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Surface Imaging of Temperature – Research Method of Heat Transfer

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ABSTRACT
The method does not differ in difficulty from the standard surface temperature imaging method, which is its unquestionable advantage. The disadvantage is the need to use test models made of materials transmitting visible light in the full range (blue light for excitation and red as a recorded result), which, with more complex shapes, makes the model more expensive. Nevertheless, the presented method is a valuable supplement to the set of methods and techniques used so far for imaging temperature fields and estimating the heat flux in the steady state.

Keywords: heat transfer, temperature, surface imaging

INTRODUCTION

Surface temperature imaging is now the standard test method for heat flows. There are many such methods, including: thermochromic thermo-sensitive inks, luminescent thermo-sensitive inks and infrared thermography. Among these techniques, the method based on the use of thermally sensitive luminescent paints [1], [2] is a relatively cheap and simple alternative to others in laboratory practice. The TSP method (Thermal Sensitive Paint) has the advantage that the entire signal is recorded in the visible light range, which enables the use of a whole range of cheap and easily workable materials, additionally, a well-calibrated method is also accurate [3]. This technique was thoroughly tested compared to other methods [4]. TSP is also convenient, simple and well-described technique [5] and has been widely used in many studies of many thermal phenomena for many years [6], [7].

In many practical issues, it is necessary to study the surface temperature distribution on different surfaces, also on the same body. Standard methods allow registration on one or several surfaces not obstructing each other and facing the same direction. The study of the temperature distribution on two opposite surfaces of the same plate (or slot) is a difficult issue, requiring the use of two recorders (cameras) and an appropriate measurement space enabling their placement (usually measurements are made in a darkroom).

In such a situation, there is a justified concern that the signals from the two cameras may not be precisely timed or that each camera records the signal in a different way (e.g. at different settings). The use of high-class equipment and exceptional measurement accuracy can completely eliminate this problem, but mistakes can happen.

In order to streamline and reduce costs, a new single-camera measurement method has been proposed [8]. This article provides a brief introduction to this method and how to validate it. This method can be used to test newly designed heat exchangers in propulsion units, e.g. hovercraft [9].

THE METHOD OF SIMULTANEOUS SINGLE-SENSOR AND DOUBLE-SIDED TEMPERATURE MEASUREMENT

The main task of the proposed method is the possibility of registering the surface temperature field on two opposite surfaces of the same body or on both internal surfaces of the plate or fracture. The measuring technique that is used for this purpose is well known, the novelty relies on its innovative using for recording two temperature fields at the same time. Taking into account, that TSP uses visible light, using two detectors and two excitation lamps may bring certain issues of both technical and economical manner. The new methos omits this issues as only one detector and one excitation LED is necessary. Because two temperature fields are recorded using the same detector, the uncertainty resulting from the use of different sensors having different properties disappears.

Of course, such surfaces obscure each other, therefore, to enable such measurement, the new method must have the following features:
1. Making the test object of transparent material.
2. Discontinuous application of thermosensitive paint to the foreground surface.

The first feature makes it possible to observe both surfaces simultaneously and completely eliminates the problem of obscuring the surface opposite to the camera by the body itself. The second feature causes the foreground coverage to not completely obscure coverage of the background surface. This means that two interlaced pictures are recorded at once. The camera does not record entire surfaces, but parts of them. This is a disadvantage of this method, however, missing data on part of both surfaces can be easily reconstructed using an appropriate algorithm [1]. The advantage of this method is the certainty that both temperature fields were registered by the detector with the same settings, operating under the same conditions and at exactly the same time. The schematic diagram of the test stand is shown in Figure 1.

METHOD VERIFICATION

Each research method, before its introduction into practice, should be checked and the obtained results subjected to critical analysis. With this method, there may be doubts as to whether the temperature field on the distal (background) surface is correctly read. The basis for such objections is the fact that this surface is on the other side of the model and the excitation and excited light must pass through it, as well as the fact that there is a foreground paint layer on the road. The latter circumstance may also cause the signal from the foreground surface to be disturbed.

In order to verify the correctness of the method, the following experiment was proposed: the phenomenon of heating a flat vertical plate by continuous impact with a single stream of hot air (Single Jet Impingement) was used [10]. This phenomenon has been described many times in the literature [11], [12]. It has been reproduced in numerical calculations [13] and [14], as well as numerous correlations allowing to calculate the Nusselt number [15] and [16] are available. In this experiment, a flat plate is placed in front of the camera and the excitation lamp, the air stream strikes the surface of the plate opposite the camera. This surface is continuously coated with TSP paint. The surface of the plate facing the camera is painted in vertical, horizontal stripes or a sparse pattern composed of squares. The diagram of the stand is shown in Figure 2. However, its implementation in the laboratory is presented in Figure 3.

The method validation procedure consists of the following actions:
1) Recording of the temperature fields on both sides of the plate.
2) Calculation of the surface distribution of the heat transfer coefficient on the surface hit by the jet.

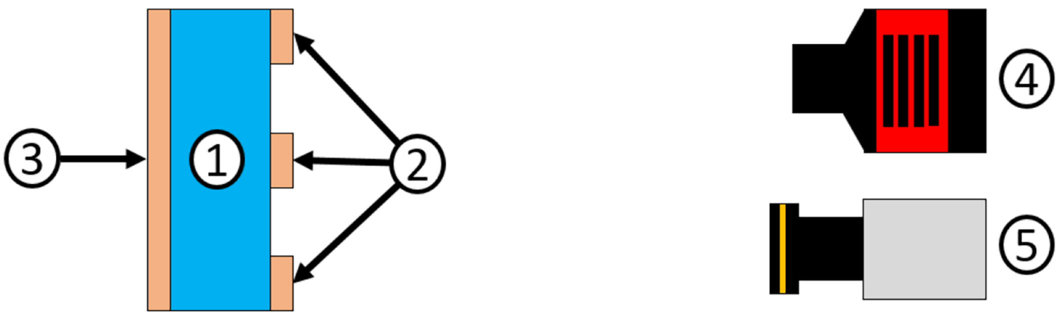

Fig. 1. Scheme of a simultaneous, double-sided, one-camera method for temperature imaging using thermal sensitive paint: 1-test object, 2-discontinuous layer of foreground paint, 3-continuous layer of background paint, 4-excitation lamp, 5 – camera.

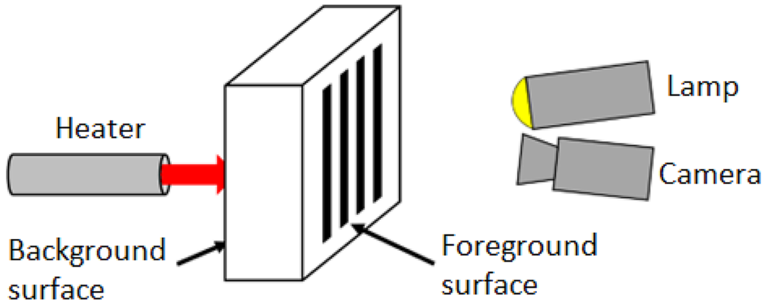

Fig. 2. Scheme of a test rig. The entire background surface is completely covered with a TSP paint.

3) Calculation of the temperature field in the entire volume of the plate using the numerical model using the boundary condition determined in point 2.
4) Comparing the experimental and calculated temperature fields on the surface opposite to the stream.

Compliance of temperature fields with point 4 ensures that the temperature measurement on the foreground surface is correct. Any disturbance or interference from the other surface would result in error amplification and significant differences. The recording of both temperature fields was made by covering the background surface over the entire surface [17] (this guarantees the smoothness of the surface hit by the stream and ensures the maximum coverage of the surface with the signal, regardless of the location of the camera) and the foreground surface was covered with a striped pattern.

Based on the recorded data, the time-dependent course of the temperature on the surface hit by the stream was determined. The method of obtaining a continuous temperature profile running very close to the stagnation point is shown in Figure 4. The features of the paint pattern used are used here.

Using the Cook-Feldermann method, it is possible to find the value of the heat transfer coefficient h for a semi-infinite body for the obtained data on the surface [18]. Thanks to the use of formula (1) and the bisection algorithm, it is possible to calculate quickly and accurately the searched value h that matches the temperature distribution at each point.

$$\boldsymbol{T_w(t) = T_i + (T_\infty - T_i) \cdot} \\ \boldsymbol{\cdot \left(1 - e^{\frac{h^2 \cdot \alpha \cdot t}{k^2}} \cdot \mathrm{erfc}\left(\frac{h \cdot \sqrt{\alpha \cdot t}}{k}\right)\right)} \tag{1}$$

where: k [W/m·K] – thermal conductivity coefficient of the solid body,
C_p [J/kg·K] – specific heat of the solid body,
ρ [kg/m^3] – density of the solid body,

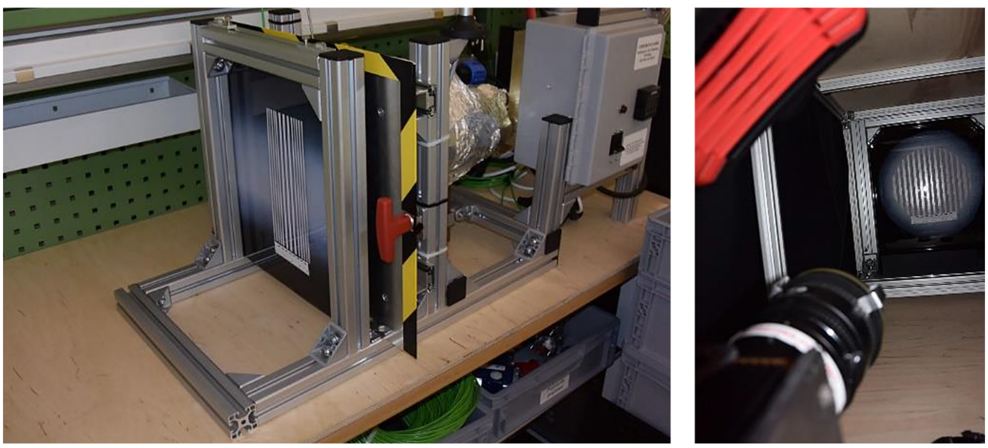

Fig. 3. Ready-to-test plate mounted in the test rig (left image) and a view inside the darkroom (right image). Plate is heated by the single jet impinging the background surface

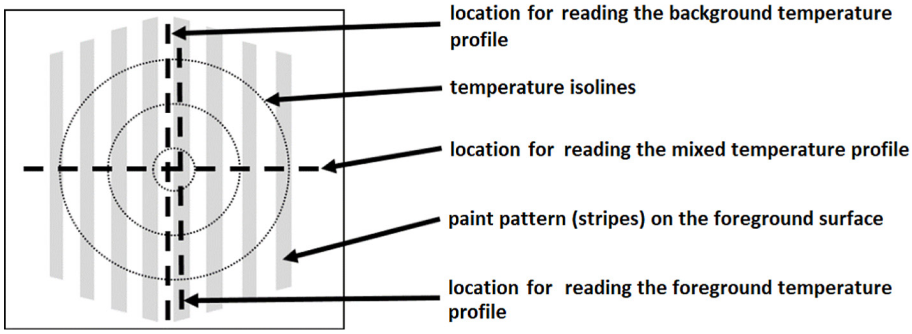

Fig. 4. Scheme for continuous temperature profile reconstruction for both sides of the plate in case of using vertical stripes template

$h\ [W/m^2 \cdot K]$ – heat transfer coefficient between a gas and a solid body
$T\ [°C]$ – temperature on the surface of the semi-infinite solid body in the time t,
T_i [°C] – initial temperature at the same point,
$T_\infty\ [°C]$ – temperature of the air jet,
$t\ [s]$ – time measured from the start of the solid body heating,
$\boldsymbol{\alpha = \frac{k}{\rho \cdot C_p}}$ $\mathbf{[m^2/s]}$ – thermal diffusivity coefficient of the solid plate.
$\boldsymbol{erfc(x) = \frac{2}{\pi} \cdot \int_x^\infty e^{-t^2}\, dt}$ [-] – complementary error function

The obtained axial-symmetric distribution of the heat transfer coefficient was approximated by the polynomial of the sixth degree of the radial variable point on the plate surface. The surface distribution of the h coefficient described in this way was used in the numerical model as a 2nd-order condition (von Neumann condition).

To calculate the temperature field in the entire volume of the slab, a numerical model was used based on the finite difference method (due to the simple geometry of the object). An explicit spatially centered difference scheme was used. The mesh of nodes used for the calculations was of a structural type with no densification.

The test campaign included a total of 23 test points, plates of 4 different thicknesses (2, 5, 10 and 15mm), flows with three different Reynolds numbers (12,000, 24,000 and 36,000) as well as three different paint patterns were tested. To visualize the results, one test point number 23 was presented, the flow was Reynolds number *Re* = 36,000, the distance of the die outlet from the plate *Z/D* = 4 with the nozzle diameter *D* = 1/2 “, the thickness of the plate was 10 mm. Figure 5 shows the original data, Figure 6 shows processed and converted data, while Figure 7 shows the separated temperature fields from the foreground and background. Figure 8 shows the result of a simple algorithm that reconstructs data in the areas where there is no data.

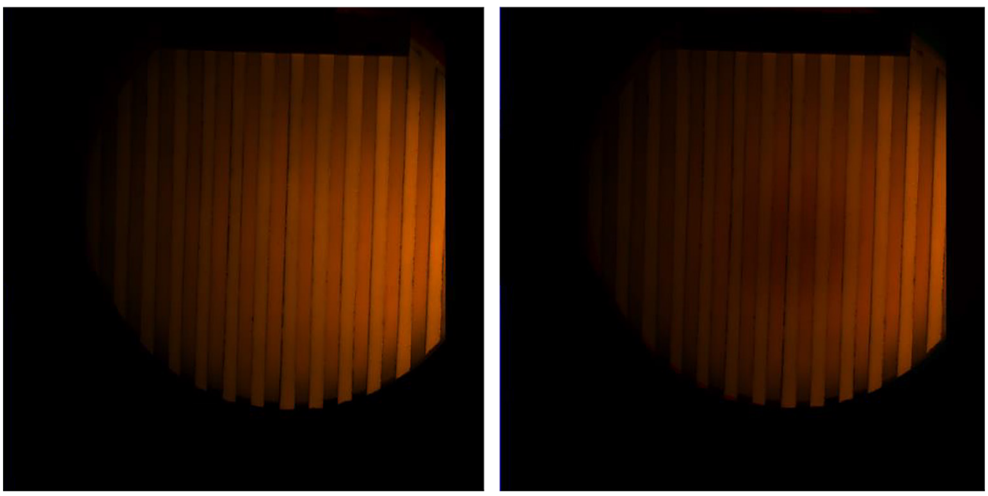

Fig. 5. Reference image (a) and the image (b) taken 60 seconds after the start of the heating. Real colors

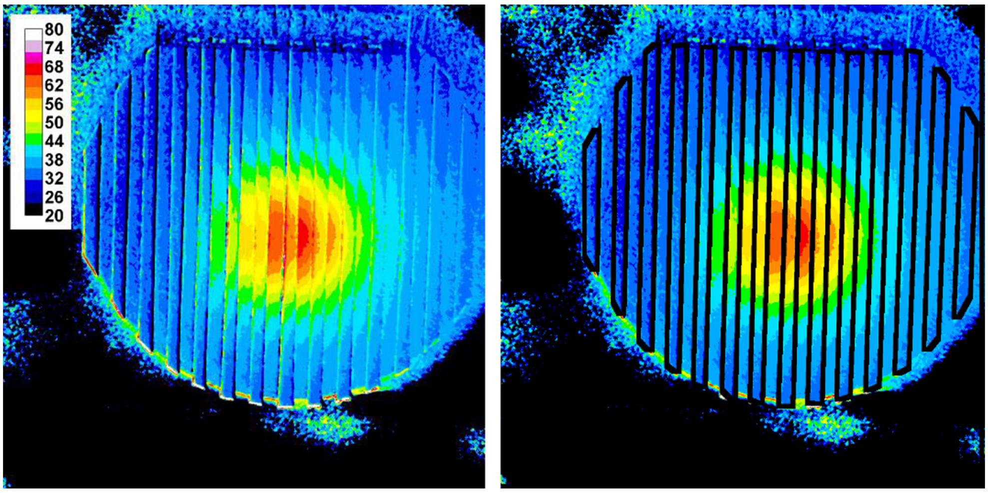

Fig. 6. Temperatur on both sides (on the left) and a decomposition into two surfaces (on the right) Temperature unit is °C

The obtained experimental data were processed as described in point 2, which allowed to determine the experimental and on its basis the approximate (model) course of the heat transfer coefficient h and the linearly related Nusselt number distribution. The results of these activities are shown in Figure 9, while the results of numerical simulations in comparison with the experimental data are shown in Figure 10. Figure 11 and Figure 12 show experimental results and its comparison with numerical calculations for another two test points from the wide range of tested ones.

Similar compliance was obtained for other test cases, but for longer simulation times (over 15 minutes) it was necessary to take into account the mechanism of free convection on the foreground side of the plate. This phenomenon was modeled by adding to the foreground a 2nd order boundary condition with a heat transfer coefficient of a few W/m^{2}K. This resulted in an accurate reproduction of the temperature profiles in terms of both value and shape. This procedure was used only for the thickest ones (15 mm), as the foreground surface heats up to a temperature of about 45 °C within 15 minutes. At the ambient temperature of approx. 25 °C, the heat exchange was thus not negligible in such a long time [19]. In turn, the thinnest plates (2 mm) heated up very quickly and it was difficult to accurately determine the *h* coefficient, also due to a certain deformability of these plates. In turn, the 5 and 10 mm plates were characterized by high stiffness and average heating times, therefore the comparison results obtained on these objects were very good.

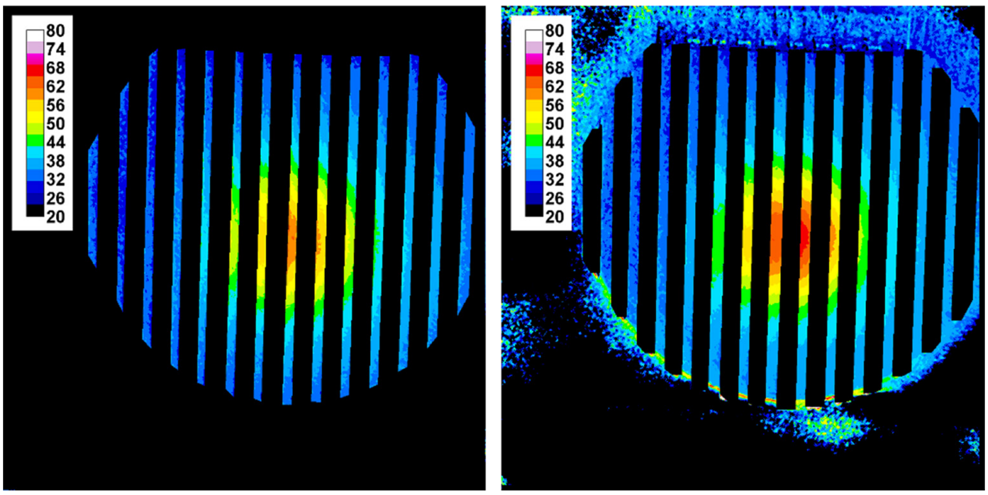

Fig. 7. Foreground temperature (a) and background temperature (b). Temperature unit is °C

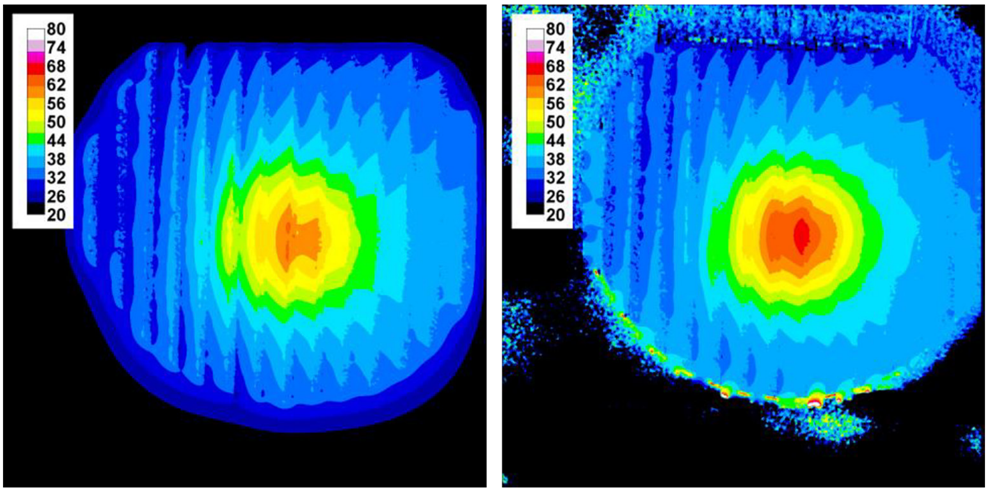

Fig. 8. Reconstruction of the foreground (a) and background temperature distribution (b). Temperature unit is °C

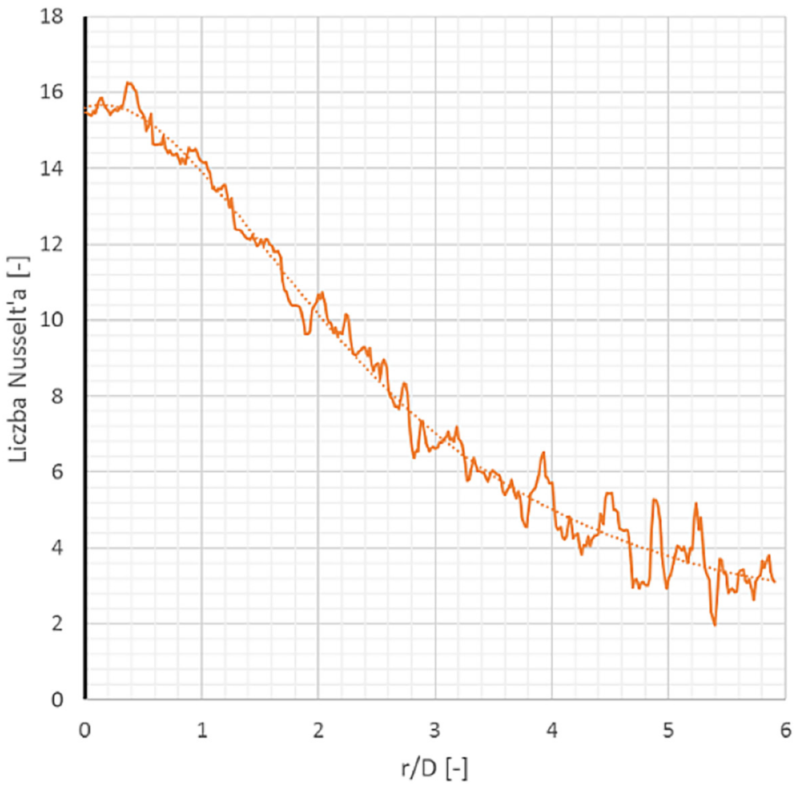

Fig. 9. The Nusselt number distribution on the background surface for the test point no. 23 (Reynolds number = 36 000, Z/D = 4, plate thickness: 10 mm, vertical stripes painting pattern)

CONCLUSIONS

On the basis of the results, it should be stated that the experimental determination of the bilateral temperature fields and thus also the heat flux in the steady state is possible. The proposed technique, like any other, has its limitations, as a partial signal is recorded, which additionally does not cover the entire registered area. However, this technique can be adapted to the examined area in various ways (e.g. by appropriate selection of the surface painting pattern) in order to increase the quality and accuracy of the results.

The method does not differ in difficulty from the standard surface temperature imaging method, which is its unquestionable advantage. Model and surface preparation procedures are the same like in other TSP experiments. Data acquisition software and hardware can be simply taken from the standard TSP test stands, what is of a huge

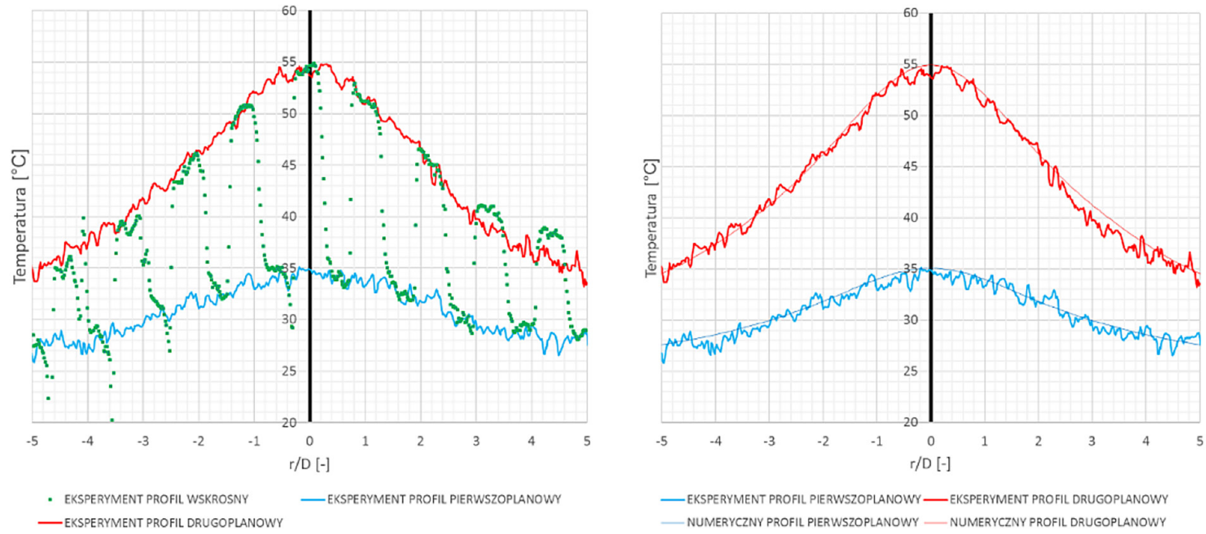

Fig. 10. Test point no. 23 (Reynolds number=36 000, plate thickness: 10 mm, vertical stripes painting pattern). Heating time was 240 seconds. Temperature profile on both sides of the plate (a) and a comparison between experimental data and a numerical calculations (b)

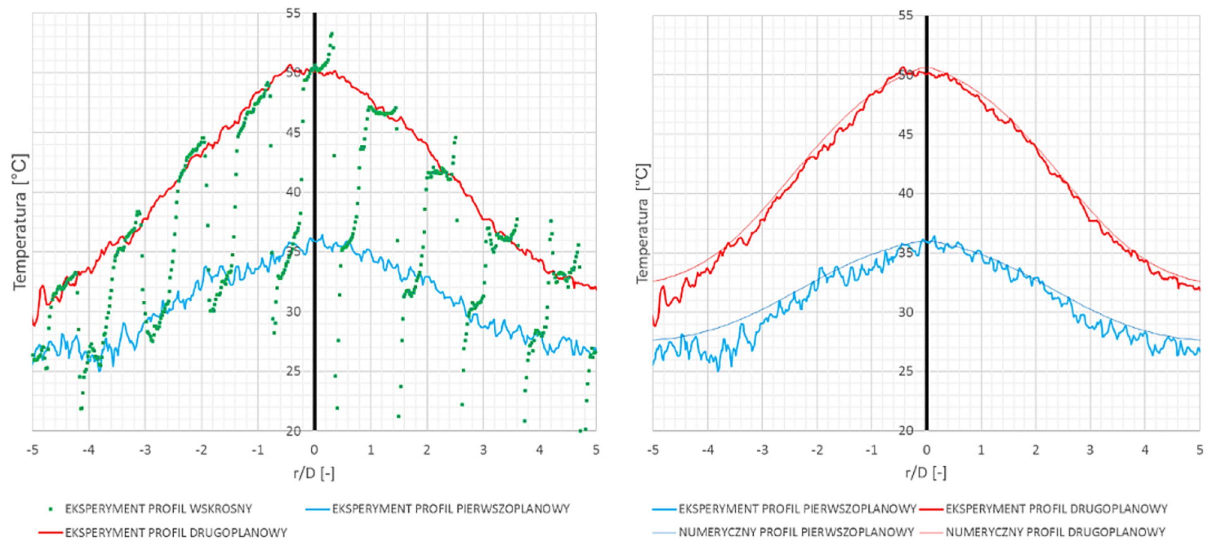

Fig. 11. Test point no. 29 (Reynolds number=36 000, plate thickness: 2 mm, horizontal stripes painting pattern). Heating time was 15 seconds. Temperature profile on both sides of the plate (a) and a comparison between experimental data and a numerical calculations (b)

practical and economical meaning. Data post-processing is not complicated and rather intuitive. No special long term experience is necessary for the right data treatment of the collected data. The impact of using different sensors for different surfaces is completely eliminated, as there is only one detector and one excitation light source.

The disadvantage is the need of using test models made of materials transmitting visible light in the full range (blue light for excitation and red as a recorded result), which, with more complex shapes, makes the model more expensive. The non-continuous paint pattern produces non physical results at the edge of the pattern and therefore some part of the recorded surface area is lost. The edge flare must be identified properly to avoid the postprocessing of a wrong signal. Independently from the wrong pattern edge signal, shadows may appear on the background surface if the excitation lamp axis is not aligned with this of the camera. This is often the case as the lamp is placed elsewhere to avoid the reflections from the foreground. Those shadows comes from the paint pattern in the foreground and additionally narrows the recorded area. Because only the interlaced signal is available, there is a need for

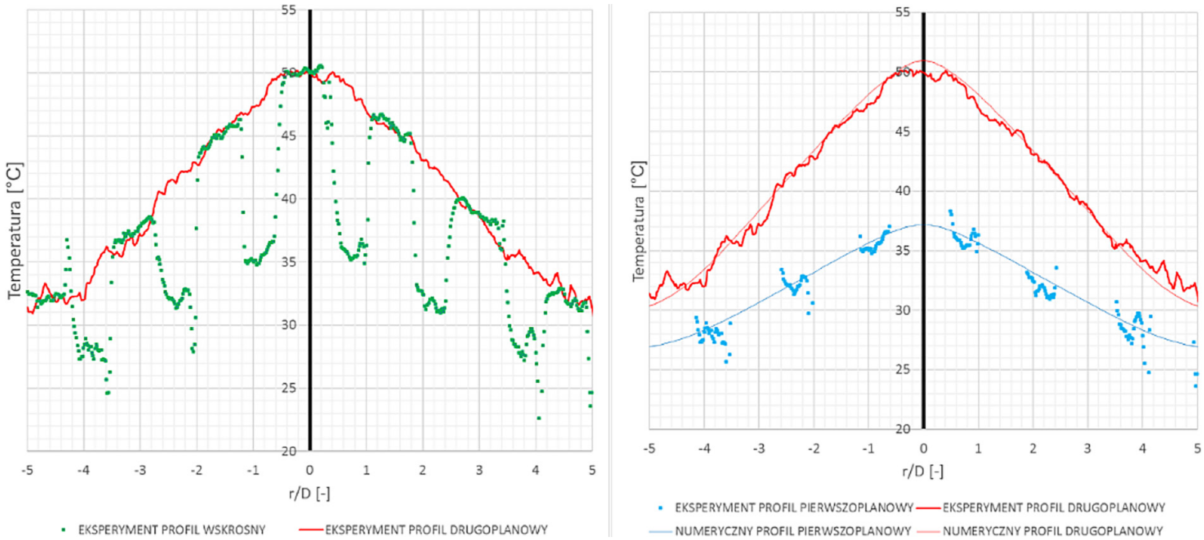

Fig. 12. Test point no. 24 (Reynolds number=36 000, plate thickness: 2 mm, chessboard painting pattern). Heating time was 15 seconds. Temperature profile on both sides of the plate (a) and a comparison between experimental data and a numerical calculations (b)

both sides temperature surface distribution reconstruction, what requires a dedicated software. Generally this technique requires more data post-processing effort than standard techniques that deal with a single surface.

Nevertheless, the presented method is a valuable supplement to the set of methods and techniques used so far for imaging temperature fields and estimating the heat flux in the steady state.

Because the method was proven for its accuracy and effectiveness, the future work can be focused on considering the geometries of more practical significance like heat exchangers, rotating blades, cooling ribs.

REFERENCES

1. Jahanmiri M. 2011. Pressure Sensitive Paints: The Basics & Applications.
2. Sullivan J. 2009. Molecular Sensors – Temperature Sensitive Paint, https://slideplayer.com/slide/1675994/
3. Schramm J.M., Hannemann K., Ozawa H., Beck W. Development of temperature sensitive paints for the high enthalpy shock tunnel Goettingen. In: 8th European Symposium on Aerothermodynamics for Space Vehicles, Lissabon; 2014.
4. Wright L.M., Gao Z., Varvel T.A., Han J.C. Assessment of steady state PSP, TSP, and IR measurement techniques for flat plate film cooling. Heat Transfer AMSE 2005; 3: 37–46.
5. Cottingham T. Characterization and optimization of temperature-sensitive microbeads for simultaneous thermometry and velocimetry for fluid dynamic applications. M.Sc. thesis, University of Washington; 2015.
6. Bell J.H. Applications of pressure-sensitive paint to testing at very low flow speeds, AIAA-2004–0878; 2004.
7. Liu Q. 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; 1993.
8. Jeziorek Ł. Efektywność wymiany ciepła na powierzchni płyt i szczelin w aspekcie jednodetektorowego, obustronnego pomiaru temperatury za pomocą farby termoczułej. Ph.D. thesis, Institute of Aviation, Warsaw; 2019.
9. Szafran K., Pągowski Z.T. Selection of propulsion unit for a new class of transport hovercraft as a compromise between technical performance and purchase and exploitation costs. Journal of KONES 2016: 519–524
10. Crafton J., Ladchenko N., Guille M., Sullivan P. Application of temperature and pressure sensitive paint to an obliquely impinging jet. In: 37th Aerospace Sciences Meeting and Exhibit, AIAA-99–0387, Reno, USA; 1999.
11. Gauntner J.W., Livingood J.N., Hrycak P. 1970. Survey of Literature on Flow characteristics of a Single turbulent Jet Impinging on a Flat Plate. NASA Technical Note, NASA TN D-5652.
12. Hrycak P. Heat transfer from impinging jets – a literature review. Report of New Jersey Institute of Technology AFWAL-TR-81–3054,, Newark, New Jersey, USA; 1981.
13. Behnia M., Parneix S., Durbin P. Simulation of jet

impingement heat transfer with the k-ε-v2 model. Annual research Briefs, Center for Turbulence Research; 1996.

14. Spring S. Numerical prediction of jet impingement heat ransfer. Ph.D. thesis, Institute of Aerospace Thermodynamics, Stuttgart University, Germany; 2010.
15. Zuckerman N., Lior N. Jet impingement heat transfer: physics, correlations and numerical modeling. Advances in Heat Transfer 2006; 39: 565–631.
16. Sharma S., Kumar R. Experimental investigation on heat transfer characteristics from liquid jet impingement to different flat plates. International Journal for Innovative Research in Science & Technology 2015; 1(12).
17. Szafran K., Jeziorek Ł., Widera P., Skalski P. Pomiar przepływu ciepła przy wykorzystaniu farby termoczułej. Autobusy–Technika, Eksploatacja, Systemy Transportowe 2018; 226(12): 424–427.
18. Domański R. Wymiana Ciepła, Wykorzystanie programu MathCad do obliczeń procesów wymiany ciepła. Biblioteka Naukowa Instytutu Lotnictwa nr. 47, Warszawa; 2016.
19. Szafran K., Jeziorek Ł., Skalski P. 2018. Heat transfer determined by the temperature sensitive paint method. Transactions on aerospace research 2018; 4(253): 57–70. DOI: 10.2478/TAR-2018–0029