# Experimental researches in high temperature facilities of TsAGI

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## Abstract

Main results of certain experimental investigations, which have been implemented in recent years in high-speed high-temperature and high-enthalpy wind tunnels of the Central Aerohydrodynamic Institute (TsAGI) are presented, including

- Heat exchange at a laminar-turbulent transition on a sharp cone;
- Flow and heat exchange on a body surface at the incidence of the shock wave;
- Flow and heat exchange at a tangential blow of gas into a wall layer of the body in flow (including the dust-laden layer) through a tangential slot, situated on its frontal surface,;
- Heat exchange and pressure distribution on a blunted cone in a supersonic wind tunnel with a high-frequency heating of gas;
- Thermophysical properties of high-temperature heat-resistant and structural materials and their coatings.

## 1. Introduction

Considerable attention of researchers in TsAGI is paid to the experimental investigations of heat exchange and heat protection of high-speed aircrafts. Both applied and fundamental investigations are being carried out. The total simulation of heat exchange and heat protection of a high-speed aircraft at real conditions of flight in ground-based facilities is known to be impossible. Therefore, the researchers have to apply the technique of partial simulation in several ground-based facilities, each of which simulate. Missing data are obtained through the numerical simulation. As a rule, after the creation the numerical code is tested through the comparison with the data that are obtained in experimental facilities.

A set of high-speed wind tunnels of TsAGI, including high-enthalpy hypersonic wind-tunnels, represented by T-117, T-121, T-122, UT-1M, GGUM, IT-2, VAT-104, T-56, enables the experimental data on heat exchange and heat protection of a high-speed aircraft to be obtained within a wide range of gas-dynamic and thermal parameters. In addition, it should be noted that the capabilities of many wind tunnels have been advanced in recent years. The measuring techniques and methods of data analysis are being improved without cease. Certain examples of results of the experimental investigations, which have been implemented in recent years in high-speed high-temperature and high-enthalpy wind tunnels of TsAGI, are presented below.

## 2. Main Results

### 2.1 Investigations of flow and heat exchange in T-117 wind tunnel

T-117 is an intermittent-operation wind tunnel, designed for the investigation of flow, aerodynamic forces that act on the model, pressure distribution, heat flux, and streamlines on the model surface [1-5]. The Mach number in the nozzle exit section is $M_\infty = 7.5 - 18.5$; the Reynolds number, calculated on the basis of the undisturbed flow parameters per one meter, is $Re_{\infty,1m} = 8\times10^3 - 1.4\times10^7$, dynamic pressure $0.5\rho_\infty u_\infty^2 = 0.8\times10^3 - 14.4\times10^4$ . The air flow stagnation temperature can vary within $T_0 = 700 - 3000$ K. The test duration range is 2 to 200 s.

The example of a fundamental investigation in T-117 is the investigation of a laminar-turbulent transition on a sharp cone with a length of $L$ =°1200 mm and with an angle of a half-expansion of 5°. The typical distribution of the Stanton number over the model length is presented in Fig. 1a. The Mach number during this test is $M_\infty$=8.3, and Reynolds number $Re_{\infty, L}$=9.04×10$^6$. The heat flux in these tests is determined using thin-film thermocouples ($\delta$ = 0.04 mm) and heat-capacity calorimeters [3]. The dependence of Reynolds number $Re_{e,t}$, calculated on the basis

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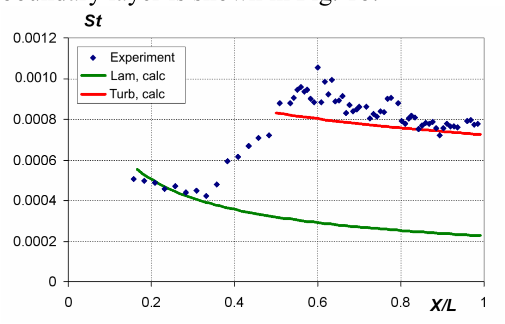
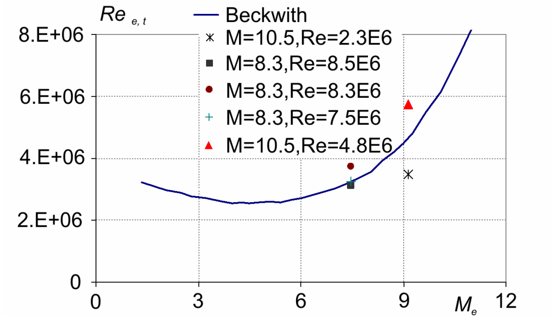
of the parameters of flow at the external boundary of the boundary layer and the distance from the vertex of cone up to the region, where the laminar-turbulent transition ends, on Mach number $M_e$ at the external boundary of the boundary layer is shown in Fig. 1b.



a)



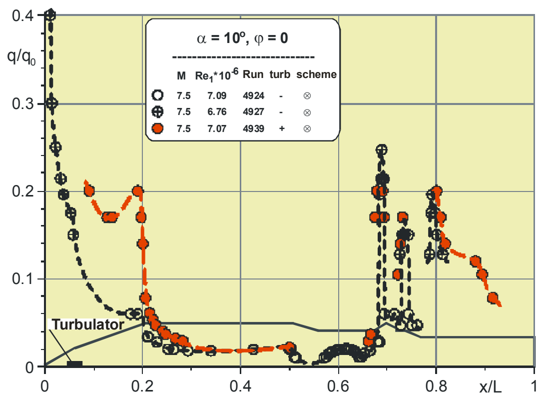
b)

Figure 1: Investigation of a laminar-turbulent transition on a sharp cone with an angle of a half-expansion of 5° in T-117 wind tunnel. $M_\infty$=10.5; $M_e$=8.3; *a)* Distribution of the Stanton number along model length x/L. $M_\infty$=8.3. $Re_{\infty, L}$=9.04×10$^{6}$. *b)* $Re_{e,t}$= f($M_e$).

It is seen that the data obtained are in a satisfactory agreement with the data, presented in [6] for the wind tunnel with a low turbulence of the undisturbed flow. Systematic investigations in T-117 have verified the influence of the unit Reynolds number on TSP. At present, this phenomenon is not explained for a while.

T-117 is widely used to solve the applied problems. As an example, the heat flux distribution over the "Angara" model (1:100) surface in the region of interaction of the shock waves, induced by the accelerating blocks is shown in Fig. 2. The distribution is obtained through the method of heat-indicating coatings (black color on the model corresponds to high heat fluxes).

a)



b)

Figure 2: Investigation of the heat exchange distribution over the "Angara" model surface inT-117. a) Photo of the model after tests b) a) Distribution of Stanton number St along model length x/L at the azimuthal angle φ = 0/

The distribution of ratio $q/q_0$ of the heat flux in a given point to the heat flux in the critical point depending on ratio $x/L$ of the distance to the critical point to the model length at the model symmetry line (between blocks on the windward generatrix of assembly) is shown in Fig. 2b. A significant increase of the heat flux in the region of incidence the shock wave from the lateral block nose on the central body is seen ($x/L$ = 0.68*)*.

## 2.2 Investigations of flow and heat exchange in UT-1M wind tunnel

Extensive investigations of a hypersonic flow over models are implemented in UT-1 wind tunnel (shock wind tunnel). This is an impulse shock wind tunnel, operating according to the Ludwieg tube scheme. The working gas before the test is put into the channel with an internal diameter of 70 mm and a length of 6 m. The electrical heater, which covers the channel from the outside, heats the channel walls and gas up to a prescribed temperature. Diaphragms, shaped nozzle, test section with a diameter of 0.5 m, and exhaust system are placed successively in the end of the channel. The duration of the gas stationary flow in the test section is about 40 msec. The gas can be heated in the channel up to 800 K, and the maximum pressure of the gas in the channel can achieve 110 bar. The maximum parameters of the flow are presented in Table 1.

Table 1. Flow characteristics in the test section of UT-1 wind tunnel

| $M_\infty$ | 5 | 6 | 8 | 10 |
|---|---|---|---|---|
| $T_t$, K | 510 | 650 | 750 | 775 |
| $P_t$, бар | 72 | 89 | 93 | 104 |
| $Re_1 \times 10^{-6}$, м$^{-1}$ | 86 | 46 | 19 | 12.4 |

UT-1 is characterized by a high efficiency and low consumption of energy and materials. For measuring the heat-transfer coefficient and pressure ratio the different types of discrete sensors are applied. In addition, the optical methods of investigation of flow characteristics have been widely applied recently. They are based on the application of quick-acting luminescent coatings, sensitive to temperature (TSP) and pressure (PSP) [7]. Visualization of limit streamlines and friction stress on model surfaces is implemented using oil, containing fluorescent particles. The optical methods are especially efficient while investigating three-dimensional flows, in particular, a laminar-turbulent transition [8].
An example of the heat exchange investigation in the bottom region of a schematic model of the Martian probe [9-11] is presented in Fig. 3. The heat-transfer coefficient is measured by the foil thermocouple sensors. Their sensitivity is sufficient for measuring the small values of the heat flux in the bottom region (of about 0.1 W/cm$^2$). The experimental data are in a good agreement with the results of numerical solution of the Reynolds equations.

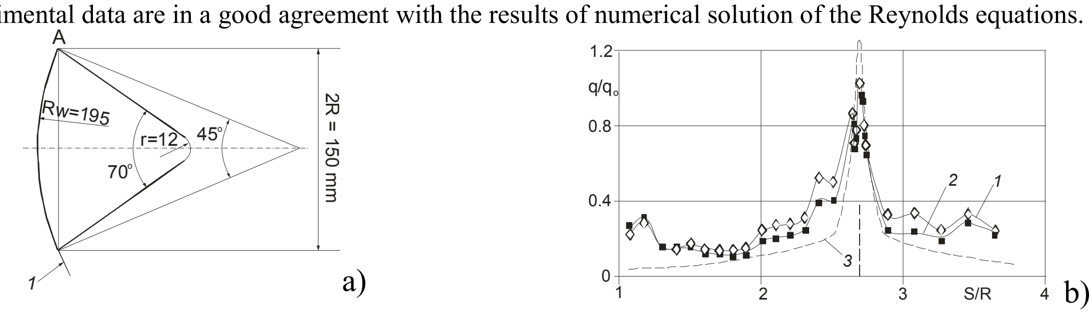



Figure 3: Heat exchange in the bottom part of the Martian probe schematic model at $M_\infty$= 8, $Re_{\infty,D}$ = 1×10$^6$: 1 – without turbulator; 2 – with the turbulator, placed on the frontal surface; 3 – calculation. $q_o$ – heat flux in the frontal point of stagnation, D=2R – overall size of the model, S – contour length from the arm.

A two-dimensional interaction of an oblique shock wave with the cylinder frontal surface [12] and flat plate surface [12-14] is investigated in UT-1. The investigations of a three-dimensional flow over a single wedge or a pair of opposite wedges are carried out at present [15]. As an example, the results of investigation of a gas flow on a plate in the vicinity of a sharp wedge are shown in Fig. 4. An oblique shock, generated by the wedge, causes the boundary layer separation. At the reattachment line, situated between the shock and the wedge, the heat flux (Fig. 4a), pressure (Fig. 4b), and friction stress (Fig. 4c; the friction stress is marked with a color) sharply increase. The results of the heat flux measurements are close to the results of numerical solution of the Reynolds equations (Fig. 5).

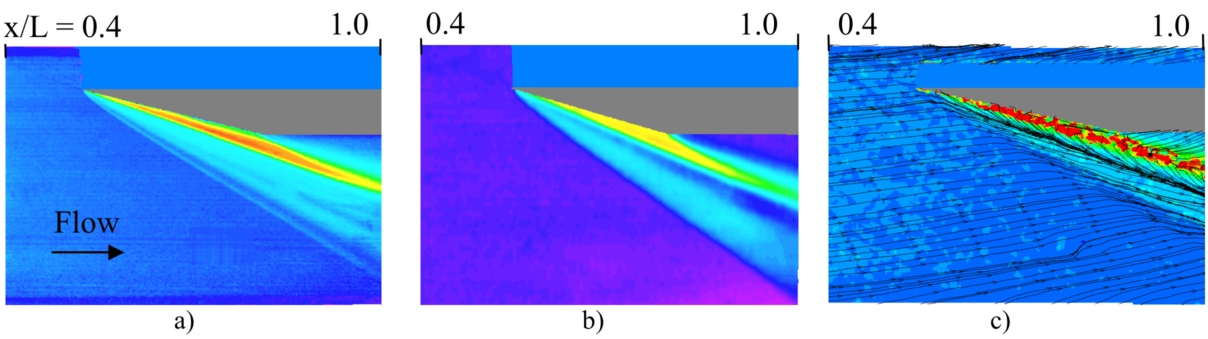



Figure 4: Flow over a flat plate with a wedge of θ =15$^o$ at M= 5 and $Re_{\infty L}$ =27x10$^6$: a – distribution of the Stanton number; b – distribution of pressure ratio $C_p$; c – limit streamlines and friction stress.

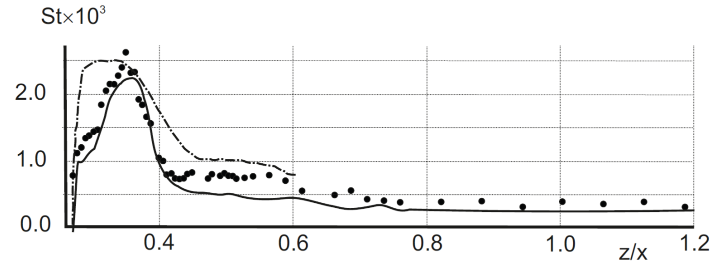
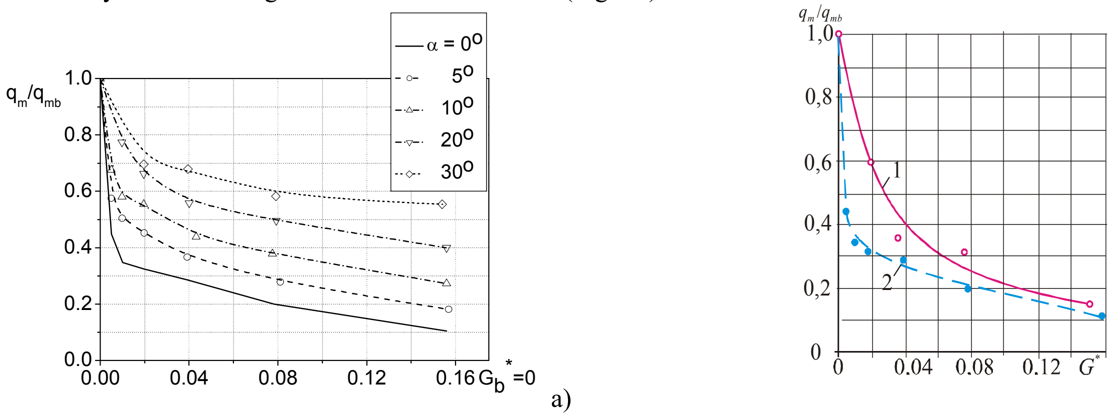



Figure 5: Stanton number distribution on a plate in the cross-section, situated at distance x =82 mm from the wedge leading edge (x/L = 0.46), at $M_\infty = 5$, $Re_{\infty L} = 27x10^6$ and wedge angle $\theta = 15^o$ : solid line – TSP, points – thermocouples, dash-and-dot line – calculation.

UT-1 is equipped with the devices for the creation of a gas-dust medium in the high pressure channel. This enables different physical effects that arise at the interaction of a high-speed dusty flow with streamlined bodies to be detected. The influence of a tangential blow of gas (air) through the axisymmetric slot with height $h$, situated near the critical point of spherical blunting of radius $R_w$ of the cylinder, streamlined in the longitudinal direction, on the flow pattern and heat flux at different angles of attack of the model (Fig. 6a) [17 - 19] is investigated using a fast-acting system of gas supply into the model. The influence of the blow of gas (air) on the heat flux is investigated in a similar way at the dusted gas flow of the wind tunnel (Fig. 6b).




a) b)

Figure 6: Influence of injection gas flow $G^*$ on the maximum heat flux to the blunting surface. a) at different angles of attack α of the cylinder . b) at different concentrations of particles in the undisturbed flow. 1 – $n$ = 1.6 %, 2 – $n$ = 0. $n$ - the weight concentration of particles $Fe_2O_3$ size $d$ = 0.37 mkm.

In the case, when the bodies are streamlined by the gas, containing microparticles, new physical effects near the frontal surface of the streamlined bodies are detected and investigated: cumulation of particles, self-luminescence of the flow, surface electrification [20-21].

## 2.3 Investigations of thermal protection in VAT-104 wind tunnel

This wind tunnel is a unique operating hypersonic wind tunnel with an inductive heating of gas. The inductive high-frequency heater ensures the working gas (air, nitrogen, heating, helium) within the range of flow stagnation enthalpy $I_0$ = 25-40 MJ/kg and pressure of total stagnation $P_0$ = 0.1-0.4 bar. The inductive heating enables the flow contamination to be avoided, high controllability and stability of flow parameters, as well as the repetition of regimes from test to test to be ensured [22-24]. The test duration can achieve 1800 sec. Degree of air dissociation α = 0.5-0.9, the degree of ionization is 0.1%.

VAT-104 is equipped with slotted and conical nozzles. While applying the conical nozzle with a diameter of 50 mm, the flow with $M_\infty = 5$ is implemented in its exit section; with axisymmetric cylinders and cones with a blunting radius of 10-35 mm, streamlines in a longitudinal direction, being usually used as the models.

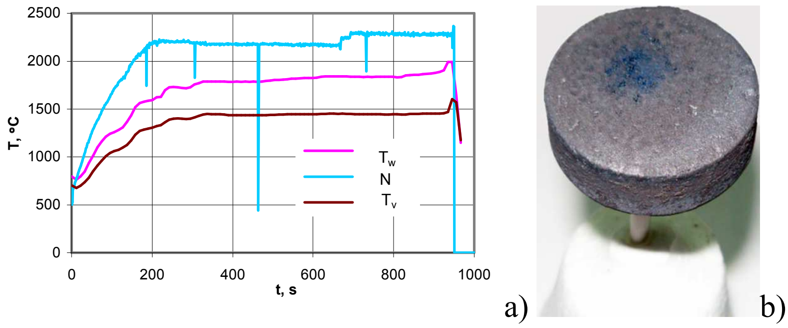



Figure 7: Tests of sample C-C with coating MAI D5.
a) power verse during test $N$=f($t$), 10kW; temperature of head surface $T_w$= f($t$), K; temperature of back surface $T_v$= f($t$), K; b) sample past test (head surface)

VAT-104 is widely applied in the investigations of heat resistance of materials, as well as coatings for chemical protection of materials. The results of tests of coating MAI D5 [25] are shown in Fig. 7 as an example. A stepwise character of the variation of power and pressure of total stagnation is set in accordance with the required character of heat load on the sample surface. At the indicated high parameters of the flow the coating is not destroyed.

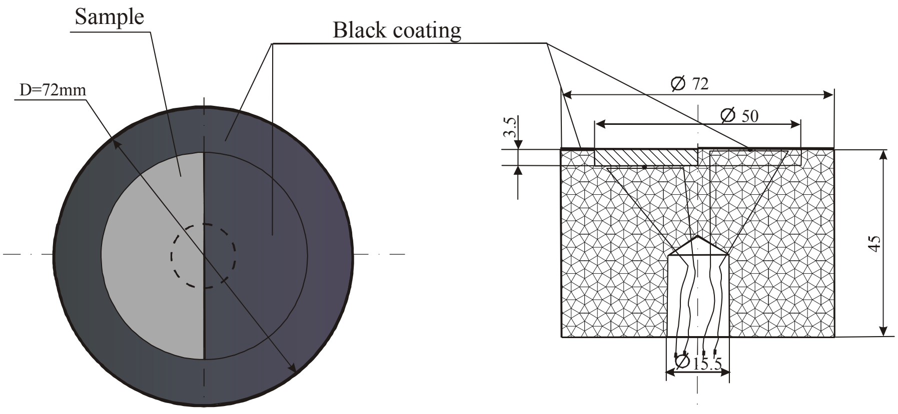



Figure 8: Model for the studies of a catalytic activity of C-C.

Investigations of catalytic peculiarities of materials in a gas flow are systematically carried out in VAT-104 wind tunnel. The catalytic activity is determined by means of a special heat-insulated model (see Fig. 8) through the comparison of established temperatures of a sample of the material under study and the reference (sample, made of a standard tablet of Shuttle "Buran" with the black coating, whose constant of heterogeneous recombination rate is $K_w$ =1 m/s). By applying the obtained difference in temperatures of the sample under study and reference, through the numerical simulation, and on the assumption that the radiating capacities of the sample and reference at the registered wavelengths are known, the constants of the recombination rates of a number of materials and coatings are obtained. It is shown, that at the temperature of the head surface of coating $T_w$ = 1500 K constant of heterogeneous recombination rate is $K_w$ =2.5 m/s.

## 2.4 Investigation of thermophysical properties of materials and coatings on T-52A facility

Radiating capacity ε and heat conductivity coefficient λ of materials and coatings significantly influence the temperature regimes of hypersonic aircrafts, as well as the efficiency and weight of thermal protection systems of high-speed aircrafts. These quantities can be determined only experimentally. For a given material (coating) ε and λ generally depend on temperature, pressure, and composition of environment. Measurements of these quantities are very important elements in the complex of investigations, ensuring the creation of efficient and reliable heat-protecting high-speed aircrafts

These investigations are being carried out at TsAGI within wide ranges of temperature, pressure and gas composition on special facilities: T-52A, VAT-3C, T-56.The thermophysical characteristics, mentioned above, are measured on these facilities usually with a higher accuracy than in the wind tunnel flows.

However, it should be noted that in the gas at rest the friction of gas flow does not influences the thermophysical characteristics under study. The influence of the gas composition nonequilibrium on these facilities also can not be studied. In general, the investigations of thermophysical characteristics on special-purpose facilities are widely applied and are being developed [26-28].

The results, obtained on T-52A, are presented below as an example. The maximum sizes of sample are 120×120×60 mm. Integral hemispherical radiating capacity ε heat conductivity coefficient λ are determined at this facility within the temperature range of samples $T_w$ = 600-2000 K. The investigations of the integral hemispherical radiating capacity of materials and coatings are implemented through the radiation method, which is based on measurements and comparison of radiant fluxes from the sample under study and blackbody model at the same temperatures. Experimental dependences of the radiating capacity on surface temperature ε = f($T$) of several materials and coatings, obtained in T-52, are presented in Fig. 9.

The technique, applied for measuring the radiating capacity on T-52A facility, is based on a contactless way of determination of a surface temperature of the sample under study using a specially made radiation-measuring instrument and a thermocouple, located in the gap between the heater and the sample. The equipment of T-52A makes it possible to carry out the experiments with the samples of almost all types of materials (heat-insulating, composite, metallic) within the range of pressures of a given equilibrium composition of gas $P = 1 - 10^5$ Pa.

The determination of temperature and barometrical dependences of heat conductivity λ of porous heat-insulating materials is implemented at the same facility through the method of flat isotherms in heated flat samples with an active compensation of heat losses from the samples and their heaters (guarded hot plate) [3, 4]. Total heat conductivity λ and its separate components (contact-conductive through the solid phase that forms the material frame; radiative, and molecular-convective heat conductivity of the gas, situated in pores) are determined on the basis of the results of measurements of temperatures in samples and heat fluxes that passed through them.

The thermophysical characteristics of fibrous materials are presented in Fig. 9: on the basis of $Al_2O_3$ and $SiO_2$ mixture (curve 1) and on the basis of $SiO_2$ (curve 2).

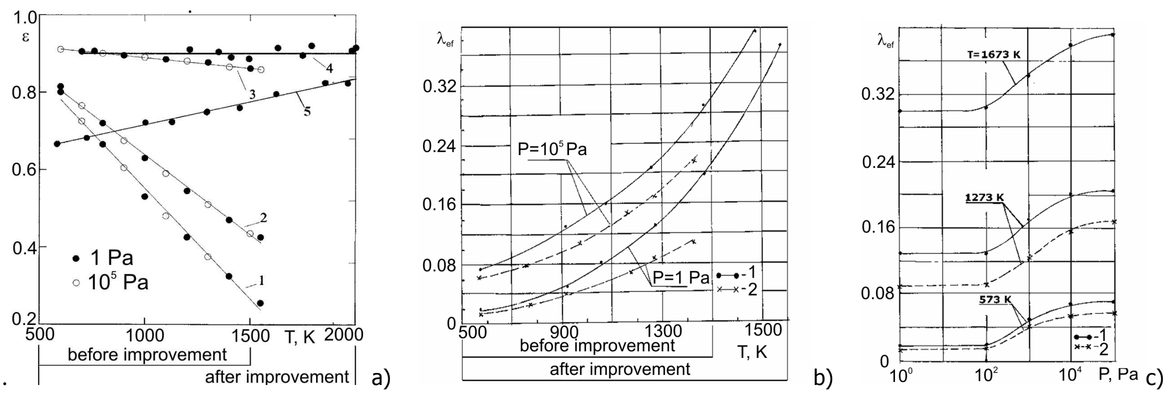



Figure. 9. Thermophysical characteristics materials. A) ε = f($T_w$) 1 – heat-protective material TZMK-10 (heat-protective material on the basis of silica fibers, analog of Li-900); 2 – white coating; 3 – black; 4- methodical graphite sample with a high artificial roughness of the surface, 5 - composite carbon-carbonic material. b) λ = f($T_w$); c) λ = f(p); 1 – on the basis of $Al_2O_3$ and $SiO_2$ mixture, 2 – on the basis of $SiO_2$).

Total coefficient of heat conductivity λ for the both materials monotonically increases at the increase of the temperature of samples and pressure of the gas medium in the chamber, Fig. 9b and 9c. The increase in $\lambda_{ef}$ of the investigated samples is generally explained by the intensification of a radiation heat transfer inside the material at the increase in temperature and molecular-convective component of the heat transfer at the increase in pressure of the gas medium.

## Conclusions

The investigations, implemented in high-temperature and high-enthalpy high-speed wind tunnels of TsAGI, made it possible to reveal and to a large extent study new physical phenomena in the field of heat exchange and heat protection of high-speed aircrafts. The numerical investigations, fulfilled for the parameters of tests and verified through the comparison of the results of physical and numerical investigations, significantly extend the understanding of nature of the phenomena under study.

## Acknowledgement

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