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MODERN PROBLEMS OF THERMAL PROTECTION

Yu. V. Polezhaev UDC 629.78:536.24

A brief review of the present state of works on the promising methods of thermal protection of thermally stressed units and assemblies in different branches of technology is given.

Introduction. The term "thermal protection" appeared in the vocabulary of scientists and engineers about 45 years ago in the course of preparation for the launching of the first intercontinental ballistic rockets. It combined the system of convective ("jacket") cooling, known earlier and widely used in internal combustion engines, and the so-called destructible "coating," i.e., a mixture of high-melting oxides and a clay-type binder, meant for protection of the foreparts of ballistic rockets against intense convective heating in the process of their flight in dense atmospheric layers.

The need for the use of a special system of thermal protection arises in the case where an unprotected structure must inevitably collapse under the action of energy fluxes (convective, radiant, electron, photon, and others). Heat fluxes of the order of 0.25 MW/m^2, which lead to higher than 1500 K equilibrium temperatures of heating of the surface, can, apparently, be considered to be the upper limit of applicability of the most heat-resistant metals without thermal protection. This threshold is of course conventional, since in most cases the heat action can be aggravated by mechanical and oxidizing actions of the environment, which also accelerates the destruction of the structure. According to the statement of specialists of the "Molniya" Science and Production Association [1], in the last decade one has been able to increase the working temperature of ceramic materials up to 2000^{o}C owing to the replacement of quartz fibers by higher-melting ones (Fig. 1). Nevertheless, even this outstanding achievement of specialists in materials science does not remove from the agenda the need for further investigations on improvement of thermal-protection systems.

Twenty five years ago the monograph "Thermal Protection" written by the author of this paper together with F. B. Yurevich was published [2]. The main objective of the book was to describe the bases of the theory and propose simple and convenient formulas for estimating different parameters of thermal-protection systems for those who are engaged in technical applications. We would like to particularly emphasize the role of Academician of the BSSR Academy of Sciences A. V. Luikov, who came up with the idea of writing such a monograph and provided a useful guide to editing and publishing it. The present brief review by no means claims to be a detailed analysis of all possible applications of thermal protection in modern technology. In the last quarter of a century, a great number of such applications have appeared.

The number of processes that have to be taken into account in thermal designing of different products also sharply increased. As a result of this, the term "multifunctional" coating is used in engineering practice more often than the term "thermal protection."

Twenty five years ago we could not even theoretically assume that the ground perfection of thermal protection would give birth to a new scientific direction, i.e., the theory of tests, in which experimental results are predicted initially by numerical modeling and only then are they confirmed (or disproved) by physical modeling.

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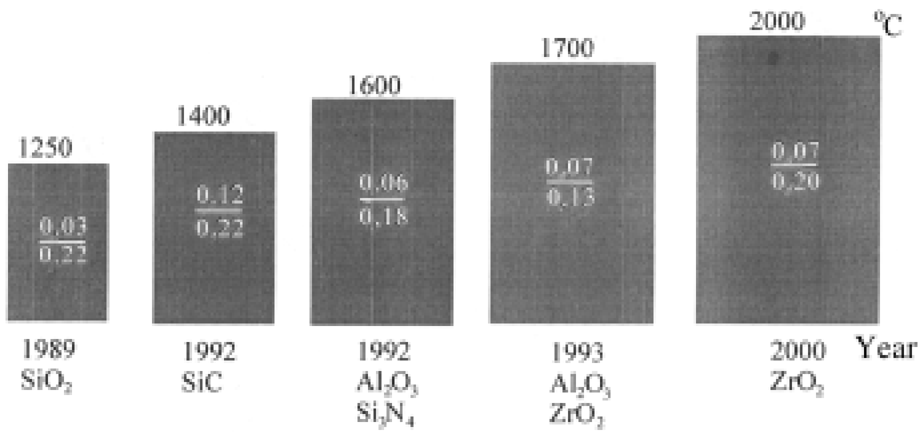


Fig. 1. Increase in the working temperatures of ceramic materials (in years) owing to the replacement of quartz fibers by higher-melting fibers [the figures are the values of the thermal conductivity at 20 and 800°C, W/(m·deg)].

And finally, at that time, thermal-protection systems only supplemented the projects of aerodynamicists and designers. However, beginning with the Shuttle reusable space system, it is precisely thermal protection that mainly determines the aerodynamic arrangement and the design of a product as a whole [1].

Thermophysical Aspects. Thermal protection is a specific method of blocking or diminishing the heat flux from the environment to the surface of a body. It is realized predominantly through the following effects: (1) heat conduction and heat capacity of the outer shell of a product; (2) convection of a special cooler in the spacing between two shells; (3) mass exchange between the cooler and the external gas flow (effect of blowing); (4) physicochemical transformations of the cooler or a special "sacrificial" layer of the outer shell (removable thermal protection); (5) reirradiation of heat from the heated shell, and (6) electromagnetic fields interacting with the environment.

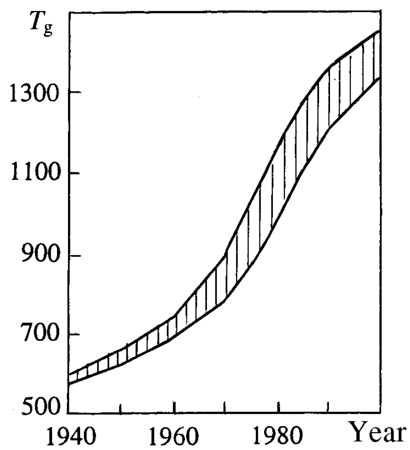
Many of these methods have been studied sufficiently well and realized in hundreds of patents; others are still waiting for their time.

We dwell on two applications that are of great importance for the development of power engineering and aviation. In both applications, interest in thermal protection has been provoked by revolutionary changes that have occurred in these branches of technology in the last decade.

Present-day civilization cannot exist without production and processing of different power resources. In developed countries, as much as 35% of the power resources are related to electricity. The prospects for the development of electric-power engineering are related to new operating cycles and working media. Whereas in the past use was predominantly made of steam-turbine plants in which the chemical energy of the fuel was expended on producing steam, now there is a marked tendency toward a wider use of gas-turbine plants and combined steam-gas plants. The efficiency of such plants is determined by the pressure differentials and temperature differences acting in them. It is precisely the limited temperature difference in steam turbines that was the main reason for the replacement of them by gas turbines in which the upper temperature limit has progressively increased in the last few years (Fig. 2).

In 1981, the STIG cycle (Steam Injection in Gas Turbine) was patented. The injection of steam makes it possible to decrease significantly (by 10–20%) the flow rate of compressor air with preservation of the same dimensions of the flowing channel. It is also important that the enthalpy of the steam is higher than the enthalpy of the air, i.e., the effective work increases substantially in this case (up to two times).

Combined gas-steam-turbine plants operating according to the STIG cycle have made a revolution in power engineering; owing to these plants, the coefficient of conversion of fuel energy to electricity has been



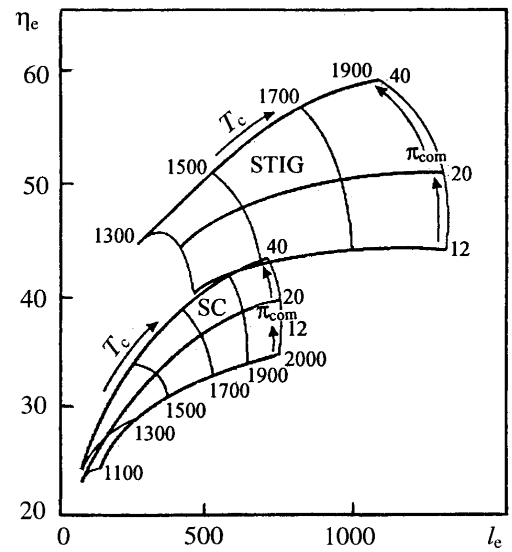


Fig. 2. Tendency toward a change in the temperature in the combustion chamber of gas-turbine power plants in years. T_g, ^oC.

Fig. 3. Comparison of the regime parameters of gas turbines operating according to the STIG and SC cycles. η_e, %; l_e, kJ/kg of air; T_c, K.

increased nearly twofold in the last 10–15 years. In Fig. 3, the simple (or classical) SC cycle is compared to the STIG cycle in terms of efficiency η_e and efficient work l_e for the presented values of the temperature in the combustion chamber T_g and degree of increase in pressure in the compressor π_{com}.

If it were possible to increase the temperature in the combustion chamber T_g to 1900 K, the economy of fuel and the level of reduction of the environmental hazard of ejections into the atmosphere would comply with all the requirements of the XXIst century.

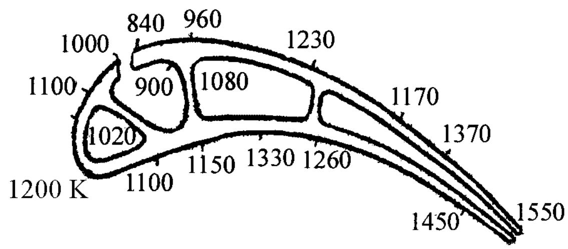
One possible trend toward such progress is the wide use of systems of penetrating cooling of gas-turbine blades in power engineering. It is precisely this problem that will be discussed in the next section.

A few words about the situation in aviation. The speeds of military and civilian airplanes have not increased by even 10% in the last 30 years. We discussed this paradox in the paper "Will there or will there not be a hypersonic airplane?" [3]. We believe that a way out of the deadlock is the development of an efficient indestructible system of thermal protection for the leading edges of the wings, the nose of the fuselage, and the input edges of the diffuser of a hypersonic ramjet engine. The replacement of hydrogen by natural gas as the fuel can also be very promising for such an airplane. Clearly, such a replacement is appropriate only in the case where it is possible to split a molecule of natural gas (methane) in advance by breaking off carbon from hydrogen. This process was given the name "vapor conversion of methane."

It is important that the large amount of heat that can be realized in the system of thermal protection of the walls of a combustion chamber be absorbed during the vapor conversion.

Hence, the possibility of overcoming the hypersonic barrier in aviation is largely dependent on how fast the problem of thermal protection of the "superthin" leading edges of the fuselage and the combustion chambers of a ramjet engine will be solved.

Penetrable Thermal Protection. Among the active methods of thermal protection, penetrable thermal protection has gained the widest acceptance. If we assume in the first approximation that blowing of a single jet (screen-type cooling) also belongs to this class of thermal protection, then the history of its creation dates back to 1923 when the German scientist Herman Obert proposed a screen for protection of the combustion chambers of liquid-propellant rocket engines.



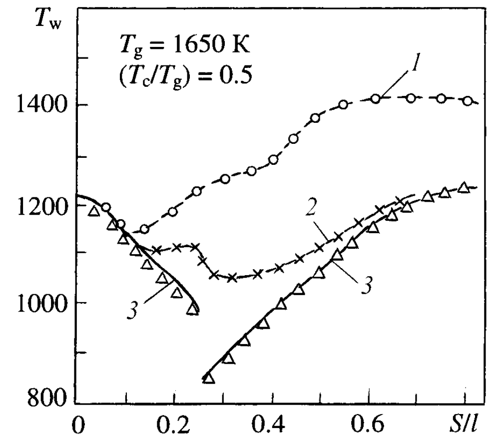


Fig. 4. Temperature distribution over the profile of the blade of a gas turbine in screen cooling (only one belt of the screen is open).

Fig. 5. Change in the temperature of the surface of the blade of a gas turbine with and without allowance for screen cooling: 1) internal (convective) cooling; 2) without allowance for the heat transfer in the channels; 3) internal plus screen cooling with allowance for the heat transfer of the cooler in the channels. T_w, K.

The essence of a thermal screen is that, for example, air is blown through a number of holes (slots) along the heated surface. As a result of turbulent mixing with the incoming hot flow the blown jet becomes a sheet that displaces the external hot flow from the wall.

The main advantage of the method of "film cooling" is its exceptional simplicity and reliability, while its main disadvantage is that it does not provide a uniform temperature of the wall along its length. The wall immediately behind the slot is cooled strongly; however, the temperature increases sharply with distance from it.

It has been noted that as the cooler is blown along the normal to the surface of the product, turbulization of the boundary layer and, consequently, intensification of the convective heat flux occur immediately behind the slot even at Reynolds numbers larger than 1000. Behind the tangential slot, even in the absence of blowing, turbulization occurs when the main flow breaks away from the slot step.

Figure 4 shows the scheme of the working blade of a gas turbine with temperature marks plotted on it, and Fig. 5 shows the change in the temperature distribution in the vicinity of a slot with allowance for the outflow of the cooler. Calculations of such heat present great difficulties because of the multidimensionality of the problem of heat conduction and the conjugate formulation.

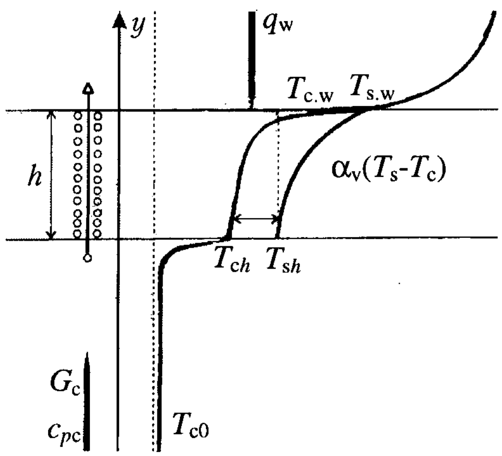
Not only does the cooler flowing out of the slots reconstruct the hydrodynamic pattern of the boundary layer, but it also creates a large temperature gradient in the structure of the blade itself. The high intensity of removal of heat in narrow and short channels leads to a "trough" in the wall temperature as compared to the case of convective (closed) cooling. The high degree of temperature inhomogeneity in turn causes a concentration of thermal stresses in the body of the blade, which leads to a decrease in service life or in the time of trouble-free operation.

The above-indicated contradictions can be resolved in two ways:

(1) through the creation of several belts of screens, in each of which the larger the number of slots, the lower the flow rate of the cooler G_c;

(2) by increasing the coefficient of internal heat exchange during the filtration of the cooler inside the shell of the blade.

Both of these ways logically lead to a system of penetrating cooling, in which finely porous materials are used.



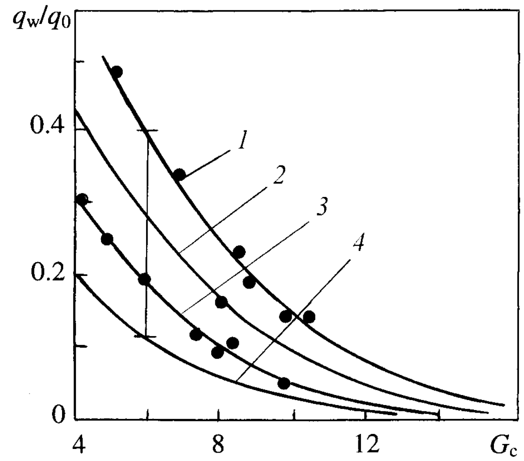


Fig. 6. Scheme of the temperature distribution and the directions of mass and heat fluxes in the system of penetrating cooling.

Fig. 7. Influence of the surface porosity Π_w on the effect of blowing: 1) $\Pi_w = 0.03$; 2) 0.12; 3) 0.36; 4) 0.45.

The mechanism of porous cooling involves two processes:

(1) internal heat exchange, during which the gas takes up the heat from the porous matrix during the filtration through the penetrable shell (Fig. 6);

(2) external heat exchange where owing to the diffusion in the boundary layer, the cooler dilutes and displaces the high-temperature incoming flow from the porous wall.

Porous cooling is among the most intense means of regulating heat exchange, which is explained by the highly developed contact (wetted) surface inside the porous matrix and the great blowing effect, i.e., the effect of decrease in the heat flux during the diffusion of the cooler in the boundary layer.

However, the blowing effect is very sensitive to the size of the holes through which the cooler flows out of the porous matrix. Figure 7 shows the experimental data of V. E. Abaltusov and colleagues on the influence of the surface porosity Π_w (i.e., the part of the surface occupied by holes) on the degree of decrease in the heat flux. The smaller the number of holes per unit area of the surface, the higher (for the same mass flow rate of the cooler G_c) the rate of outflow of the cooler into the boundary layer and the greater the probability that the blown gas jet will "break through" the boundary layer without producing substantial changes in the heat transfer in it.

It has been proved that the size of the holes in a porous matrix must be smaller than the thickness of the boundary layer. As applied to the blades of the high-temperature bladings of a gas turbine, this means that the diameter of the channels in the porous matrix must be of the order of 20–30 μm.

Of all the variants of realization of penetrating cooling, a high coefficient of internal heat exchange α_v can be attained only within the framework of finely porous shells, which guarantees the similarity of the temperature profiles $T_s(y)$ and $T_c(y)$ (see Fig. 6).

The complete system of equations describing the one-dimensional problem of the thermal state of a porous matrix through which the gas cooler is filtered has the following form:

$$\lambda_s (1 - \Pi) \frac{d^2 T_s}{dy^2} = \alpha_v (T_s - T_c) \,, \quad - \lambda_c \Pi \frac{d^2 T_c}{dy^2} + c_{pc} G_c \frac{dT_c}{dy} = \alpha_v (T_s - T_c) \,. \tag{1}$$

The coordinate system and the directions of the mass and heat fluxes are shown in Fig. 6. The thermophysical properties of the matrix (λ_s) and the cooler (λ_c, c_{pc}) are considered to be independent of the temperature.

A method of solution of the system of equations (1) with corresponding boundary conditions is described in [4, 5]. Clearly, the calculation results largely depend on the laws of internal heat exchange. It is important to have clear information on how the coefficient of internal heat exchange α_v depends on the characteristic scale d_{eq} and the porosity Π of the penetrable matrix as well as on the flow rate of the cooler G_c and the ratio of the thermal-conductivity coefficients (λ_c/λ_s).

The main difficulty of experimental determination of the heat-exchange coefficient α_v in porous structures is measuring the difference of the temperatures of the filtered cooler at the inlet (T_{ch}) and the outlet ($T_{s.w}$) of the porous matrix. Neglect of the heat exchange at the inlet $T_{ch} \approx T_{c0}$, accepted in the majority of works, is justified only for small differences between the temperature of the cooler in the receiver T_{c0} and the temperature of the inner surface of the porous wall T_{sh} [6].

Direct measurement of the cooler temperature in the pores is difficult because of the small size of the pores and the smallness of the thermal-conductivity coefficients of both the matrix itself and, especially, the gaseous cooler. This creates steep temperature gradients for which the size of the sensitive element has a catastrophic influence on the measurement error. This problem becomes even more complex when the flow rate of the cooler G_c or the Reynolds number $\mathrm{Re}_d = (G_c d_{eq})/\eta$ increases, since the wire (electrode) of the thermocouple "averages" several hundreds of degrees of the temperature profile.

In the case of measuring the temperature of the porous wall itself, apart from the errors which are typical of thermocouples and are associated with the removal of heat through the junction by the wires, there arise errors caused by clogging of the pores with the junction itself and by the intense blowing of the wires.

According to numerous literature publications, as the characteristic linear dimension d_{eq}, one most commonly uses the diameter of structure-forming particles or fibers d_p or different modifications of these dimensions which take into account the porosity Π. However, practically in all the applications, the diameter of structure-forming elements d_p experiences large changes and ranges from d_1 to d_2 during the technological preparation of porous matrices. The porosity Π also changes as strongly as this.

Consequently, a control system or an objective method for estimating the characteristic scale d_{eq} of porous structures is required. In our opinion, only the measurement of the hydraulic resistance Δp, namely, its dependence on the flow rate of the filtered gas G_c, can provide such a method.

For a macroscale description of the hydraulic resistance, wide use is made of the modified Darcy equation

$$\frac{\Delta p}{h} = A\eta V + B\rho V^2 , \tag{2}$$

where A and B are the viscous and the inertial coefficients of resistance of the porous matrix, η and ρ are the viscosity and density of the filtered liquid, and V is the filtration rate.

It has been proposed in [6] that the ratio between the inertial and viscous coefficients be taken as the characteristic scale:

$$B/A = d_{eq} .$$

In later investigations [8], in which a larger array of experimental data were analyzed, it has been proposed that the ratio of the coefficients B/A be abandoned in favor of the square root of the viscous coefficient in the Darcy law:

$$d_{eq} = \frac{12}{\sqrt{A}} ,\ \mathrm{m} , \tag{3}$$

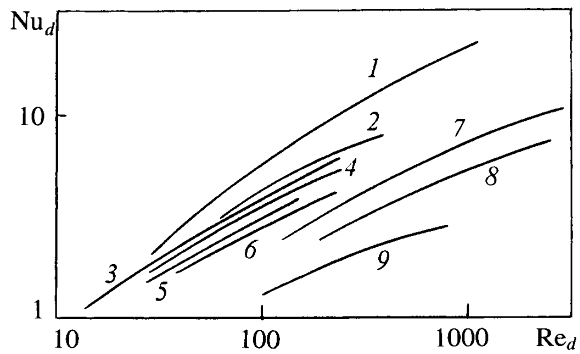


Fig. 8. Comparison of the experimental data on the intensity of convective heat transfer in porous nozzles (1–6) and smooth microchannels (7–9). The parameters are given in Table 1.

TABLE 1

Number of curve	d_{eq} Pr/L	k_λ	Material of particles	Working body
1	0.08	1	Hollow body	Air
2	0.034	1	Glass	Water
3	0.02	2	Bronze	"
4	0.02	1.5	Stainless steel	"
5	0.01	2	Bronze	"
6	0.02	1	Glass	"
7	0.048	–	"	"
8	0.034	–	"	"
9	0.028	–	"	"

and it has been shown that experimental data on the heat exchange in porous matrices can directly be compared to analogous data for smooth microchannels on condition that the hydraulic diameter of the microchannel coincides with the linear scale (3) of the porous structure.

Figure 8 shows a summary of experimental data on heat exchange from [8]. Two facts have engaged our attention:

(1) the similarity of the dependences of the Nusselt number on the Reynolds number for all the cases of flow (in a porous matrix and in a microchannel);

(2) the large difference of the Nusselt number from Nu ≈ 4 corresponding to the so-called stabilized regime of laminar flow in a smooth tube for numbers $\mathrm{Re}_d < 600$.

Having taken the quantity d_{eq} as the linear scale of a porous structure according to formula (3), we were able to obtain a universal form of the dependence of the intensity of internal heat exchange α_v or the Nusselt number Nu_d on the Reynolds number:

$$\overline{\mathrm{Nu}} = \mathrm{Nu}_\infty \left(1 + 2\frac{L_\mathrm{T}}{h}\right)^{0.4} K_\mathrm{m} K_\lambda\,, \quad \mathrm{Nu}_\infty = 4 - 3.5\exp\left(-\frac{\mathrm{Re}}{300}\right), \quad K_\mathrm{m} = 2\,, \quad K_\lambda = \left(\frac{\lambda_\mathrm{s}}{\lambda_\mathrm{c}}\right)^{0.07}. \tag{4}$$

The existence of the universal formula (4) for the intensity of internal heat exchange α_v makes it possible to bring the solution of the system of equations (3) to a concrete result and optimize the thermal regime of a porous matrix for all the diagnostic variables (determining parameters), first of all, for the thickness of the shell h and the ratio of the thickness h to the characteristic scale d_{eq}.

The temperature profiles $T_s(y)$ and $T_c(y)$ themselves are of little use for comparison and analysis. It is important to find a criterion making it possible to estimate the efficiency of porous cooling as a system of

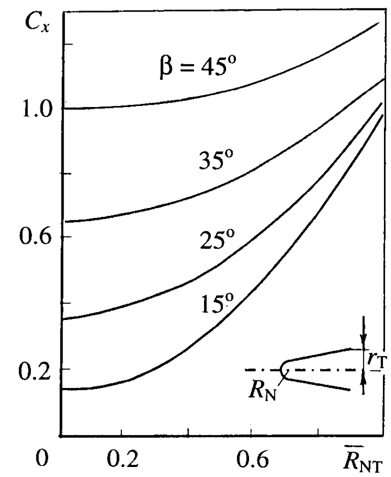


Fig. 9. Dependence of the coefficient of aerodynamic drag C_x of a blunt cone on the ratio of the radius of bluntness R_N to the radius of the mid-section of the cone r_T.

thermal protection. As such, we have chosen the ratio of the heat transferred from the porous matrix to the cooler in the process of its filtration through the wall to the heat flux q_w delivered from the outer surface of the porous shell:

$$\Psi = \int_0^h \alpha_v (T_s - T_c)\, dy / q_w \, .$$

A large set of parametric calculations made it possible to establish that the optimum thickness of the penetrable shell h_{opt} must satisfy the inequality

$$h_{opt} \frac{G_c c_{pc}}{\lambda_s} \frac{\Pi}{1 - \Pi} > 3 \, ;$$

the ratio of the characteristic diameter of the pore channels d_{eq} to the thickness of the porous wall must be determined by another inequality:

$$h_{opt} / d_{eq} > 10 \, .$$

Evidently, one should also take into account the restrictions imposed on the diameter of the porous channels by the external problem of heat exchange (which have already been discussed in analysis of the effect of blowing through a perforated wall).

Radiative-Conductive Method of Protection of Leading Edges of Hypersonic Aircraft. The results of theoretical and experimental investigations show that the influence of the degree of bluntness of the nose on the flow around the entire body can be very substantial. It enhances further with increase in the Mach number of the incoming flow. In the hypersonic range of flying speeds, the blunt nose changes the character of the flow in the disturbed region with a length of tens and hundreds of diameters of bluntness; the thinner the body (or the smaller the cone angle β_{cone}), the more extended this region (Fig. 9).

At a zero angle of attack the drag coefficient C_x at the blunt cone is higher than that at the pointed cone:

$$C_x = 2 \sin^2 \beta_{cone} + \overline{R}_{NT}^2 \cos^4 \beta_{cone} \, ,$$

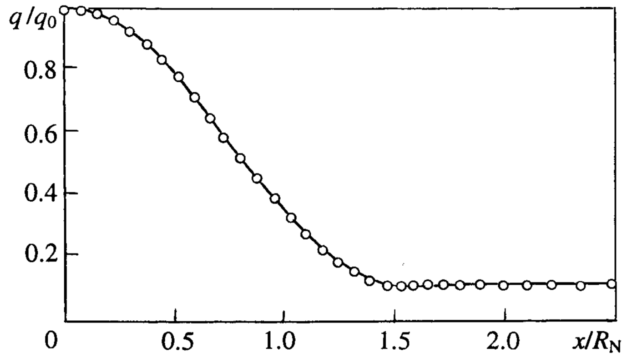


Fig. 10. Distribution of the heat flux over the surface of a blunt cone in hypersonic flight.

where $\overline{R}_{NT}$ is the ratio of the radius of bluntness R_N to the radius of the midsection of the cone r_T.

The influence of the bluntness on the resistance can be decreased to a minimum only in the case where $\overline{R}_{NT} < 0.05$, i.e., the radius of bluntness accounts for no more than several percent of the maximum diameter of the body in flow.

In reality, all bodies of revolution are blunt to a certain degree, since it is technologically impossible to make an ideally pointed nose. The bluntness increases under random mechanical actions; moreover, the nose can become blunt as a result of fusion in the case where the body moves with a very high velocity in a dense gas medium. Practically all recoverable spacecraft have a blunt shape differing strongly from the geometry of supersonic airplanes.

A practically important aerodynamic property of blunt bodies is that, all other things being equal, they are heated and collapse in an incoming flow to a lesser extent than pointed bodies.

In front of a blunt body in a supersonic flow there arises a back shock wave, behind which the velocity of the flow decreases to a subsonic one and the total head also decreases significantly. Because of the decrease in the local Reynolds number, the laminar regime of flow gives way to a turbulent regime much farther downstream. All this contributes to the reduction in the local heat fluxes to the surface of the body.

Hence, the choice of the radius of bluntness is a problem far short of ordinary and requires simultaneous consideration of both the aerodynamics of flow around a body and the processes of heat transfer in the boundary layer.

The essence of a new method of thermal protection for nose cones and leading edges is that it makes it possible to decrease abruptly the radius of bluntness R_N and simultaneously decrease the integral heat flux over the entire surface of a sharp edge. In this case, as a result of conductive heat transfer, the heat can be removed from the leading edge through the metallic shell. The heat from the side surface is reemitted to the environment by the laws of thermal radiation, i.e., in proportion to the shell temperature T_{wx} raised to the fourth power. In this case, it is taken into account that the convective heat fluxes at the bluntness differ from the fluxes at the side surface by almost an order of magnitude (Fig. 10).

The change in the density of the heat flux along the generatrix of the bluntness surface is described by the relation

$$q(\theta)/q_0 = 0.55 + 0.45 \cos(2\theta) ,$$

where q_0 is the density of the heat flux at the front critical point ($\theta = 0$):

$$q_0 = 0.44 \cdot 10^{-4} \sqrt{\frac{p_s}{R_N}}\, V_\infty^2 = 0.44 \cdot 10^{-4} \sqrt{\frac{\rho_\infty}{R_N}}\, V_\infty^3 , \quad \mathrm{W/m^2} .$$

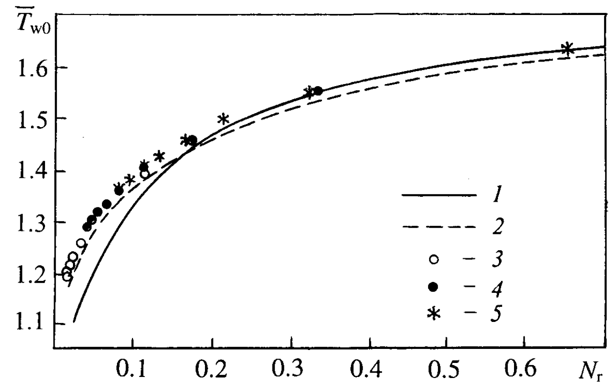


Fig. 11. Ratio of the temperature at the critical point T_{w0} and on the side surface of a blunt cone T_{wx} as a function of the radiative-conductive parameter N_r. One-dimensional model: 1) numerical solution and 2) approximation; two-dimensional model: 3) R_N = 1, 4) 2, and 5) 3 cm.

The density of the incoming flow decreases with height H as

$$\rho_\infty = \rho_0 \exp(-\beta H), \quad \text{kg/m}^3,$$

$\rho_0 \approx 1$ kg/m^3 and β = (7000 m)$^{-1}$.

Assuming that the side surface of a hypersonic aircraft is cooled due to thermal radiation and the leakage of heat into the aircraft is negligibly small, we obtain the relation for estimating the equilibrium temperature of the surface T_{wx}:

$$T_{wx} = \sqrt[4]{q_0/\varepsilon_w\sigma},$$

where ε_w is the integral hemispherical radiating power (emittance) of the outer surface of the aircraft.

It is easy to verify that the equilibrium temperature at any point of this surface T_{wx} depends on the speed and altitude of the flight (V_∞ and H), the emittance ε_w, and the radius of bluntness R_N as

$$T_{wx} \sim \frac{V_\infty^{3/4}}{R_N^{1/8}\varepsilon_w^{1/4}} \exp\left(-\frac{H}{56\,000}\right).$$

If the bluntness is connected to the side surface of the body in flow by a heat-conducting shell of thickness δ, the temperature at the critical point will be lower due to the leakage of heat along this shell. The diagnostic variable of the radiative-conductive method of removal of heat will be the parameter N:

$$N_r = \frac{\varepsilon_w \sigma T_{wx}^3 R_N^2}{\lambda\delta}.$$

Here λ is the thermal-conductivity coefficient of the material from which the thermal-protection shell is made; T_{wx} is its temperature, which is dependent on the cone angle θ_0. If θ_0 = 5°, then

$$T_{wx} = \frac{3V_\infty^{3/4}}{R_N^{1/8}\varepsilon_w^{1/4}} \exp\left(-\frac{H}{56\,000}\right).$$

Figure 11 shows the relative temperature $\overline{T}_{w0}$ at the front critical point of the bluntness as a function of the radiative-conductive parameter N_r for three different values of the radius R_N. It is seen that all the calculated data obtained by numerical solution of the two-dimensional problem of heat conduction (with variation of the thickness of the shell δ from 1 to 8 mm) fit well the universal dependence $\overline{T}_{w0}(N_r)$ that differs only slightly from the curve obtained in solving the simplest one-dimensional problem. The dashed line denotes the approximating dependence

$$\overline{T}_{w0} = \frac{T_{w0}}{T_{wx}} = 1 + 0.754\,[1 - \exp(-2.1\sqrt{N_r})]\,.$$

The results presented show that with a flying speed of V_∞ = 3000 m/sec at an altitude H = 30 km it is possible to make a nose edge of radius R_N = 1–2 cm; the temperature of this edge will be no higher than 1600–1700 K, which is 40% lower than in the case of a heat-insulated surface.

Conclusions. We have presented some results of investigations conducted at the Institute of High Temperatures of the Russian Academy of Sciences on promising methods of thermal protection. It is shown that the present level of these works makes it possible to reveal and optimize the most important thermophysical and structural parameters of thermal-protection systems, such as the thickness and the equivalent diameter of pore channels in the case of penetrating cooling or the radius of bluntness and the thickness of the shell in the case of radiative-conductive cooling of the leading edges of a hypersonic aircraft.

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NOTATION

A and *B*, coefficient of viscosity and inertial coefficient in the Darcy law; d_{eq}, equivalent diameter of the pore channels; L_T, length of the initial thermal portion; h, thickness of the penetrable wall; H, flight altitude; G_c, flow rate of the cooler; p, pressure; V, velocity; T, temperature; R_N, radius of curvature of the blunt body; q, heat flux; α_v, coefficient of internal heat exchange; ε_w, emittance; θ, angular coordinate; Π, porosity; δ, Stefan–Boltzmann constant; Nu and Re, similarity criteria. Subscripts: 0, initial level; w, outer surface; wx, side surface; ∞, incoming flow; N, bluntness; eq, equivalent; com, compressor; e, effective; g, gaseous; v, volumetric; c, cooler; s, solid; p, particle; opt, optimum; m, mixing; cone, cone; r, radiation.

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