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Application of temperature-sensitive paint with two channels for studying thermal processes in short duration gas dynamic facilities

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Abstract. Specialists from TsAGI have developed a unique two-channel luminescent transducer, a temperature-sensitive paint that allows the measurement of full-field surface heat transfer rates in short-duration wind tunnels. The paper contains a description of the features of the method, its advantages, as well as a brief review of several main results obtained in the study of complex heat transfer structures under high gas flow velocities.

Keywords: wind tunnel, shock tube, heat flux, TSP

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Материалы конференции
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Применение двухканальных люминесцентных преобразователей температуры для исследований тепловых процессов в трубах кратковременного действия

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Аннотация. Специалисты ЦАГИ разработали уникальный двухканальный люминесцентный преобразователь температуры — термочувствительную краску, которая позволяет измерять тепловые потоки к поверхности модели в аэродинамических трубах кратковременного действия. Статья содержит описание особенностей метода, его преимуществ, а также краткий обзор нескольких основных результатов, полученных при исследовании сложной структуры течений в условиях высоких скоростей набегающего газового потока.

Ключевые слова: аэродинамическая труба, ударная труба, тепловые потоки, ЛПТ

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Introduction

Luminescent temperature transducers, which are used in aerodynamic experiments to determine thermal characteristics, are of two types: those based on organic phosphors and those based on crystal phosphors. In the literature, the first ones are called TSP (temperature-sensitive paint), and the second TGP (thermographic phosphors). TSPs emerged and developed in parallel with luminescent pressure transducers (Pressure Sensitive Paint, PSP) as a “co-product”. Sensors based on crystal phosphors appeared earlier; their scope is not limited to aerodynamics [1].

TSPs are used to study the laminar-turbulent transition of the boundary layer and measure heat fluxes [2]. In the first case, TSP compete with the thermal imaging method [3, 4], and when measuring the heat flux, they also compete with thermal melting indicators [5–7]. The sensitivity of modern thermographic cameras is higher than TSP with a larger dynamic range; it also does not require the application of a sensitive coating on the model and the organization of model lighting. However, the spatial resolution of camera matrices is still significantly inferior to CCD and CMOS matrices. Another disadvantage of the thermal imaging method (as well as pyrometry) is the influence of external thermal illumination, which can penetrate, for example, from the test section of a wind tunnel (the metal walls of the nozzle and the working part are mirror for IR radiation). Also in cryogenic installations (large Reynolds numbers) [8–10] the surface temperature of the model is 110–140 K, the thermal imager cannot measure such temperatures. Finally, most thermal imagers use matrices of bolometers, the information from which is read sequentially. The non-simultaneity of temperature measurement must be taken into account when studying fast processes – if the heating time is comparable to the time of reading the matrix, then the use of a thermal imager is impossible.

Simultaneity of temperature measurement is an important advantage of TSP over melting temperature indicators. In contrast, TSPs do not absorb energy for phase transition and can be thinner, which also reduces their heat capacity and allows them to be used in short duration shock tubes. Also TSP is a reversible sensor, i.e. it is enough to apply TSP only once for the entire cycle of thermal testing of the model.

This work contains a description of a two-channel TSP developed by TsAGI specialists and which makes it possible to register the thermal features of short duration high-speed gas-dynamic flows with particular accuracy. A brief overview of some of the studies performed with this tool is also provided. There are works where TSP based on organic phosphors are used to measure heat fluxes and study the transition of the boundary layer in short duration facilities [11–13]. However, in all works, single-channel (single-color) TSPs are used, which lose in accuracy to two-channel transducers.

Creation of two channel TSP

The temperature transducer should not feel pressure; the excited state time should be very small. It is necessary either to provide short-lived fluorescence or to place the phosphor molecules in a polymer matrix that is impermeable to oxygen [14]. Or, it is necessary to use molecules with deep-lying transitions that are inaccessible for oxygen quenching. It is desirable to have a high luminous intensity of the sensor coating with high sensitivity, which means that temperature quenching should occur in a limited, given temperature range. For short duration shock tubes, the temperature range of 10–150 °C is of interest. The mechanism of temperature dependence of fluorescence (internal conversion) can be described as:

$$I = h\nu_f \Omega k_f \frac{k_{ex} I_{ex} n_{S0}}{k_f + k_{ms}} = \frac{I_0}{1 + b \cdot \exp\left(-{}^{\Delta E_m}\!/_{kT} \right)}. \tag{1}$$

Where v_f is the frequency of luminescence light, k_{ex} is the rate constant of excitation of luminophore molecules, k_f is the fluorescence emission rate constant, n_{S0} is the concentration of luminophore molecules in the ground state, I_0 is luminescence intensity in the absence of oxygen or at absolute zero temperature, Ω is luminescent sensor volume, k_{ms} is the rate constant of nonradiative transitions, I_{ex} is the intensity of the exciting radiation, b is distortion factor, ΔE_m is the activation energy of internal conversion, I_0 is the luminescence intensity in the absence of temperature quenching at $T = 0$ K. The sensitivity is described by the expression:

$$dI/I = -\frac{b \cdot \exp\left(-\Delta E_m/kT\right)}{1 + b \cdot \exp\left(-\Delta E_m/kT\right)} \frac{\Delta E}{kT} dT/T. \tag{2}$$

If the quantum yield is not optimized, then the sensitivity can be written as:

$$\frac{dI}{IdT} = -\frac{\Delta E_m}{kT^2}. \tag{3}$$

The activation energy cannot be greater than the energy of the excited state $-\Delta E_m \ll hv_f = hc/\lambda_f$. I.e. under normal conditions, it is impossible to obtain a high sensitivity of the luminescence intensity to temperature in a limited temperature range. It is necessary to look for other mechanisms. Such mechanisms may include concentration quenching or intermolecular energy transfer, if these processes are controlled by the mobility of molecules in the polymer matrix and, therefore, are determined by temperature.

The lanthanide ions Ln^{3+} have a rather bright luminescence due to radiative transitions inside the 4-f shells, and these transitions are inaccessible for oxygen quenching. Good results can be obtained with the cluster luminescence of one of the Europium complexes ($Eu(dbm)_3phen$). Its molecules practically do not luminesce either in solution or in crystals, but clusters consisting of several molecules have bright luminescence that is not quenched by molecular oxygen. The temperature dependence of this luminescence is determined by the mobility of molecules of Europium complex in the polymer. This allows one to adjust the temperature sensitivity, but all the imperfections of the polymer (relaxation after polymerization, temperature hysteresis) affect the calibration characteristic. It means that TSP needs to be calibrated.

Epoxy resin E-41 without polymerization turned out to be the optimal polymer for creating a converter based on the Europium complex. At temperatures up to 100 °C, the resin remains solid. The calibration characteristic of such a sensor is shown in Fig. 1, *a*. Temperature sensitivity can be changed by adding a plasticizer.

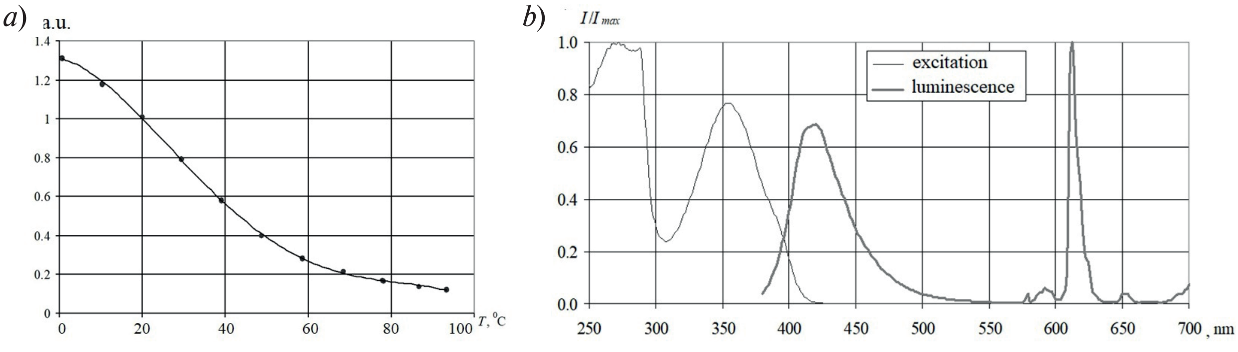


Fig. 1. TSP calibration curve (*a*); excitation and luminescence spectra (*b*)

Many recipes for TSP have been proposed, including the complexes of Europium and Terbium lanthanides [15–17]. The application methods of TSP and PSP are very close, with the only difference being that TSP are temperature sensitive and not pressure sensitive, while PSPs sense both. For accurate temperature measurement, two-channel TSP must be used.

TsAGI specialists developed a two-color TSP containing an additional reference phosphor, the luminescence of which does not depend on temperature, the Coumarin-7 laser dye. Its luminescence is used for pixel-by-pixel correction of changes in the intensity of the exciting radiation. Both phosphors are excited simultaneously from the same light source, but emit light in different spectral regions and can be easily separated (see Fig. 1, *b*). The two-channel TSP does not exclude a normalization frame at a known temperature of the model to eliminate the inhomogeneity of the ratio of active and reference phosphors on the surface under study. In this case, it is necessary to ensure the isothermality of the model and measure its temperature. It is interesting that the TGP application technique also uses registration in two spectral regions [18]. However, no other two-channel (two-color) TSP have been developed.

As with the PSP, markers must be applied to the surface of the model to match the images with and without flow from each luminophore. They (with known 3D coordinates) are also used to transfer the measurement results to the 3D surface of the model.

The central point of the thermal experiment is the choice of the model material. It must be heat-insulating, homogeneous in terms of thermophysical properties and technologically advanced. The use of optical methods also imposes additional conditions: optical uniformity of the surface, light color and opacity. TSP is applied to the surface of the model with a spray gun like ordinary paint. The layer thickness after drying is 3–5 microns, which makes it practically invisible and significantly complicates the application process. However, control of the thickness and uniformity of the coating can be carried out in ultraviolet light. After applying TSP, markers (black dots) are applied to the surface of the model. More detailed information about the features of the experiment, the method of application and post-processing of the results can be found in [19, 20].

Application of TSP at different facilities

1. Wind tunnel UT-1M TsAGI

In this installation, operating on the principle of the Ludwig tube, a series of experimental studies of heat transfer on the surface of sharp and blunt plates near a single wedge and near a pair of wedges was carried out at Mach numbers M = 5–10 and several values of the Reynolds number corresponding to laminar, transitional and turbulent boundary layer states in front of the wedge. The research results are presented in [21—24]. The possibilities of TSP are illustrated in Fig. 2, *a*, which shows the heat flux distribution on a flat plate between two wedges for two bluntness radii of the leading edge of the plate at M = 6 and Re = $1.5 \cdot 10^6$. It is very difficult to obtain heat flux information with such a spatial resolution by any other method. Studies of the transition of the boundary layer on blunt cones were also carried out (Fig. 2, *b*).

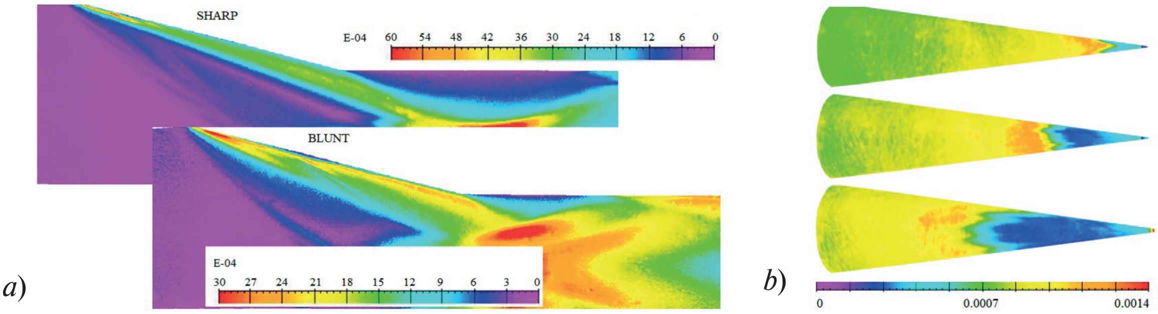


Fig. 2. Excitation and luminescence spectra of a two-color TSP (*a*); boundary layer transition on a cone depending on bluntness (*b*)

2. Wind tunnel AT-303 ITAM SB RAS

Here, TSP was used to study the transition of the boundary layer on a model of a hypersonic demonstrator. In the studied modes (M = 5.73; 7.75), in comparison with UT-1M, the AT-303 wind tunnel has high stagnation temperatures. Some of the results obtained are shown in Fig. 3, where the fields of the conditional Stanton number are shown in color. In all launches at M = 5.73 (Fig. 3, *a*), the heat flux increased approximately twice immediately behind the bow, which can be interpreted as a transition of the boundary layer. Decreasing Re from $13.8 \cdot 10^6$ to $9.2 \cdot 10^6$ results in a slight downstream shift of the transition. The level of values of the Stanton number on the line of symmetry in turbulent flow agrees in order of magnitude with the calculated values for a flat plate. At the Mach number M = 7.75 (Fig. 3, *b*) at Re = $6.1 \cdot 10^6$, a natural transition is also observed. The experiment in AT-303 is described in more detail in [25].

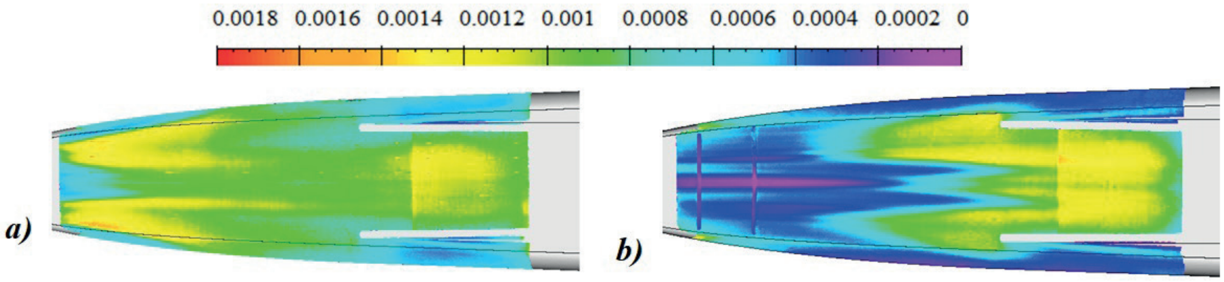


Fig. 3. St distributions at M = 5.73 (*a*); 7.75 (*b*) [25]

3. HAST IPMech RAS

Experiments with TSP have been prepared and carried out to visualize the temperature field on the surface of models at the HAST IPMech RAS, which functions as shock tube with aerodynamic section. Results with triple angle semi-wedge imitating scramjet air intake are shown in Fig. 4.

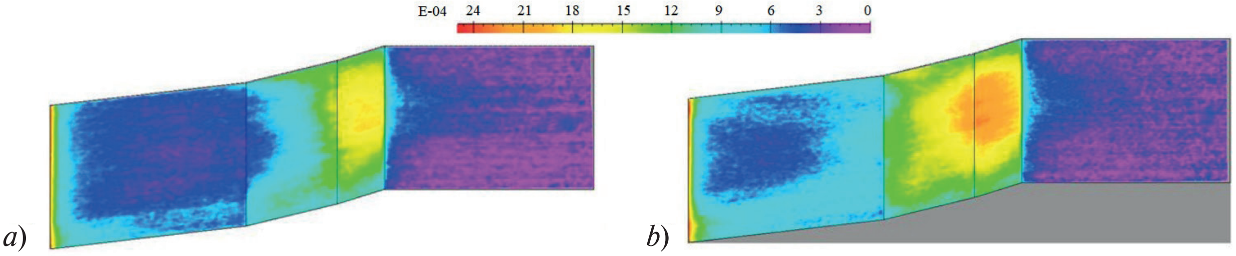
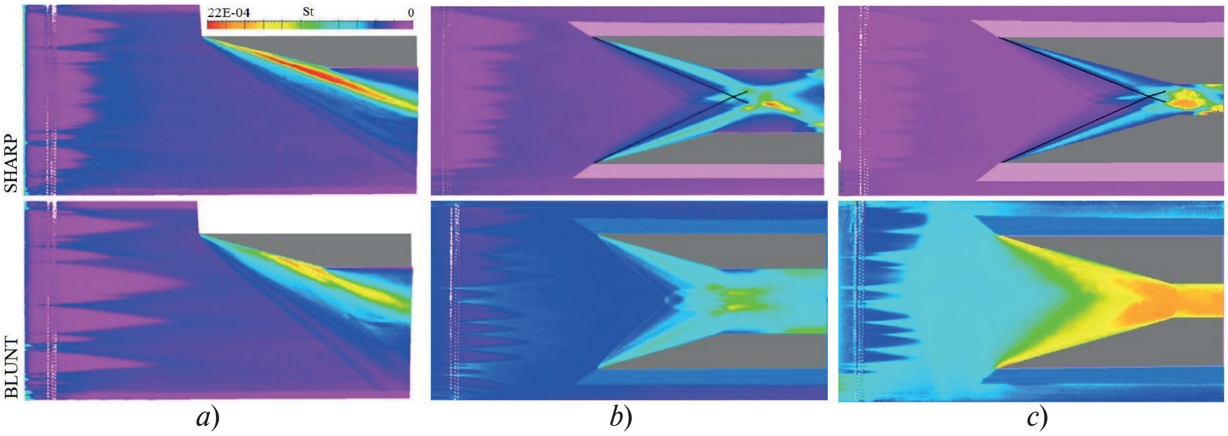


Fig. 4. Model surface temperature processed data at M = 5.3 (*a*); 5.5 (*b*) [26]

Heat transfer structures

Influence of entropy layer generated by blunt plate leading edge on the flow over different wedge configurations was studied experimentally by means of TSP [27]. It was shown that even a small bluntness of the plate leading edge considerably changes the heat transfer distributions at shock wave/boundary layer interaction (Fig. 5, *a*), and under certain conditions it results in the change of flow structure (Fig. 5, *b*, *c*).



a) *b*) *c*)

Fig. 5. St distributions at M = 5 gas flow on the sharp and blunt plates with 15° wedge configurations [27]

In [28, 29] a generic inlet with flat walls and rectangular cross section was considered (Fig. 6, 7). Also the data about an influence of upper cowl on heat transfer and flow structure inside an inlet are obtained (Fig. 6, 7, *b*).

The flow around a cylinder mounted on a sharp or blunted plate is experimentally studied in [30, 31].The results on the flow structure and heat transfer on the plate surface ahead of the cylinder and in its vicinity are described (Fig. 8). It was founded that heat-transfer coefficient peak values in interference regions decrease with increases in plate bluntness and distance from cylinder to leading edge.

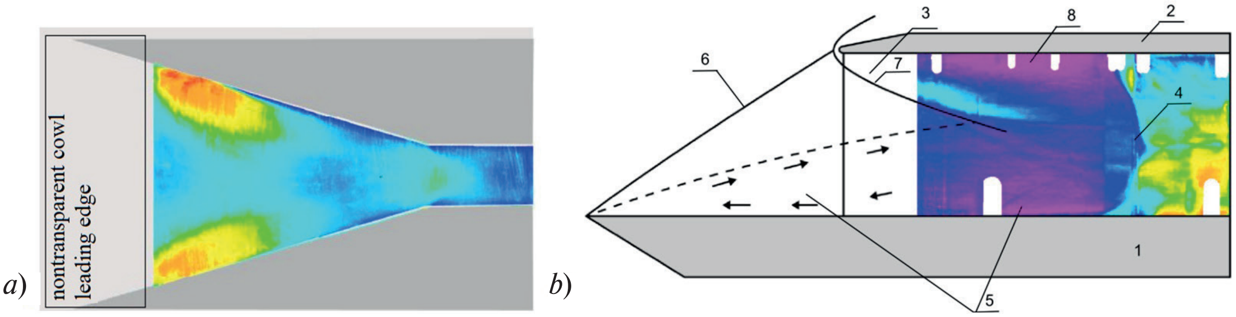


Fig. 6. St distributions on the cowl (*a*) and flow structure on a wedge in the inlet with blunted cowl (*b*) [28]

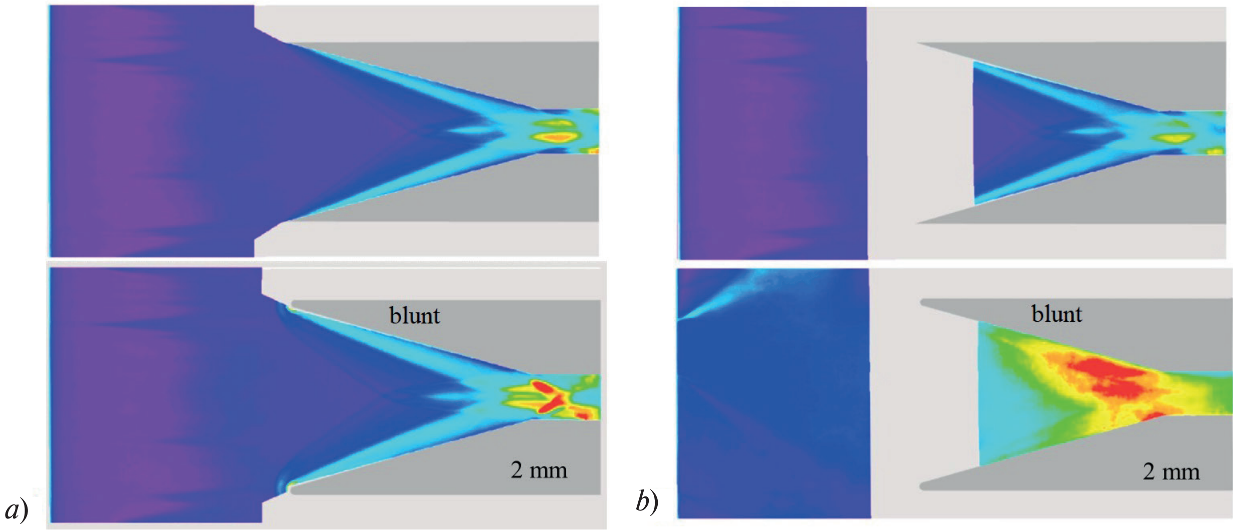


Fig. 7. Results of M = 5 on the plate with (*b*) and without a cowl (*a*) [28]

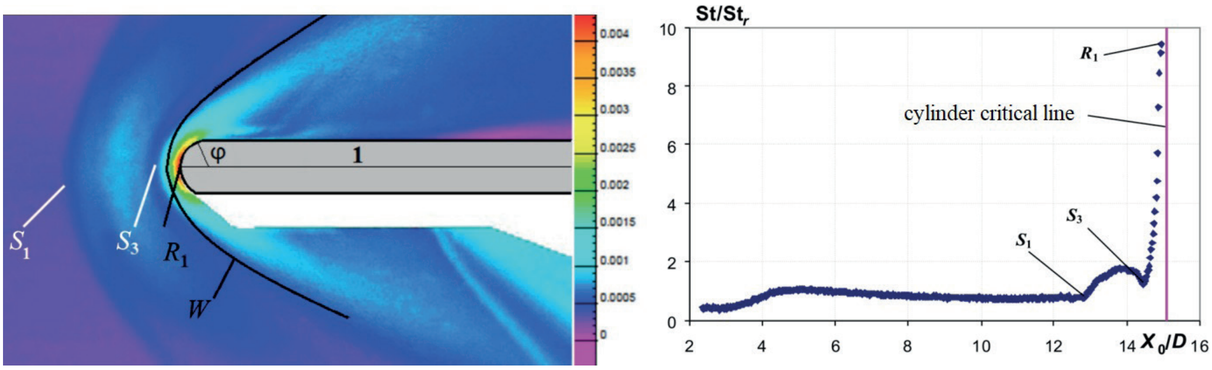


Fig. 8. Heat transfer picture and the distribution of St along the line of symmetry [30]

Heat transfer over 15° compression corner flow affected by reattachment vortices of controllable intensity are carried out in [32].The intensity of the vortices was varied by accurate controlling the height of a spanwise rake of cylindrical pins placed on the plate. It helped to determine the state of boundary layers at reattachment as close to laminar or transitional (Fig. 9).

The influence of flow parameters and nose radius of blunt cone on the location of laminar–turbulent transition is investigated in [33]. It is shown that transition reversal can occur either in the absence of turbulent wedges or at a constant level of freestream disturbances. Both increasing and decreasing branches of $Re_{\infty,t}$ ($Re_{\infty,R}$) dependency were observed at constant nose radius while varying only the unit Reynolds number (Fig. 10).

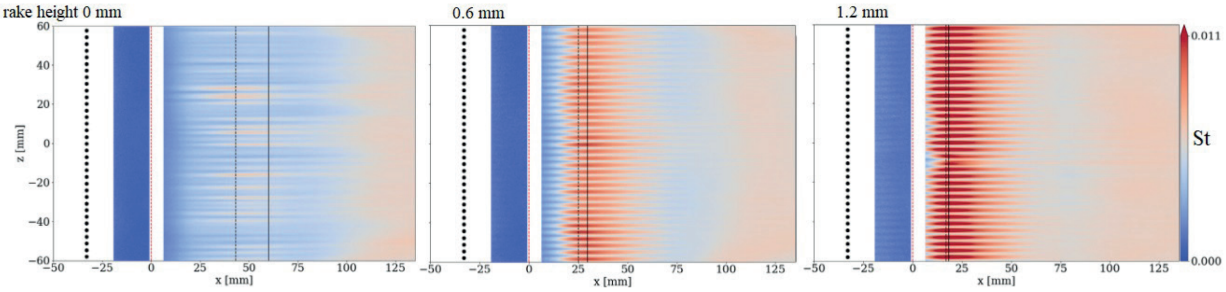


Fig. 9. Example distributions of St over compression corner surface showing appearance of reattachment vortices at rake height growth [32]

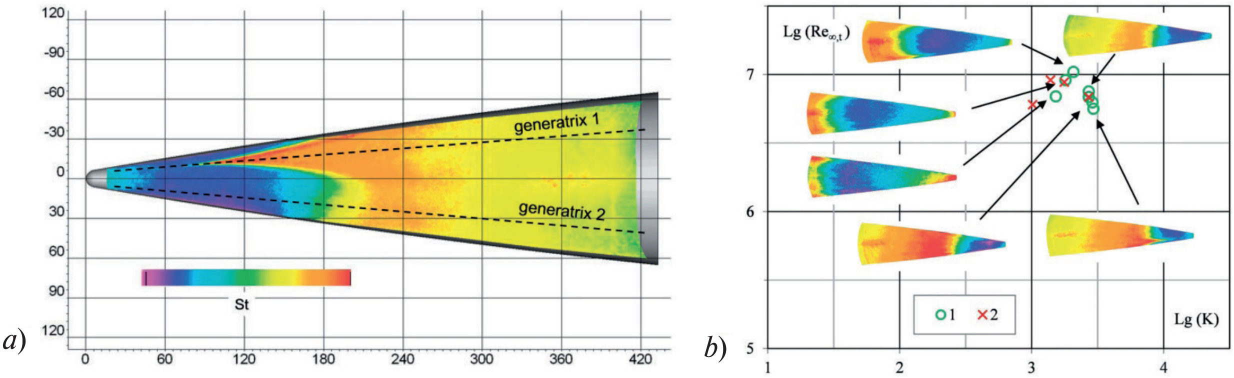


Fig. 10. Transition location determination by St distribution (*a*); Panoramic St distributions and its correspondence to points of *Lg* (Re$_{\infty,t}$) [33] (*b*)

Conclusion

TsAGI scientists have created two-channel TSP, which can significantly improve the accuracy of temperature measurement. On the basis of digital technologies for recording and processing images, the measurement of thermal parameters of gas on the surface of bodies has been worked out. A technique has been developed for measuring heat flux fields in short duration gas dynamic facilities. A brief analysis of some of the results obtained in recent years and demonstrating a wide range of applications of the developed methodology is presented.

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REFERENCES

1. **Khalid A.H., Kontis K.,** Thermographic Phosphors for High Temperature Measurements: Principles, Current State of the Art and Recent Applications 2008 Sensors 8.

2. **Tianshu Liu, et al.,** Pressure and Temperature Sensitive Paints Springer Cham 2021.

3. **Carlomango G.M., et al.,** Infrared Thermography as a Tool for Thermal Surface Flow Visualization 1998 Journal of Visualization 1 1.

4. **De Luca L., et al.,** Flow Visualization and Heat Transfer Measurement in a Hypersonic Wind Tunnel 1992 Experimental Heat Transfer 5 65–78.

5. **Ardasheva M.M., et al.,** Primenenie plavyashikhsya termoindikatorov dlya izmereniya teplovykh potokov k modelyam v aerodinamicheskikh trubakh 1972 Uch. Zap. TsAGI 1 (in Russian).

6. **Ardasheva M.M., et al.,** Primemenie termoindikatornykh pokrytij v issledovaniyakh teploobmena 1975 Trudy TsAGI 1162 14-17 (in Russian).

7. **Ardasheva M.M., et al.,** Primemenie termoindikatornykh pokrytij v issledovaniyakh teploobmena 1975 Trudy TsAGI 1692 (in Russian).

8. **Asai K., et al.,** 1996 Detection of Boundary-Layer Transition in a Cryogenic Wind Tunnel by Using Luminescent Paint AIAA Paper 1996–2185.

9. **Iijima Y., et al.,** 2003 Optimization of Temperature Sensitive Paint Formulation for Large-Scale Cryogenic Wind Tunnels 20th ICIASF Aug 25—29.

10. **Fey U., et al.,** 2003 Transition detection using temperature sensitive paint at Cryogenic Temperatures in the European Transonic Wind Tunnel (ETW) 20th ICIASF, Aug 25-29.

11. **Hubner J.P., et al.,** 2002 Heat Transfer Measurements in Hypersonic Flow Using Luminescent Coating Techniques AIAA Paper 2002—0741.

12. **Popernack T.G., et al.,** 1997 Application of temperature sensitive paint for detection of boundary layer transition 17th International Congress on Instrumentation in Aerospace Simulation Facilities Sep 29-Oct 2 77–83.

13. **Mclachlan B.G., et al.,** 1993 Boundary layer transition detection by luminescence imaging AIAA Paper 1993. — 0177.

14. **Borovoy V.Ya.,** Techenie gaza i teploobmen v zonakh vzaimodeystviya udarnykh voln s pogranichnym sloem Mashinostroenie, 1983

15. **Liu T., Sullivan J.P.,** Pressure and temperature sensitive paints Springer-Verl 2005.

16. **Campbell B., et al.,** Temperature measurement using fluorescent molecules 6th International Symposium on Applications of Laser Techniques to Fluid Mechanics Portugal Lisbon. 1992.

17. **Shinya Katagiri, et al.,** New strategy for thermo-sensing dye based on the back energy transfer in photosensitized luminescence Proceedings of International Workshop on Molecular Imaging for Interdisciplinary research Japan Sendai Nov 8–9, 2004

18. **Buck G.M.,** An Imaging System for Quantitative Surface Temperature Mapping Using Two-Color Thermographic Phosphors 34th International Instrumentation Symposium NM Albuquerque, 1988.

19. **Mosharov V., et al.,** Temperature sensitive paint (TSP) for heat transfer measurement in short duration wind tunnels 20th ICIASF, 2003, 351–356.

20. **Mosharov V.E., Radchenko V.N.,** Izmerenie polej teplovykh potokov v trubakh kratrovremennogo dejstviya s pomoshyu lyuminiscentnykh preobrazovatelej temperatury, 2007 Uch. Zap. TsAGI 1 2 (in Russian).

21. **Borovoy V.Y., et al.,** Laminar-turbulent flow over wedges mounted on sharp and blunt plates 2009 Fluid Dyn 44 382—396.

22. **Borovoy V., et al.,** Three-Dimensional Shock-Wave/Boundary-Layer Interaction at the Presence of Entropy Layer EUCASS St. Petersburg Jul 4–8, 2011.

23. **Borovoy V., et al.,** Temperature sensitive paint application for investigation of boundary layer transition in short-duration wind tunnels Flight Physics book of EUCASS 2011, 109–118.

24. **Mosharov V., et al.,** Hypersonic turbulent heating of sharp and blunt plates near a wedge 2011 Visualization of Mechanical Processes 1.

25. **Borovoy V., et al.,** Issledovanie perekhoda pogranichnogo sloya s pomoshyu lyuminiscentnykh preobrazovatelej temperatury v aerodinamicheskoy trube impuslnogo dejstviya AT-303 Proc. pf ICMAR 2010 Novosibirsk Nov 1-6 (in Russian)

26. **Mosharov V.E., et al.,** 2018 J. Phys.: Conf. Ser. 1009 012036.

27. **Borovoy V., et al.,** 2014 Influence of entropy layer on the airflow over a wedge and a pair of wedges on the plate AIAA Paper 2014–1139.

28. **Borovoy V., et al.,** 2015 Gas Flow in a Generic Inlet with Blunted Leading Edges AIAA Paper 2015–1061.

29. **Borovoy V., et al.,** Influence of leading edge bluntness o hypersonic flow in a generic internal-compression inlet 2015 Progress in Flight Physics 7 419–436.

30. **Borovoy V.Y. et al.,** Shock Wave Interaction Near a Cylinder Aligned Normal to a Bluntede-Part I: Gas Flow and Heat Transfer on a Plate Near a Cylinder 2018 TsAGI Science Journal 49 2.

31. **Borovoy V.Y. et al.,** Interaction of Shock Waves Near a Cylinder Perpendicular to a Blunt Plate, Part II: Heat Transfer on a Cylinder 2018 TsAGI Science Journal 49 6.

32. **Chuvakhov P.V., Radchenko V.N.,** Effect of Gцrtler-like vortices of various intensity on heat transfer in supersonic compression corner flows 2020 Int J Heat Mass Transf 150 119310.

33. **Vaganov A. et al.,** 2020 Laminar—turbulent transition reversal on blunt ogive body of revolution at hypersonic speeds Proc. of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering 234 1 102–108.

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