THERMAL PROTECTION OF POWER PLANTS

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Keywords: Heat transfer, thermal protection, porous cooling, block cooling, jet cooling

Contents

Summary

This chapter deals with thermal protection of power plants. In power plants of flying vehicles, for example, in jet engines the heating up of a working body is carried out over the temperature range 2000...5000 K exceeding the one allowable for modern structural materials. In plasma installations the temperature of the body can reach 50000 K and more. In all these cases, it is necessary to provide the thermal protection of the members of the design of power plants that are subjected to the action of a high-temperature gas flow and large heat loads.

1. Thermal Protection Methods

The use of the heat capacity of material, i.e., the ability of material to absorb heat is the most straightforward method for thermal protection of heat-stressed designs of flying vehicles and power plants. Such a method of thermal protection is used at short-time heat loads, for example, in non-cooled solid-fuel rocket engines. If at the initial time moment (at the moment of starting an engine) the walls of the combustion chamber and those of the nozzles of the jet engine undergo heat loads of fixed intensity, then in the unsteady process of its heating (heat conduction) the supplied heat will be spent for heating up the wall material and the temperature will attain its permissible value only after a lapse of certain time (t_0).

The heat load time (engine operation time) is chosen from the conditions, at which the allowable (from strength considerations) values of the surface temperature under unsteady heating up of a design are not exceeded.

Convective cooling of a heat-stressed surface is the most widespread method. In this case, the surface is streamlined by a high-temperature gas flow on one side and is cooled by a liquid or a gas on the other (Figure 1). Convective cooling is widely used for thermal protection of combustion chambers and nozzles of liquid rocket engines, turbine blades and disks of gas-turbine jet engines, optical systems of laser installations. In the case of convective cooling of a flat plate with the thermal conductivity λ and the thickness δ (Figure 1)

$$q_w = \frac{T_{f1} - T_{f2}}{1/\alpha_1 + \delta/\lambda + 1/\alpha_2} = \frac{T_{f1} - T_{w1}}{1/\alpha_1}, \quad (1)$$

where T_{f1}, T_{f2} are the temperatures of the gas flow and coolant; T_{w1}, T_{w2} are the surface temperatures on the outer and inner sides of the plate; α_1 ,α_2 are the heat transfer coefficients on the side of the hot gas flow and coolant, q_w is the heat flux density.

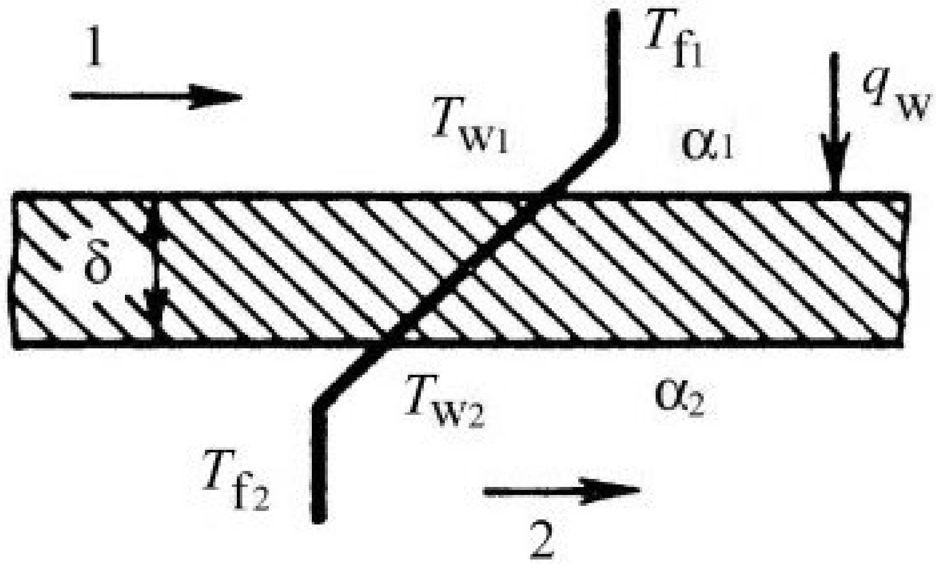

Figure 1: Convective cooling scheme: 1- high-temperature gas flow; 2 –coolant

From this relation it is follows that the efficiency of convective cooling will be determined by the relative temperature

$$\Theta_{w1} = \frac{T_{f1} - T_{w1}}{T_{f1} - T_{f2}} = \frac{1}{1 + \alpha_1 \delta/\lambda + \alpha_1/\alpha_2}. \quad (2)$$

This relation is evident of the fact that the larger the coefficient of heat transfer from the inner surface to the coolant (α_2) and the smaller its temperature (T_{f2}), the less is the outer surface temperature, i.e., the larger is the efficiency of convective cooling. Therefore, to improve the convective cooling efficiency it is advisable to utilize coolants with a large value of heat capacity, which affords their small heating, and to adopt different methods for enhancement of the process of heat exchange between the inner surface and the coolant, which provides a basis for increasing the heat transfer coefficient α_2. To enhance the heat transfer process on the inner surfaces, the latter is equipped with different-type intensifiers: fins located longitudinally or normal to the main coolant flow, different-type flow swirlers in the form of separated members.

Figure 2 shows the schemes of heat transfer enhancement on the cooling blades of gas turbines by both longitudinal fins and cylindrical intensifiers. The jet cooling is the most efficient method for convective cooling of a heat-stressed surface. In this case, the coolant in the form of a system of jets is supplied normal to the cooled surface (Figure 3). The effect of increasing the heat transfer coefficient (α_2) is achieved from decreasing the boundary layer thickness due to an elevated value of the velocity gradient in the region where the jet flows past a surface and due to the high turbulence intensity.

The intensity of heat transfer involving the interaction of jets with surfaces is approximately by an order of magnitude higher as against the one using other methods for its enhancement.

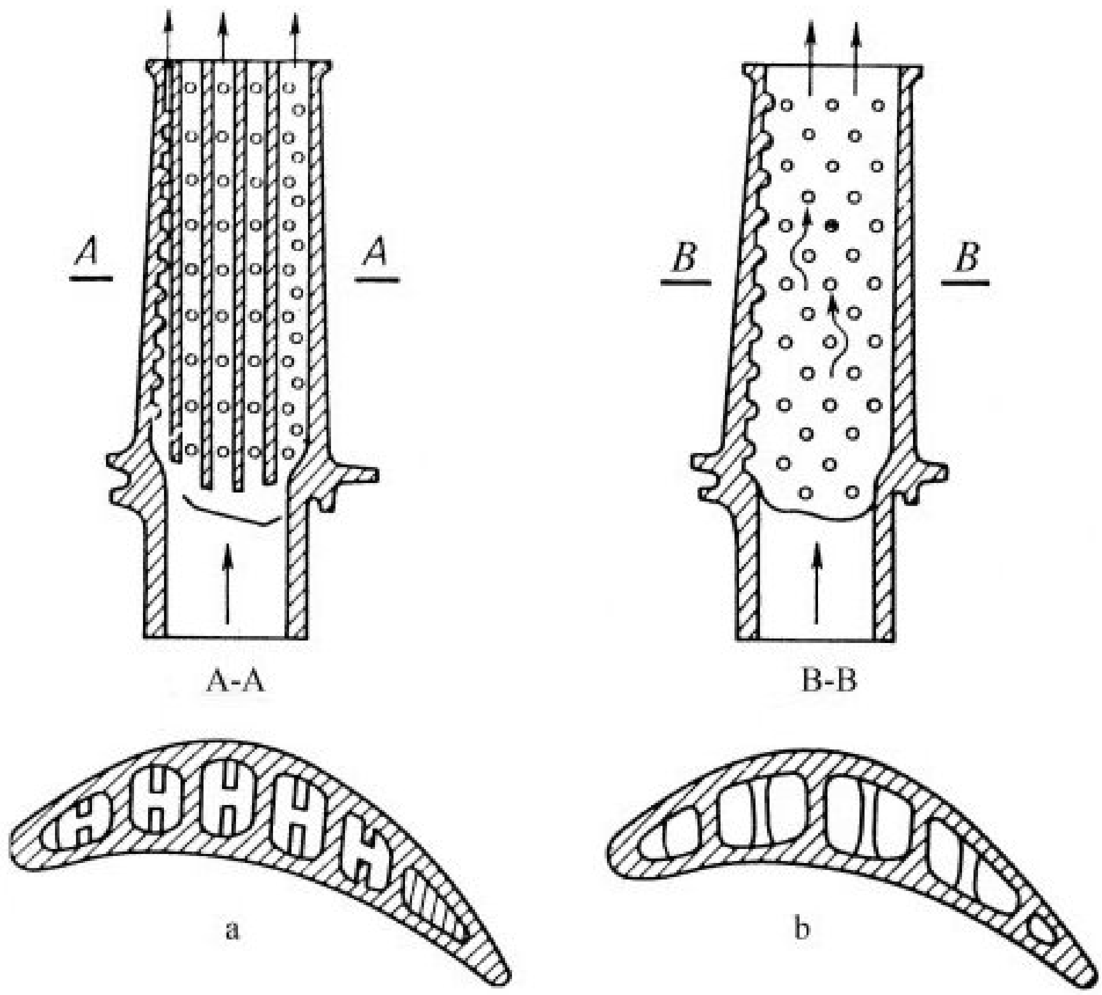

Figure 2: Methods of heat transfer enhancement in the channels of cooled gas turbine blades: a - fins; b – cylindrical intensifiers

The jet cooling system finds a wide use in different branches of technology and, in particular for the cooling of the optical systems of laser installations and the blades of gas turbines. Figure 3b shows the jet cooling scheme of a gas turbine blade. The cooling air enters an inner deflector and then through a system of holes built in it is supplied in the form of jets to a cooled surface.

Such a cooling method enables one to essentially improve the efficiency of thermal protection of a gas turbine blade, especially, over its heat-stressed section, namely, over the inner surface of the leading blade edge where its maximum heat stress is realized.

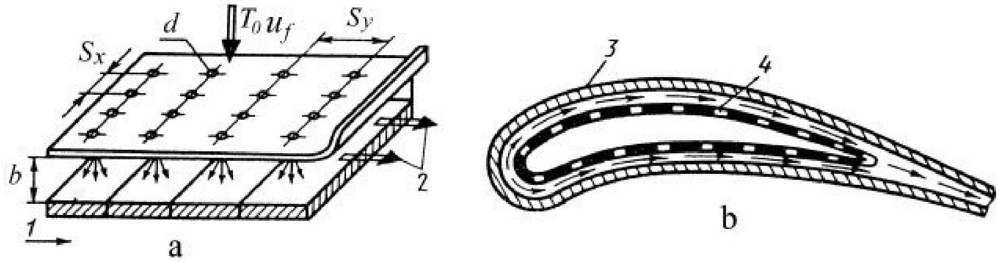

Figure 3: Jet cooling of the surface: a – jet cooling scheme; b – jet cooling of a gas turbine blade: 1 – high-temperature gas flow; 2 – coolant, 3 – outer casing; 4 –deflector

However, the convective cooling of heat-stressed surfaces at high temperatures and large heat fluxes is not an efficient means of thermal protection. Even at comparatively high values of the heat transfer coefficient of coolant $\alpha_2 \rightarrow \infty$ with large heat loads the outer surface temperature can much exceed the acceptable value $T_{w1} \rightarrow T_{f1}$. In these cases, it is necessary to decrease the hot gas flow temperature and to reduce heat fluxes near the surface. To do this, block cooling and porous cooling are used.

Surface cooling is arranged through the coolant supply to the outer surface (Figure 4). The coolant in this case can be supplied by a great variety of procedures (through a flat slit, through a system of slits or a system of holes, through a porous insert, etc.). When a gas coolant is supplied through a flat slit, near a surface to be protected there arises a wall coolant jet, whose temperature is smaller than that of the high-temperature gas flow. As the distance from the injection place increases, the cold gas jet is progressively mixed with the hot gas, thus causing the surface temperature to increase. Therefore, depending on the specific conditions it is necessary to make sequentially several holes along the surface. Block cooling has found a widespread application for thermal protection of combustion chambers and nozzles of jet engines, blades of high-temperature gas turbines.

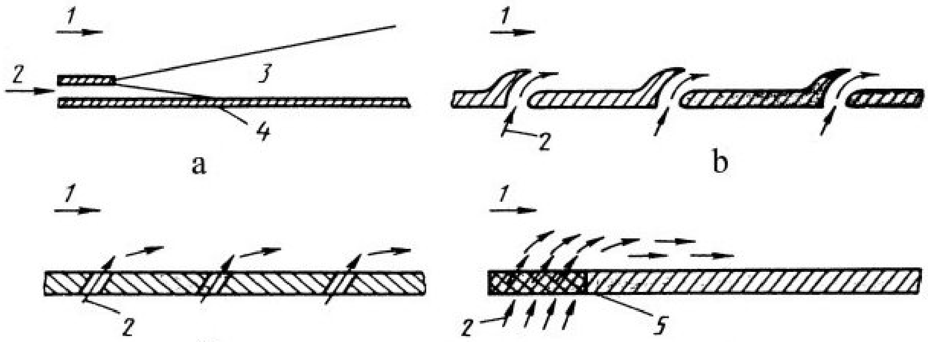

Figure 4: Schemes of coolant supply at block cooling of the surface: a – flat slit; b – system of slits; c – system of holes; d – porous insert; 1 - high-temperature gas flow; 2 – coolant; 3 – mixing region; 4 – protected surface; 5 – porous insert

Figure 5 shows the cooling scheme of the cylindrical combustion chamber of the air-jet engine. For thermal protection of the wall of the combustion chamber convective cooling is arranged over its outer surface and wall cooling is realized by the cooling air supply through the cylindrical slot over its inner surface (on the side of the hot gas flow). Block cooling of gas turbine blades is as a rule organized by supplying the cooling air through a system of holes (Figure 6).

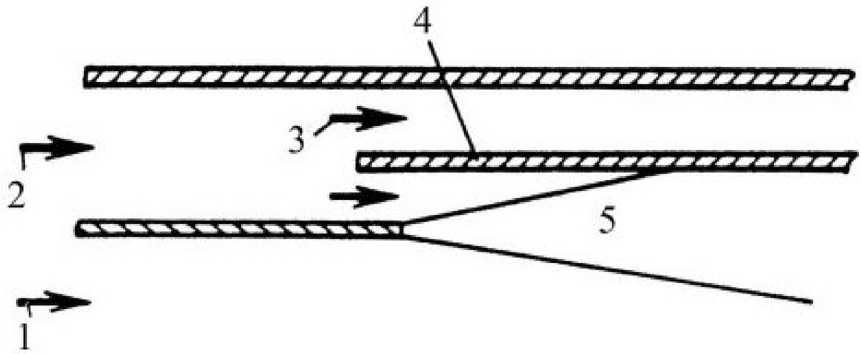

Figure 5: Scheme of combined cooling of the flame tube wall of the combustion chamber; 1 – high-temperature gas flow; 2 – coolant; 3 – convective cooling; 4 –flame tube wall of the combustion chamber

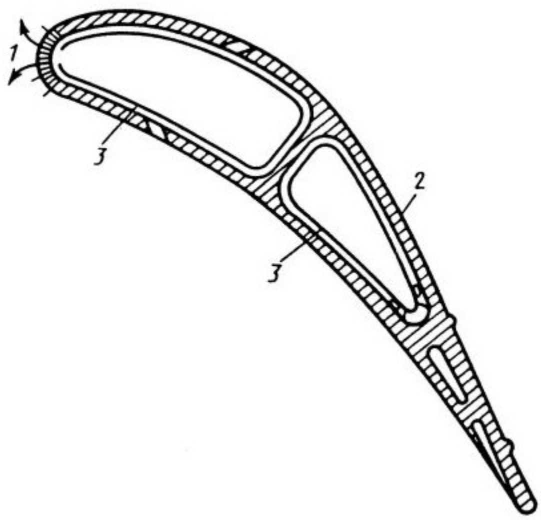

Figure 6: Scheme of convective-film cooling of the gas turbine blade: 1 – hole for coolant blowing-out; 2 – outer casing of the blade; 3 – deflectors

At block cooling of rocket engine nozzles a coolant is supplied in the same manner. In this case, as a coolant use is made of the liquid – fuel which is supplied through a system of holes in the region of the nozzle throat to the outer block surface, thus forming a protective liquid film. The use of the liquid as the coolant improves the thermal protection efficiency since in this case, the heat supplied to the coolant is spent not only for its heating but also for its evaporation. Block cooling realized through the liquid blowing-out to a surface to be protected is sometimes called film cooling.

Porous cooling assumes the use of porous (permeable) materials. Porous materials have pores, i.e., voids that form capillary channels. Porous materials are cooled by the liquid or gas being pumped through the capillaries. In this case, the high efficiency of the heat transfer process is attained due to an essential increase in the surface of contact of a porous skeleton with the coolant. The porous material is in essence impregnated with the coolant. Therefore, the application of porous materials for thermal protection enables one to much improve its efficiency. The filling of the cooling channel (Figure 7) with a porous material allows one to dramatically enhance the process of heat transfer from the surface to be protected to the coolant. For example, the cooling efficiency of a gas turbine blade can be much augmented, if the cooling channels over its heat-stressed sections are filled with the porous inserts made of the material with a large thermal conductivity (Figure 7b). The porous materials can be applied to arrange the coolant supply to the outer surface to be protected (Figure 7c).The coolant injection into the boundary layer through a porous (permeable) surface affects its structure so that the heat transfer coefficient and, hence, the heat flux from the hot gas flow to the porous surface decrease. Thus, when the coolant is injected through the porous surface the increase in the thermal protection efficiency is due to two factors: first, the enhancement of heat exchange between the porous material and coolant; second, the decrease in the heat flux from the hot gas to the outer surface as a result of the action of the coolant injection upon the boundary layer structure. Porous cooling involving the blowing-out of the coolant into the boundary layer is used for thermal protection of the combustion chambers and nozzles of the rocket engine over its most heat-stressed sections and can also be adopted as an efficient means for thermal protection of gas turbine blades. In this case, the cooling air is supplied to the inner blade cavity and is injected through the porous wall (Fig. 7b).

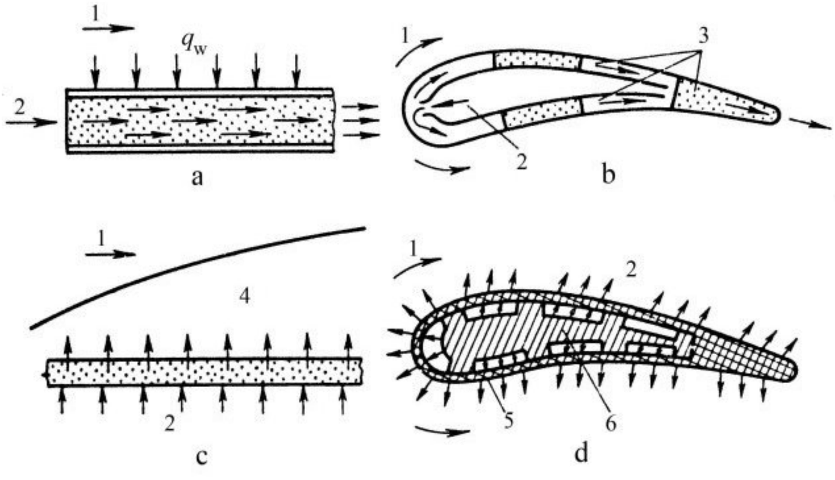

Figure 7: Schemes of porous cooling of protected surfaces: a – channel with a porous filler; b – cooled blade of the gas turbine with porous inserts; c –coolant injection into the boundary layer through the porous wall; d – porous cooling of the blade of the gas turbine with coolant blowing-out to its outer surface; 1 – high-temperature gas flow; 2 – coolant; 3 – porous inserts; 4 – boundary layer; 5 – porous wall; 6 – force rod

In aviation and rocket-space engineering heat-protective coatings that are applied over the outer surface (Figure 8) are widely used for arranging thermal protection. By convention such coatings are divided into two classes: indestructible (multiple use) and destructible (one-time use). In the first case, the temperature over the outer surface of a heat-protective coating must be less than the admissible one, at which the coating starts destructing (melting point). These coatings are used for thermal protection of the surfaces of vehicles, combustion chambers of jet engines, gas turbine blades. Heat-protective surfaces of multiple use are made from refractory materials with a low value of thermal conductivity and are not exposed to the chemical action of the hot gas flow. Among these materials are carbides, oxides of refractory materials, for example, ZrO_2, VjC, WC, ZrC, etc. Because of a small value of thermal conductivity a thin layer of refractory material can much decrease the surface temperature of a metallic design acted upon by the high-temperature gas flow.

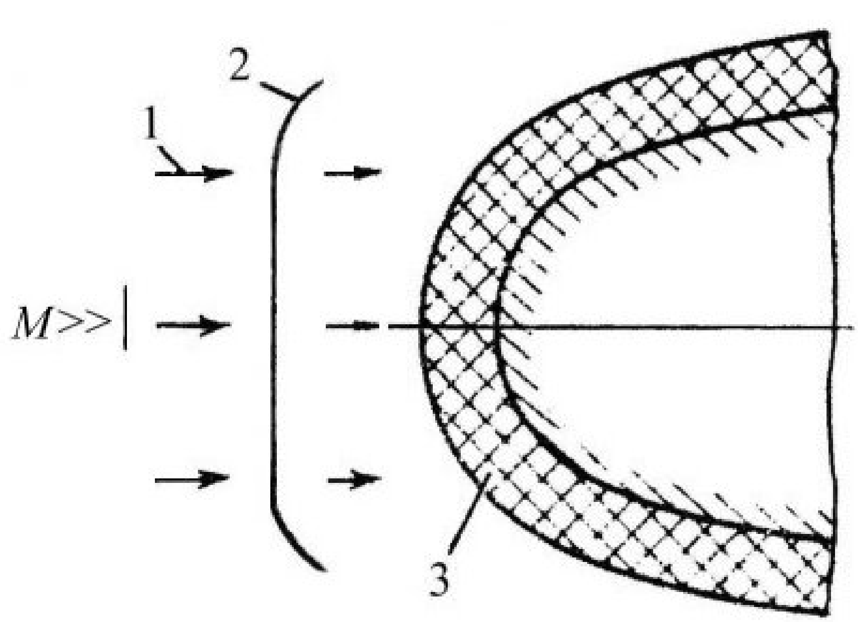

Figure 8: Schematic of the heat-protective coating of the frontal part of the flying vehicle: 1 – high-temperature gas flow; 2 – shock wave; 3 – heat-protective coating

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Biographical Sketch

B.M. Galitseyskiy: Professor of the Department of Aviation-Space Thermal Techniques of Moscow Aviation Institute – MAI. 4. Volokolamskoe shosse, Moscow 125993, Russia.

Date of birth – 13.07.1936 Engineer (Moscow Aviation Institute) – 1958. Doctor of Philosophy (Moscow Aviation Institute) - 1965. Doctor of Technical Sciences (Moscow Aviation Institute) - 1976. Titled Professor (Moscow Aviation Institute) - 1980, Russian Federation State Prize Laureate –1990, MAI Prize Laureate – 1989, 2000, Honored Scientist of Russian Federation – 1998

He is a well-known specialist in the heat-mass transfer and space thermo techniques. He conducted the investigations of heat transfer in oscillating flows, porous systems, jet systems, cooling systems of power plant. He is specialized in effective methods of the heat transfer intensification and highly productive methods of systems cooling calculation.

He is author of more then 250 published works, including the monographs: Heat Transfer in the Power Installations of Spacecrafts (1975), Heat and Hydrodynamic Processes in Oscillating Flows (1977). Heat transfer in aviation engines (1985). Fundamentals of Heat Transfer in Aviation and Rocket-space Technics (1992, in cooperation with other authors). Thermal protection of turbine blade (1996).