] Wierciński, Z., Kaiser, M., Żabski, J., 2007, "Extended Reynolds Analogy for Different Flow Conditions of the Heated Plate," Transactions of the Institute of Aviation, No. 2 (191), pp. 83-91.

[11] Borovoy, V., Mosharov, V., Noev, A. and Radchenko, V., 2012, "Temperature Sensitive Paint Application for Investigation of Boundary Layer Transition in Short-Duration Wind Tunnels," Progress in Flight Physics 3, pp. 15-24.

[12] Szafran, K., Shcherbonos, O. and Ejmocki, D., 2014, "Effect of duct shape on ducted propeller trust performance," Transactions of the Institute of Aviation, No. 4 (237), pp. 85-91.

[13] Ruchała, P. and Szafran, K., 2016, "Praktyczne Aspekty Zastosowania Otunelowanych Śmigieł Pchających," (ang. The Aspects of Practical Application of Ducted Fans), Transactions of the Institute of Aviation, No. 3 (244), pp. 257-266.

[14] Navarra, K. R., 1997, "Development of the Pressure-Sensitive-Paint Technique for Advanced Turbomachinery Applications," Ms.C. thesis, Virginia Polytechnic Institute and State University.
[15] Liu, Q., 1993, "Study of Heat Transfer Characteristics if Impinging Air Jet Using Pressure and Temperature Sensitive Luminescent Paint," Ph.D. thesis, Nanjing University of Aeronautics and Astronautics.
[16] Zuniga, H. A., 2009, "Study of Film Cooling Effectiveness: Conical, Trenched and Asymmetrical Shaped Holes," Ph.D. thesis, University of Central Florida, Orlando.
[17] Wright, L. M., Gao, Z., Varvel, T. A., and Han, J.-C., "Assessment of Steady State PSP, TSP, and IR Measurement Techniques for Flat Plate Film Cooling," Heat Transfer: Volume 3, ASME, 2005, pp. 37-46.
[18] Crafton, J., Ladchenko, N., Guille, M. and Sullivan, P., "Application of Temperature and Pressure Sensitive Paint to an Obliquely Impinging Jet," 37th Aerospace Sciences Meeting and Exhibit, AIAA-99-0387, Reno, USA.
[19] Cottingham, T., 2015, "Characterization and Optimization of Temperature-Sensitive Microbeads for Simultaneous Thermometry and Velocimetry for Fluid Dynamic Applications," M.Sc. thesis, University of Washington.
[20] Jeziorek, Ł., 2017, "Rozwój Metodologii TSP (Farba Termoczuła) i Potencjału Badań Laboratoryjnych z Nią Związanych," (ang. Development of Thermal Sensitive Paint Methodology and Its Research Capabilities), Sprawozdanie z pracy badawczej nr 2017/PS/01, Institute of Aviation, Warsaw.
[21] Product catalog, 2017, Innovative Scientific Solutions Inc.

TECHNIKA FARBY TERMOCZUŁEJ W POMIARACH TEMPERATURY

Streszczenie

Artykuł porusza praktyczne aspekty pomiaru temperatury za pomocą techniki farby termoczułej TSP (ang. Thermal Sensitive Paint). Farba tego typu, po uprzednim wzbudzeniu promieniowaniem o barwie niebieskiej, emituje promieniowanie o barwie czerwonej i intensywności zależnej od jej temperatury. Właściwy pomiar temperatury poprzedza kalibracja farby, wykonywana w warunkach najbardziej zbliżonych do warunków pomiarowych. Celem kalibracji jest znalezienie zależności pomiędzy intensywnością promieniowania rejestrowanego przez kamerę a temperaturą. Specjalna procedura obliczeniowa jest używana do przeliczenia zdjęcia na pole temperatury. Omówiono sposób i urządzenie użyte do kalibracji farby, jak również sposób przygotowania próbek pomiarowych. Pokrótce omówiony został sposób obliczania temperatury na podstawie zdjęć. Przedstawiono wyniki otrzymane podczas kalibracji farby termoczułej. Finalnie omówiono dalsze perspektywy użycia farby termoczułej w praktyce laboratoryjnej, jej ograniczenia i zalety w odniesieniu do innych, obecnie stosowanych metod pomiarowych.

Słowa kluczowe: farba termoczuła, TSP, pomiar temperatury.