MODELING AND IDENTIFICATION OF THE PROCESSES OF HEAT EXCHANGE IN POROUS MATERIALS OF THERMAL PROTECTION OF REUSABLE AEROSPACE SYSTEMS


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The features of aerospace systems as transport facilities for exploration of near-earth space and high-velocity intercontinental transportation have been considered. Problems of complex investigations of the processes of heat exchange in porous materials of thermal protection of prospective reusable aerospace systems have been formulated.

Features of Aerospace Systems as Facilities for Orbital and Intercontinental Transport. Until recently, there have been significant differences in the technique of exploration of the air ocean and outer space. The hardware for firing into space and returning from space was initially expendable, since it was constructed on the basis of modified missiles, whereas vehicles for atmospheric flights — balloons, airplanes, gliders, and dirigibles — were not thought of as other than reusable. In designing transport facilities meant for atmospheric and space flight, the reliability of performing purpose-oriented functions and economic efficiency are equally important. For aircraft moving with a high velocity in the atmosphere, the two properties are directly related to the capacity of the structure for withstanding the action of thermal loads. The degree to which such a capacity is ensured is determined by the required service life, weight-size characteristics, and cost [1–3]. In recent years, the problem of overcoming a "thermal barrier" (this barrier was faced even in creating the first long-range ballistic rockets and supersonic airplanes [4]) has been solved due to switching increasingly more completely from expendable structural elements to reusable elements.

The high reliability of modern expendable launchers such as Soyuz, Molniya, Proton, and Zenit and descent spacecraft of the ballistic type has been attained owing to the development of the production technology and operation of many years. As far as the prospective launchers Angara (Russia), Atlas III and Atlas V (USA), GSLV Mk I-Mk III (India), Great March (CZ-5, China), and others [5] are concerned, it is planned that their high reliability will be ensured by the employment of stages of the same type. The introduction of combined methods of designing and production and testing and operation with a powerfully computer-aided life cycle (CALC technology) is considered to be a strong means.

The ratio of the payload mass to the launching mass attains 0.029 in modern Proton and Zenit launchers for a low near-earth orbit [6]. Theoretically, it can be more than doubled in expendable launchers. A substantial influence on the weight efficiency of launchers is exerted by the low (close to unity) values of the safety factors. The economic efficiency of the hardware for access to space can be spoken of only in terms of comparison by virtue of the uniqueness of launchers and descent spacecraft as expendable transport facilities. The cost of one kilogram of payload in a low near-earth orbit is 1000 to 5500 US dollars [6].

It cannot be said that the creators of launchers reject the idea of multiple employment of the matériel. This idea has already been realized in recoverable stages of the Russian launchers Energiya and Angara. A number of large
European companies are jointly developing reusable launchers within the framework of the Everest program [5]. They are considering the designs of a two-stage fully reusable launcher, a two-stage launcher with a reusable first stage, and a launcher with reusable accelerators.

For aerospace systems — aerospaceplanes, aviation-space rocket complexes, and interorbital transport vehicles with aerodynamic deceleration — the multiplicity of employment of propellant tanks, engines, instruments, and other elements is an integral property of the structure. Aerospace systems can be classified according to the following features: partially reusable/fully reusable systems; single-stage/multistage ones; those with a horizontal/vertical start; orbital/suborbital systems; those with a ballistic/ gliding descent; winged/wingless systems. The advantages of aerospace systems are high load-carrying capacity, velocity, and maneuverability, the possibility of taking-off from airfields and landing on them, and the capacity to deorbit bulk payloads [7, 8].

It was expected that preservation of the matériel of aerospace systems would significantly decrease the cost of delivery of payloads to the earth’s orbit, which served as a strong incentive to create aerospace systems. According to optimistic evaluations, the cost of one kilogram of payload delivered by the Space Shuttle to a low near-earth orbit was expected to be 200 to 1000 US dollars, however, it currently exceeds 10,000 US dollars [6].

In a number of designs, the launching stage of an aerospace system represents a reusable winged hypersonic aircraft with a combined propulsion system changing over to jet, ramjet, or liquid-propellant rocket engines in a certain range of altitudes and velocities. In the future, such aircraft will play an independent role as a transport facility for high-velocity intercontinental cargo and passenger transportations [2]. In the latter case, aircraft will have flight trajectories different from those of the facilities for firing into space. Structural-layout solutions will be constructed on the basis of a fairly long duration of a hypersonic flight in the atmosphere (thousands of seconds) and the necessity of using air oxygen for a propulsion system. For aerodynamics reasons, structures with sharp foreparts of the fuselage, leading edges of the wing and the empennage, and shells of the engines’ air intakes are being proposed, which will result in the appearance of local zones of extremely high thermal loads. The commercial appeal of this class of aircraft depends on the overall dimensions, and they in turn are reflected on the area of surfaces interacting with a high-velocity air flow. Evaluations show that in prospective aircraft, the area lies in the range from several tens to several thousands of square meters.

The problem of thermal protection remains the central problem of reusable launchers and aerospace systems. Classification and Principles of Construction (Aufbau Principles) of Reusable Thermal Protection. Reusable thermal coatings must not irreversibly change their shape, size, and aerodynamic and thermal-protection characteristics from flight to flight because of fusion, ablation, shrinkage, swelling, and other physicochemical and structural transformations. Consequently, relatively heavy ablating polymer composite materials traditionally used in expendable rockets and descent spacecraft are not suitable for reusable thermal coatings. Thermal protection systems without an irreversible disturbance of the thermal stability of the structure can be subdivided into passive, active, and combined systems.

In passive systems that are the most developed, the transfer of heat into the bearing structure is blocked by the low thermal conductivity and high capacity of the material, backward scattering of the internal radiation flux on optical inhomogeneities, shielding, and reradiation by the internal layers and from the surface. Recombination on the surface is suppressed.

The main advantage of passive thermal protection systems is the relative simplicity of their technical implementation and the associated reliability of operation. Materials from SiO$_2$ and Al$_2$O$_3$ fibers, having a porosity of higher than 90% and possessing a high thermal and chemical stability, meet the stringent requirements imposed on their use in such systems. The fibers forming these materials are partially transparent to external radiation sources and to the intrinsic radiation in the visible range and in a part of the infrared range. In such materials, the energy is transferred by heat conduction, radiation, and convection simultaneously with the predominance of radiative-convective heat exchange, whereas the physicochemical transformations in the operating range of temperatures are excluded.

In active systems, use is made of a liquid or gaseous coolant. Supply of the coolant makes it possible to remove excess heat from the rear side or from the volume in pressure filtration through a porous material or through orifices, to take off the excess heat with the use of physicochemical transformations, and to create curtains on the surface heated. Active thermal protection systems are technically more complex, as a rule, than passive systems. The presence of vessels with a coolant, pipelines, pumps or pressure accumulators, and other accessories reduces their