Вісник Тернопільського національного технічного університету
https://doi.org/10.33108/visnyk_tntu
Scientific Journal of the Ternopil National Technical University
2024, № 1 (117) https://doi.org/10.33108/visnyk_tntu2025.01
ISSN 2522-4433. Web: ***visnyk.tntu.edu.ua***

UDC 536.24

JUSTIFICATION OF THE CHOICE OF COMPONENTS OF THE AEROSPACE VEHICLE PROTECTION SYSTEM

Olexandr Iskra; Elina Plisetska; Olexandr Lobunko

Education and Research Institute of Aerospace Technologies, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine

Abstract. *During operation, aerospace vehicles are exposed to various factors specific to the external environment. The design of aerospace vehicles is a complex scientific and technical task, during the solution of which it is necessary to take into account the possible effect of factors on the structural elements and systems of the apparatus, and to include in the concept of the apparatus the means of its protection and ensuring its functioning in the expected conditions of use. This article presents the results of a review of the latest scientific research on improving the understanding of operating conditions and substantiating options for the elements of the aerospace vehicle protection system. Designers increasingly rely on computer modeling to assess the operating conditions of the objects they design and manufacture. Computer models are widely used to create and evaluate the effectiveness of various concepts of monitoring the technical condition and protection of aerospace systems, as well as to overcome significant problems at various stages of designing protection systems. The model of the object under study is discretized into elements with a uniform temperature field. Modeling and analysis were performed using specialized software, which is designed for the formation of a finite element model, performing all necessary calculations, presenting the results for further analysis and improving the properties of research objects.*

Key words: *aerospace vehicles, finite element method, mathematical modeling, thermal protection systems, thermal scheme, heat transfer.*

https://doi.org/10.33108/visnyk_tntu2025.01.042 *Received 30.10.2024*

1. INTRODUCTION

The choice of aerospace vehicle (AV) protection systems is determined by flight conditions and mission tasks. The operating conditions of AVs are influenced by specific environmental factors that shape the design requirements for the vehicle and its systems. During the AV life cycle, besides the operational phase, there are stages of design, launch preparation, and the launch itself, each with distinct factors affecting the shape and design of the AV. However, the phase of space operation involves radically different conditions that require special attention in the design of the AV, its systems, and components.

The advancement of aerospace technology, marked by qualitative differences in each new system architecture, drives the need for enhanced principles and technical solutions for protection systems, as discussed by Aditi Ahuja [1] and Rodmann et al. [23]. A combination of external and internal space environment factors can have a destructive impact on the materials and structural elements of AV systems, making resistance to such factors critical for successful and long-term operation [36]. The design of reusable AVs must consider the influence of operational factors on systems and components, ensuring proper thermal design, micrometeorite protection, and resistance to deep vacuum, radiation, and other specific space conditions.

2. LITERATURE REVIEW

The selection of thermal protection materials is governed by the thermal environment, duration of exposure, and the frequency of application. AV temperature conditions involve external and internal radiative heat exchanges with space, determined by direct solar radiation, Earth's reflected solar radiation, Earth's thermal emission, and AV heat release [7]. Aerothermodynamic heating during atmospheric descent critically influences TPS design.

Asgar et al. [3] analyzed ablative materials and passive TPS using reusable heat-resistant tiles like HRSI, FRCI, and LRSI for reusable aircraft. Ablative materials protect AVs from reentry overheating where high temperatures threaten payload or crew safety [18]. Junjie et al. [11] studied the char layer microstructure in low-density resin-based ablative insulation, modeling residual carbon deposition and predicting thermal conductivity via finite element methods. Riccio et al. [22] detailed optimization procedures for AV ablative heat shields.

Brociek et al. [5] reproduced aerothermal heating profiles for RLV TPS using a one-dimensional heat conduction equation with time-dependent surface heat flow, employing implicit finite difference schemes. Xu et al. [24] proposed an integrated TPS (ITPS) combining thermal insulation and load-bearing capacity, optimizing unit cell topology to minimize thermal conductivity and elastic strain energy while maintaining structural efficiency. Piacquadio et al. [19] investigated integrating TPS into load-bearing structures, incorporating phase-change materials into metal lattices to reduce wall temperatures and enable the use of materials with high specific mechanical properties; additive manufacturing aids localized structural optimization.

Dang [6] studied Woven Thermal Protection Systems (WTPS) like HEEET for interplanetary missions, using thermal and structural modeling to enhance understanding and predictability of WTPS behavior.

Al-Jothery [2] explored AV structural materials for oxidation and rapid heating environments exceeding 1700 °C. Gupta and Ramkumar [8] examined metallic TPS options and treatment methods. Wilken et al. [10] addressed integrating cryogenic insulation and TPS on fuel tanks of winged reusable aerospace objects, emphasizing durability over multiple thermal and mechanical load cycles without major reconstruction.

Ma et al. [15] investigated an active thermal insulation system with a spiral ring cooling plate, phase-change material container, and aerogel mat for high-temperature and pressure environments, demonstrating satisfactory thermal protection.

Ferrone [22] highlighted active magnetic shielding using high-temperature superconducting coils to create intense magnetic fields around spacecraft, effectively deflecting charged particles and reducing astronaut radiation exposure, offering mass savings over passive materials. Naito et al. [16] assessed radiation shielding materials via Monte Carlo simulations, evaluating aluminum, polyethylene, hydrides, complex hydrides, and composites, considering stopping power and fragmentation cross-section. Composites like carbon fiber-reinforced plastic showed promising shielding capabilities, significantly reducing doses compared to aluminum while maintaining high mechanical strength.

Thus, AV protection system design must integrate with other design aspects. Key tasks using computer simulation during the AV life cycle include assessing the feasibility of protection systems, determining parameters and conducting thermal calculations to compare options, calculating required heat exchange areas, selecting radiative-optical surface characteristics, specifying thermal insulation requirements, evaluating temperature fields of structures, determining coolant flows and heat exchanger parameters, defining characteristics of systems consuming working substances, developing design requirements considering other systems, and modeling post-flight thermal state to assess reuse potential.

Thermal design necessitates identifying the most heat-stressed AV areas, assessing the need for special thermal protection, and selecting appropriate materials with determined thicknesses, despite limited information about thermal loads on specific AV sections.

3. MATERIALS AND METHODS

3.1. Thermal models and schemes

Thermal modeling of a 3D object provides a comprehensive assessment of thermal interactions, to identify the main parameters characterizing such interactions, to check the influence of these parameters on the temperatures of certain elements, and to obtain dependencies that allow predicting possible temperature fields $\boldsymbol{T}(F,\ \tau)$ at effects of external and internal factors $\boldsymbol{F}$ during the flight time $\boldsymbol{\tau}$ [14]. At the initial stage, a thermal diagram representing key nodes is formed, AV elements with an indication of all significant thermal connections, as well as external and internal thermal effects (Figure 1).

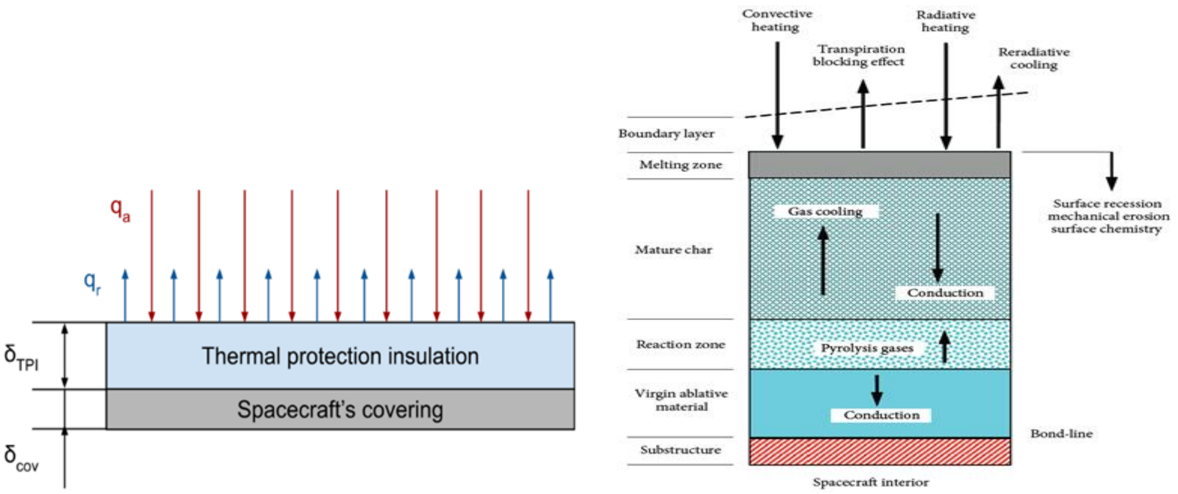


Figure 1. The explanation of the heating of the object with an external protection system (a), schematic [4] of the ablation phenomena (b)

Ablation combines material removal and thermal protection under external heat flow. Heating pyrolyzes the outer layer into a charred zone; escaping volatile gases provide cooling and reduce material thickness, as shown in Figure 1(b) with layers – melting zone, mature char, reaction zone, virgin material – and heat transfer processes like conduction, gas cooling, and radiative cooling. Thermal and mechanical effects during ablation lead to surface recession and potential erosion, critical for long-duration space missions.

Based on the thermal scheme, a calculation scheme was developed to describe thermal interactions among structural elements and assumptions for mathematical heat exchange analysis. Using the finite element method, the object was discretized into nodes with uniform temperature fields. Thermal interactions among nodes and with the environment are described by elementary heat balance equations from the thermal scheme. This model represents selected nodes, showing significant thermal connections and external and internal thermal effects, visually depicted in a thermal diagram. The heat balance equation of nodes is presented as [12, 13, 14]:

$$(cm)_i \cdot \frac{dT_i}{d\tau} = q_i(\tau) \cdot S_i + \sum_{j=1, j\neq i}^{N} k_{i,j}\left(T_j - T_i\right) + \sum_{j=1}^{N} a_{i,j} \cdot \sigma T_j^4 + Q_i \,, i = 1,2..N \qquad (1)$$

Designing AV protection systems requires detailed thermal analysis using mathematical models of varying detail. Early stages employ «first level» models with minimal elements and thermal connections to explore options and justify thermal characteristics, allowing independent thermal calculations of components. Modern software solves nonlinear, non-stationary spatial problems by specifying boundary conditions, altering object geometry, determining temperature distribution, and accounting for contact effects between elements and environments.

During flight, the thermal state of AV cladding is defined by gas flow interactions with protection system surfaces. Heat transfer from the high-speed gas medium to the protection system (cladding walls) occurs mainly via convective heat exchange, depending directly on flow characteristics, velocity distribution, and boundary layer flow regime. Heat conduction equations calculate heterogeneous thermal states of solids; generally, the non-stationary thermal conductivity equation has the form:

$$\frac{\partial T}{\partial \tau} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{w}{c_p \rho} \qquad (2)$$

Equation (2) assumes constant thermophysical characteristics without considering different temperature fields.

Equation (1) has multiple solutions and reflects heat transfer in solids. In order to obtain a calculation that will characterize a specific process and contain a mathematical description of this process, it is necessary to use additional conditions in the main equation, which will include geometric conditions (body shape and dimensions), physical conditions (properties of the body and environment) and boundary conditions (initial and boundary). Thermal state studies use boundary conditions of the first, second, third, fourth order, etc. As a rule, the thermal interaction between the surface and the environment during analytical studies of heat transfer in solid bodies washed by a flow of gases is described by boundary conditions of the third kind:

$$-\lambda \frac{\partial T}{\partial n} = \alpha(T(x_n, y_n\, z_n, t) - T_C) \qquad (3)$$

Boundary conditions of the third kind provide for setting the intensity of heat supply (removal) from the body surface, which most accurately reflect convective heat exchange.

3.2. Evaluation of protection systems

Design-theoretical-experimental evaluation of AV thermal protection systems ensures flight safety and efficiency by testing materials under simulated entry conditions.

A re-entry simulation chamber examines thermal and mechanical loads using gas dosing to simulate atmospheric pressure and induction heating – conductive materials directly, insulators via susceptors or tubes. A servo-hydraulic testing machine applies loads with specified profiles, measuring deformation via laser speckle systems or strain gauges.

Used for thermal shock testing, thermal and gas cycling, thermomechanical testing, sintering, or hot pressing, the device achieves vacuums better than 10^{-5} mbar, heating at 20 K/min, cooling at 50 K/min, isothermal holds at 1,800 °C, total experiment times up to 3 hours, with parameters monitored by advanced software.

Other tests [4], like infrared evaluations, assess HTPS thermal properties concerning differential thermal expansion coefficients. Also vibration resistance is critical. Barcena et al. [4] tested 4 mm thick ablation material with two adhesives, using accelerometers to measure response per CTA protocol and ECSS-E-ST-10-03-C standard, including oscillation and random vibration along all axes. Integrated thermocouples ensure accurate temperature measurement.

Assessing thermal protection involves determining maximum thermal power and load to optimize protection thickness and minimize mass loss ($\Delta m(\tau) \rightarrow min$). Ground tests, including plasma arc and radiant heater tests, establish temperature limits and assess material degradation.

4. RESULTS AND DISCUSSION

To study the aerodynamic heating of the AV surface via finite element analysis, the authors developed a computer model of the prototype, incorporating known characteristics of modern reusable AVs (Table 1). Noting the tendency among analogues to use relatively small «spaceplane»-type AVs for unmanned cargo and vehicles with detachable descent capsules for manned flights (the remainder being disposable or reusable, returning separately), a «spaceplane»-type AV model was selected for this study.

Table 1

Reusable AV

Name	Type and purpose	Status, year of 1st launch	Characteristics
Space Shuttle	Cosmoplane. Manned orbital flights	Closed, 1981	Length 37.24 m, wingspan 23.8 m, height 17.25 m, take-off weight 110,000 kg
Boeing X-37	Cosmoplane. Unmanned missions, exact destination not disclosed	Actual, 2010	Length 8.9 m, wingspan 4.5 m, height 2.9 m, take-off weight 4989 kg
Orion	Launching spacecraft. Piloted studies in low Earth orbit	Actual, 2014	Height 3.3 m, diameter 5.03 m, starting mass 33446 kg
SpaceX Dragon 2	Spacecraft with a descent capsule. Flights to the International Space Station (manned, unmanned)	Actual, 2015	Height 8.1 m, diameter 4 m, starting weight 12519 kg
Dream Chaser	Cosmoplane. Flights to the International Space Station (manned, unmanned)	In development, 2024	Length 9 m, wingspan 7 m, height 2.9 m, starting weight 11340 kg

The problem of thermal conductivity is solved by the finite element method using modern software and hardware complexes. In this study, a methodology was developed and implemented, which is presented in Figure 2.

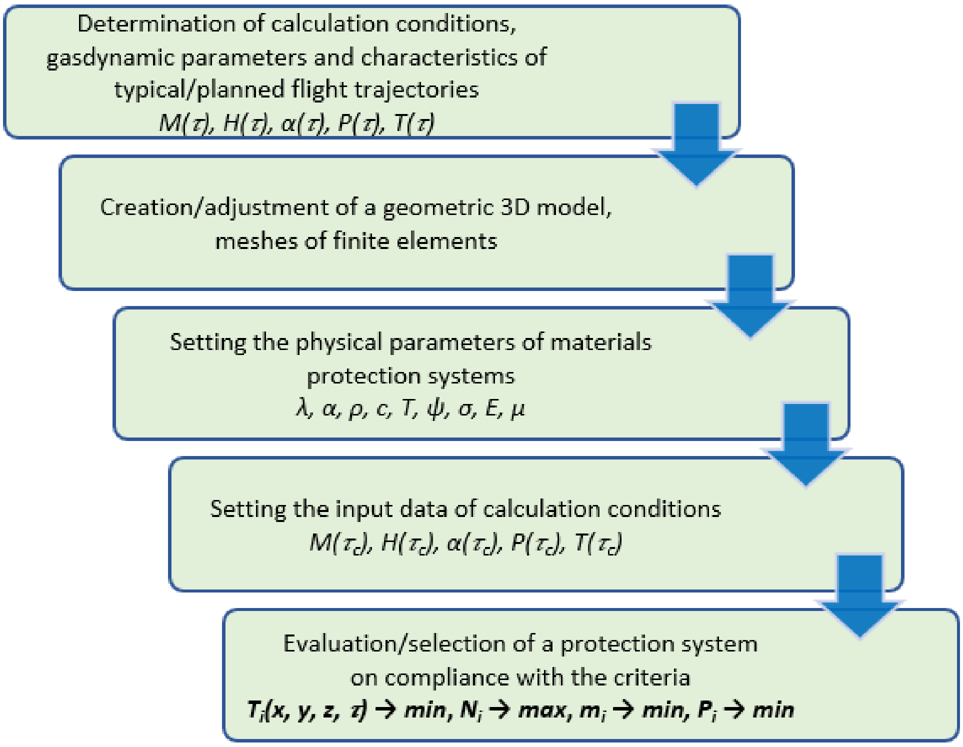


Figure 2. Generalized scheme of justification for choosing a thermal protection system

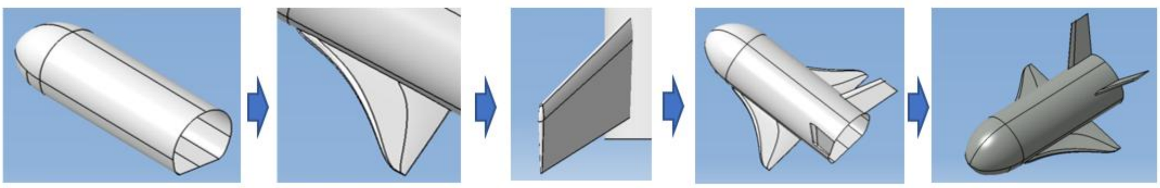
A solid-state model displaying the main geometric dimensions, shapes, and elements of the AV was constructed using the CATIA software environment (Dassault Systèmes), adopting the following dimensions: length 11.6 m, wingspan 9.4 m, fuselage height 3 m, fuselage width 3.8 m, wingspan 6.5 m, height including feathers 4.25 m. The main stages of creating the solid model are:

1. Creation of the fuselage cross-section and nose rounding outlines, according to which the fuselage surface was built (Figure 3-a).

2. Creation of the wing console outline and its profile (an approximately symmetric profile), according to which the wing console surface was constructed (Figure 3-b).

3. Creation of the plumage outline (at a 45° angle to the AV's plane of symmetry) and its symmetric profile, according to which the plumage surface was constructed (Figure 3-c).

4. The surfaces of the cantilever and tail are symmetrically displayed, all surfaces are united (Figure 2-d), and a solid model is created on their basis (Figure 3-e).

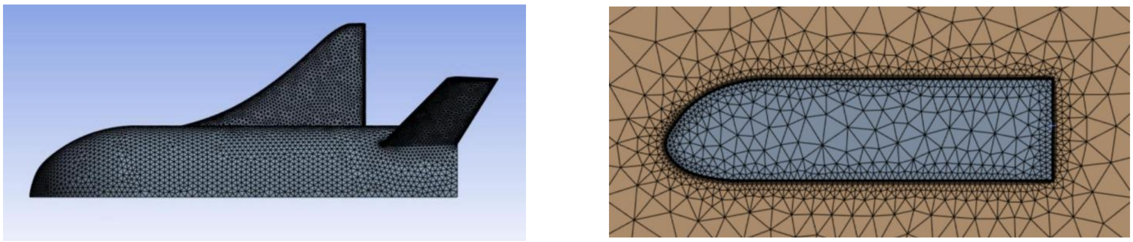


a b c d e

Figure 3. Visualization of the main stages of building an AV calculation model:
a) construction of the fuselage; b) construction of the wing console; c) construction of plumage;
d) symmetry, union of surfaces; e) finished solid model

Further work was performed in ANSYS Workbench (student version). In the Geometry module, the model's geometry was refined, and a calculation domain – a sphere of radius 60 m representing the surrounding air – was created. In the Mesh module, a finite-element mesh was generated by partitioning the model's surfaces and the internal surfaces of the calculation domain in contact with it as follows: edges of the wing and tail, and the smoothing zone of the wing-fuselage junction – 0.02 m; wing area and feathers near the edge – 0.06 m; surface of the wing and tail, nose part of the fuselage – 0.1 m; rest of the fuselage surface – 0.15 m.

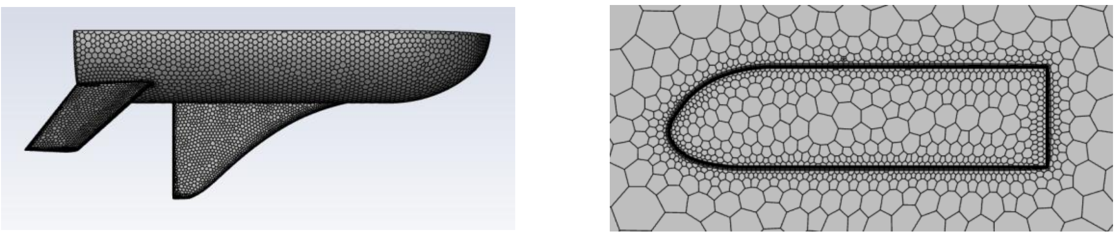
Thin boundary layers of the calculation domain mesh near the model's surface were also created. The grid construction type is Explicit. Element sizes were selected based on the model's dimensions and the limitations of the ANSYS student version, which restricts the number of elements. The resulting finite element mesh has triangular elements (Figure 4) and consists of about 450,000 elements.



a) b)

Figure 4. Triangular calculation mesh generated in the ANSYS Mesh module: a) on the surface of the model; b) in the plane of symmetry

The meshed model was then loaded into the Fluent module for further simulation. In Fluent, the finite-element mesh was converted to a polyhedral one (Figure 5), which the program processes more efficiently.



a) b)

Figure 5. A polyhedral calculation mesh generated on the basis of the triangular one in the module ANSYS Fluent: a) on the surface of the model; b) in the plane of symmetry

At the next stage, the operating conditions of the elements of the AV passive thermal protection system were modeled. The aerodynamic heating of the AV surface at the stage of atmospheric descent is simulated for different conditions ($M = 25 \rightarrow 10$) and flight altitudes ($h = 80 \rightarrow 24$ km above sea level) in order to study the change in the heating pattern depending on these parameters. The cases of different combinations of the values of selected heights and M numbers at the angle of attack $\alpha = 30°$ are considered. A certain height is simulated by specifying the characteristics of the environment for the calculation domain – atmospheric pressure, temperature, density and viscosity of air.

The ANSYS Fluent module includes the following physical models for calculation: Energy, Viscous (Spalart-Allmaras). For the calculation domain, the «pressure-far-field» type is set, the material is air from the ANSYS library (student version), the «kinetic-theory» method is set for the calculation of air parameters. When specifying the material of the solid-state model, parameter values similar to those for heat-resistant FRCI plates are set.

The results of the calculation of the temperature fields are shown in Figures 6, 7. To display the picture of the temperature distribution on the surface of the model, the color scheme is adjusted in such a way that the surface heating zones are depicted with clear edges that correspond to the divisions of the scale.

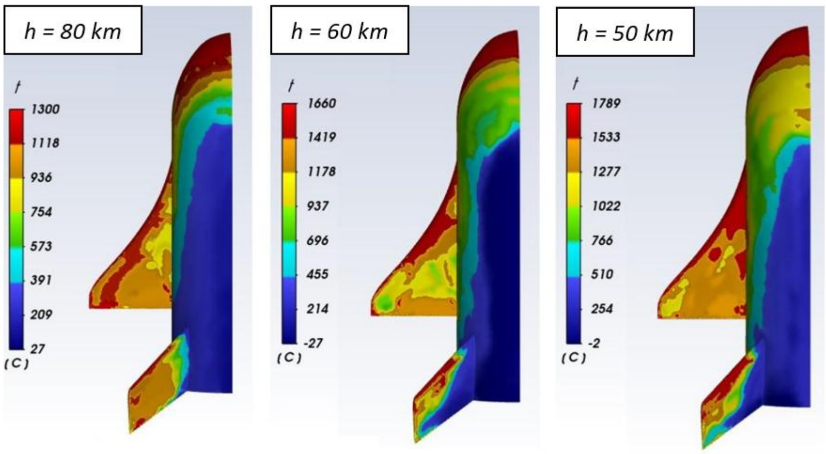


Figure 6. Change in the pattern of heating of the upper part of the AV surface at M = 20 depending on the flight height

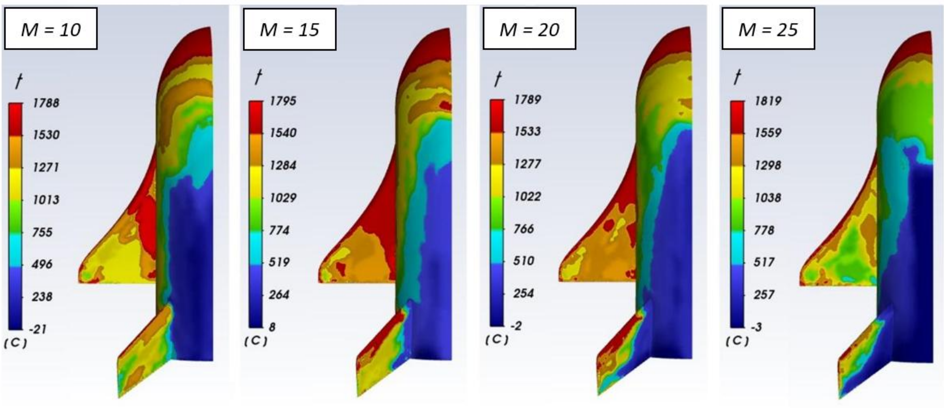


Figure 7. Change in the pattern of heating of the upper part of the AV surface at an altitude of h = 50 km depending on the number M

Simulation results indicate the highest heating risk for all investigated Mach numbers at an altitude of 50 km. As the Mach number increases, the maximum heating temperature rises by up to 100 °C. The total area of the highest heating zones slightly increases with decreasing altitude and decreases with increasing Mach number. Among the calculated cases, the most heat-loaded scenario is at h = 50 km and M = 25.

For further research on optimizing the layout of AV passive thermal protection system elements, it is important to consider changes in surface heating patterns along the descent profile, accounting for speed reduction as flight altitude decreases. As a first approximation, the descent profile from Zhou C. et al. [25] can be used.

Similar to the previous calculations, the calculation is carried out for these cases. According to the obtained results (Figure 8), the calculated height of 50 km remains the most heat-loaded.

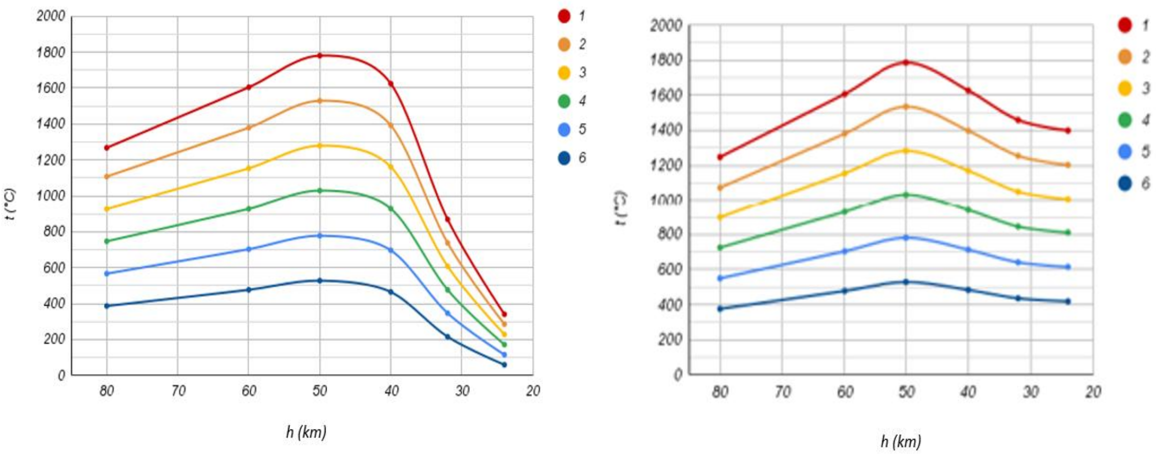


Figure 8. Graphs of the dependence of the highest temperatures in the heating zones of the AV surface on the flight height, taking into account the change in speed during descent

The resulting picture of the temperature distribution over the surface of the AV calculation model during aerodynamic heating for the most heat-loaded section of the atmospheric descent (h = 50 km) makes it possible to determine the characteristic zones of heat loads on the surface of the AV. According to the heating zones of the surface of the AV model, it is possible to determine the areas of the surface that require the use of heat-protective coatings of a certain operating temperature. It is advisable to choose reusable heat-resistant plates as coatings. Based on the picture of the distribution of the calculated temperature on the AV surface, it is thus possible, in a first approximation, to determine the location zones of the thermal protection system with the corresponding operating temperature (Table 2).

Table 2

Areas of heat loads of the AV surface during atmospheric descent according to simulation results

№	t, °C	Variants of heat-resistant plates	AV surface areas
1	1530... 1780	TUFROC, RCC	Lower surface, nose and lower side of the fuselage, leading edge and leading part of the upper surface of the wing, edges and outer surface of the tail
2	1280... 1529	RCC	The lower middle part of the fuselage, the rear part of the upper surface of the wing, the inner surface of the tail
3	1030... 1279	TUFI	The upper middle and tail part of the fuselage
4	779... 1029	TUFI, HRSI, FRCI, CRI	The upper part of the fuselage is closer to the bow
5	< 778	HRSI, FRCI	The upper part of the fuselage is closer to the tail

Given the fact that the simulated heating areas have uneven borders and are located in rather narrow spaces in some areas, and therefore, the exact repetition of their contours in the layout of the heat-resistant plates would lead to the complication of the coating design, as well as the fact that the heating areas intersect operating temperatures of various heat-resistant plates, the diagram of their location is proposed to be drawn up with a generalization and simplification of the contours of the heating zones.

As a basis for the areas of location of heat-resistant plates, the limits of the areas of heating of the AV surface, obtained as a result of modeling, are taken; the uneven boundaries of the heating areas are generalized by smooth lines towards a higher operating temperature; small areas with a lower heating temperature are considered part of a zone with a higher heating temperature; zones 1 and 2, as well as 4 and 5, which allow the use of coatings of the same operating temperature, should be combined with each other. A general outline of AV protection systems is presented in Figure 9.

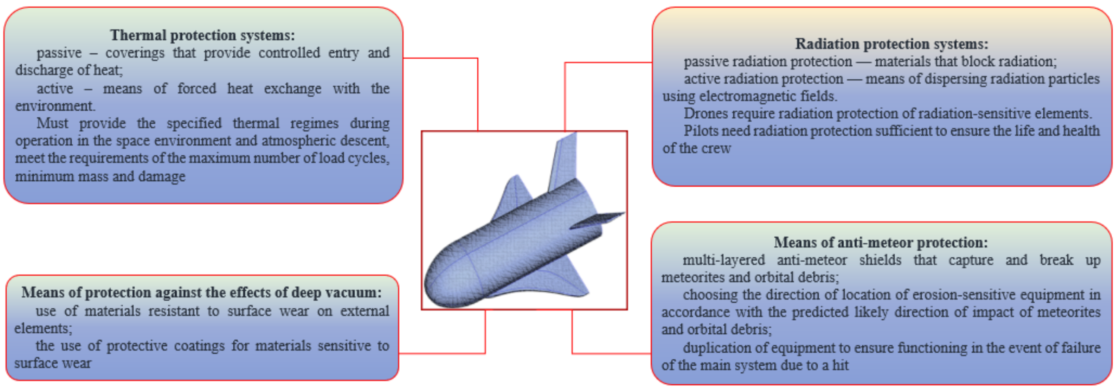


Figure 9. General outline of the systems of protection of reusable spacecraft

Based on the research, it is proposed to continue exploring concepts for reusing aerospace systems, including necessary thermal analysis technologies and protection of scarce, high-cost, critical structural elements [20, 21]. Thermal protection manufacturing technology must incorporate processes that minimize defect risks and ensure material homogeneity. High-precision manufacturing and geometry control of thermal protection elements are essential to mitigate aerodynamic risks during flight [20]. Recommendations for selecting manufacturing technology and monitoring the technical condition of AV thermal protection are grounded in the experience of the NASA Ames Thermal Protection Materials Laboratory. Various tools assess the physical and mechanical properties of processed materials [17].

Thermogravimetric analysis measures material mass loss at different temperatures and examines carbon residue formation and other critical properties. Control of TPS technical condition and characteristics begins with analyzing process variables affecting product quality and determining their relative values and numerical sensitivities. Subsequently, critical process factors are monitored to detect and manage defects that may occur during operation. TPS system failure risk is evaluated using a probabilistic physical engineering model that simulates the impact of failure modes on system risk.

5. CONCLUSIONS

A review of the latest publications in the field of designing components of AV protection systems against the influence of external operating factors was carried out. To substantiate the outline of promising AV protection systems, a method of computational and analytical studies using finite element analysis programs is proposed. A solid-state AV model was built in the CATIA software complex. A calculation experiment of the operation of the elements of the reusable AV passive thermal protection system at the stage of atmospheric descent with variations in height and speed was carried out in the ANSYS software environment (student version). The algorithm for calculating the model of the passive AV thermal protection system in the process of aerodynamic heating during the descent stage has been developed. The choice of the best variant of the location of the elements of the passive thermal protection system of the AV surface is justified.

References

1. Ahuja A. (2020). Active Thermal Protection System for a Reusable Launch Vehicle: A Conceptual Design. Delft: Delft University of Technology, 98 p.
2. Al-Jothery H. K. M., Albarody T. M. B., Yusoff P. S. M., Abdullah M. A., Hussein A. R. (2019). A review of ultra-high temperature materials for thermal protection system. *IOP Conference Series: Materials Science and Engineering*. *Symposium on Energy Systems 2019*. Kuantan, Malaysia, 1–2 October 2019. https://doi.org/10.1088/1757-899X/863/1/012003
3. Asgar A., Raj S. N. S, Varghese J. T. (2019) Ablative Heating Technology in Hypersonic Re-entry Vehicles and Cruise. *Aircrafts International Journal of Recent Technology and Engineering*, no. 8, pp. 3007–3014. https://doi.org/10.35940/ijrte.C4844.098319.
4. Barcena J., Garmendia I., Triantou K., et al (2017). Infra-red and vibration tests of hybridablative/ceramic matrix technological breadboards for earth re-entry thermal protection systems. Acta Astronaut 134, pp. 85–97. https://doi.org/10.1016/j.actaastro.2017.01.045
5. Brociek R., Hetmaniok E., Słota D. (2022). Reconstruction of aerothermal heating for the thermal protection system of a reusable launch vehicle. *Applied Thermal Engineering*, no. 219. 13 p. https://doi.org/10.1016/j.applthermaleng.2022.119405
6. Dang D. Z. (2021). Thermal and Structural Response Modeling of a Woven Thermal Protection System. Ann Arbor : The University of Michigan. 149 p.
7. Di Fiore F., Maggiore P., Mainini L. (2021). Multifidelity domain-aware learning for the design of re-entry vehicles. *Structural and Multidisciplinary Optimization*, no. 64, pp. 3017–3035. https://doi.org/10.1007/s00158-021-03037-4
8. Gupta R. K. & Ramkumar P. (2015). Titanium Aluminides for Metallic Thermal Protection System of Reusable Space Transportation Vehicle: A Review. *Frontiers in Aerospace Engineering, 4 (1).* https://doi.org/10.12783/fae.2015.0401.02
9. Iskra O., Lobunko D., Lobunko O. (2023). Research of mechanisms of destruction and protection complex thermodynamic systems. *European Science, 1* (sge23–01), 60–77. Available at: https://doi.org/10.30890/2709-2313.2023-23-01-015.
10. Jascha Wilken, Steffen Callsen, Dennis Daub, Alexander Fischer, Martin Liebisch, Carolin Rauh, Thomas Reimer, Henning Scheufler, Martin Sippel (2022). Combined cryogenic insulation and thermal protection systems for reusable stages. 9^{th} European conference for aeronautics and space sciences.
11. Junjie G., Jijun Y., Haitao H., Daiying D. (2019). Prediction of Heat Transfer Characteristics of the Carbonized Layer of Resin-Based Ablative Material Based on the Finite Element Method. *International Journal of Aerospace Engineering*. 14 p. https://doi.org/10.1155/2019/8142532
12. Lobunko O. P. & Iskra O. O. (2023). Mathematical Modeling of the Thermal Conditions of Aerospace Products' Protection Systems. Cherkasy, Ukraine, September 12–14, pp. 8–10.
13. Lobunko O. P. & Iskra O. O. (2023). Substantiation of the protection system's configuration for the reusable spacecraft. Brussels, Belgium, 16–18 August 2023, pp. 189–194.
14. Lobunko O. & Iskra O. (2023) Substantiation of the protection systems' technical outline for the aerospace objects. Scientific Journal of TNTU, no. 112, pp. 102–114. Available at: https://doi.org/10.33108/visnyk_tntu2023.04. https://doi.org/10.33108/visnyk_tntu2023.04.102
15. Ma S., Zhang S., Wu J., Zhang Y., Chu W., Wang Q. (2023). Experimental Study on Active Thermal Protection for Electronic Devices Used in Deep – Downhole − Environment Exploration. Energies 2023, 16, 1231. https://doi.org/10.3390/en16031231
16. Masayuki Naito, Satoshi Kodaira, Ryo Ogawara, Kenji Tobita and other (2020). Investigation of shielding material properties for effective space radiation protection. Life Sciences in Space Research, 26, pp. 69–76. https://doi.org/10.1016/j.lssr.2020.05.001
17. National Aeronautics and Space Administration (2023). Thermal Protection Materials Branch – Testing and Fabrication. Available at: https://www.nasa.gov/thermal-protection-materials-branch-testing-and-fabrication/.
18. Paglia L., Genova V., Tirillò J., Bartuli C., Simone A., Pulci G., Marra F. (2021). Design of New Carbon-Phenolic Ablators: Manufacturing, Plasma Wind Tunnel Tests and Finite Element Model Rebuilding. *Applied Composite Materials*, no. 28, pp. 1675–1695. https://doi.org/10.1007/s10443-021-09925-8
19. Piacquadio S., Pridöhl D., Henkel N., Bergström R., Zamprotta A., Dafnis A., Schröder K.-U. (2023) Comprehensive Comparison of Different Integrated Thermal Protection Systems with Ablative Materials for Load-Bearing Components of Reusable Launch Vehicles. *Aerospace*, no. 10. 30 p. https://doi.org/10.3390/aerospace10030319

20. Plisetska E. I. & Lobunko O. P. (2023). Thermal analysis and protection of modern aerospace systems. *XV International Conference of Students and Young Scientists «Intelligence. Integration. Reliability»*. Kyiv, Ukraine, 7–8 December 2023.
21. Reusability for European strategic space launchers – technologies and operation maturation including flight test demonstration. European Union Framework Program for Research and Innovation "Horizon Europe" (2021–2027).
22. Riccio A., Raimondo F., Sellitto A., Carandente V., Scigliano R., Tescione D. (2017). Optimum design of ablative thermal protection systems for atmospheric entry vehicles. *Applied Thermal Engineering*, no. 119. P. 541–552. https://doi.org/10.1016/j.applthermaleng.2017.03.053
23. Rodmann J., Miller A., Traud M., Bunte K. D., & Millinger M. (2021). Micrometeoroid Impact Risk Assessment for Interplanetary Missions. *8th European Conference on Space Debris*, ESA Space Debris Office.
24. Xu Q., Li S., Meng Y. (2021). Optimization and Re-Design of Integrated Thermal Protection Systems Considering Thermo-Mechanical Performance. *Applied Sciences*, no. 11. 21 p. https://doi.org/10.3390/app11156916
25. Zhou C, Zhijin W., Zhi J., Kretov A. (2017) Aerothermodynamic Optimization of Aerospace Plane Airfoil Leading Edge. *Journal of Aerospace Technology and Management*, no. 9. P. 503–509. https://doi.org/10.5028/jatm.v9i4.820

УДК 536.24

ОБГРУНТУВАННЯ ВИБОРУ КОМПОНЕНТІВ СИСТЕМИ ЗАХИСТУ АЕРОКОСМІЧНОГО ТРАНСПОРТНОГО ЗАСОБУ

Олександр Іскра; Еліна Плісецька; Олександр Лобунько

Навчально-науковий інститут аерокосмічних технологій, Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», Київ, Україна

Резюме. *Проєктування аерокосмічних транспортних засобів – складна науково-технічна задача, в ході розв'язування якої необхідно враховувати можливу дію факторів на конструктивні елементи й системи, і закладати в концепцію апарату засоби його захисту й забезпечення функціонування в очікуваних умовах застосування. Представлено результати огляду останніх наукових досліджень щодо покращення розуміння умов роботи та обґрунтування вибору варіантів і конструкційних матеріалів елементів системи захисту аерокосмічного транспортного засобу. Сучасний етап науково-технічних досліджень проєктантів все більше залежать від комп'ютерного моделювання очікуваних умов роботи об'єктів розроблення й виготовлення. Комп'ютерні моделі широко використовуються для створення й оцінювання ефективності різних концепцій моніторингу технічного стану і захисту аерокосмічних систем, а також для подолання суттєвих проблем на різних етапах проєктування систем захисту. Розглянуто і враховано відомі характеристики сучасних аерокосмічних транспортних засобів багаторазового використання. Побудовано твердотільну комп'ютерну модель прототипу, яка відображає основні геометричні розміри, форми й елементи аерокосмічного транспортного засобу. Проведено розрахунковий експеримент роботи елементів пасивної системи теплового захисту моделі прототипу на етапі атмосферного спуску при варіації висоти й швидкості. Модель зовнішньої поверхні досліджуваного об'єкта дискретизовано на елементи з однорідними температурними полями. На основі отриманих даних моделювання запропоновано варіанти конструкції елементів системи теплового захисту. Для обґрунтування обрису систем захисту аерокосмічних об'єктів запропоновано методику розрахунково-аналітичних досліджень. Результати досліджень можливо використати в процесі проектування й досліджень перспективних систем захисту аерокосмічних транспортних засобів багаторазового використання*

Ключові слова: *аерокосмічні апарати, метод скінченних елементів, математичне моделювання, системи теплового захисту, теплова схема, теплообмін.*

https://doi.org/10.33108/visnyk_tntu2025.01.042 *Отримано 30.10.2024*