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Thermal regime of large space structure with transformable elements from hybrid composite

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Abstract. Composite materials are planned to be widely used in prospective large-sized space structures. The functional characteristics of such structures depend on the thermal regime. The report reveals the features of modeling the thermal regime of a large-sized space structure on the example of a space debris trap. It is intended that the transformable power elements of the trap have to be made of carbon composite, and the panels, holding space debris – from the hybrid composite. Estimations of the temperature levels of the structural elements corresponding to the flight conditions along the geostationary orbit are given. The hazard level of permissible temperatures exceedence and their effect on the resistance of a hybrid composite material (CM) panels to small space debris particles impact is analyzed.

1. Introduction
The creation of large-sized space structures (LSSS) with the use of transformable (changing shape and size) elements from composite materials (CM) is of great interest for outer space development [1-9]. The examples are the reflectors of space antennas, in which the rod elements made of carbon composite are used to fasten the metal radio reflecting mesh. Another group of structures - inflatable modules with a multilayer shell of polymeric fabrics, films, cables, intended for residential and office buildings in low-earth orbit and stellar bodies. The third group includes space debris traps, which are opening conical or pyramidal devices consisting of rod-shaped force elements and fabric or mesh screens for collecting and utilizing used spacecraft and their elements. Another group - solar power plants with elements concentrating solar radiation (Winston concentrator) for improving energy efficiency.

The requirement of weight efficiency and high reliability with functional characteristics preservation during long-term space flight (10-15 years) is common for all listed facilities. To fulfill these requirements, CMs with high specific strength and rigidity as well as with the possibility of imparting additional functions by hybridizing the structure, are best suited. There are combinations of polymer films and fabrics with metallic or ceramic coatings, polymer binders, polymer foam layers, etc. in the structure of hybrid CM, having more than two components of different nature with a clearly defined boundary, depending on the purpose.

When designing the LSSS, it is necessary to take into account the change in their temperature state during heating by direct sunlight and the sunlight reflected from the stellar body, cooling in the shadow of the stellar body, shading with other structural elements and heat emission by internal onboard sources. The temperature state information is necessary for the analysis of stresses and displacements, it is a basis for determining the change in shape, size and resistance to the action of space factors, for example, to impacts of meteoroids and space debris elements.
Determination of the temperature state of the LS SS with transformable elements is a very difficult task for a number of reasons:

- a variety of structural materials with highly variable thermophysical and optical characteristics;
- lack of reliable reference information on the thermophysical characteristics of CM, which depend not only on the composition, but also on the form and technology of production of specific parts;
- a combined nature of heat exchange in the LS SS, caused by the mutual influence of essentially non-uniform temperature fields and heat radiation fields;
- a strong difference in the geometric dimensions of the LS SS transformed elements of hybrid CMs, for example, of small thickness (microns, millimeters) and large length (meters).

Modern methods of multiscale mathematical modeling allow to overcome these difficulties.

2. Space debris trap project

As an example, the results of the research of the thermal regime of the space debris trap construction with transformable elements made of hybrid composite are presented in the report (figure 1).

![Figure 1. The space debris trap, one of the panels is not shown: 1 - trap panel; 2, 3 - mesh power elements; 4 - base; 5 – fastening.](image-url)

The trap is designed to protect space vehicles with a cross-section of 3x3 m$^2$ from the destructive impact of small space debris (SSD) objects moving at speeds of 2 km/s and having a size of up to 10 mm and up to 7 km/s speed with a size of up to 2 mm. Such a trap can be used to ensure the reliable operation of important telecommunication satellites located on the geostationary orbit. To ensure the protection of the spacecraft from the impact of SSD, the transverse size of the trap was selected to be $4.5 \times 4.5$ m$^2$. A trap of this size can not be carried into the outer space in the assembled state, since the internal diameter of the payload fairings of modern Russian launch rocket Proton-M and Angara is 4.1 m. Therefore, the trap design it is proposed to be made transformable, brought into operational order on the geostationary orbit. To reduce the weight of the trap, it is planned to use various types of CM
widely. So, to create a basic structure of the trap, it is advisable to use mesh constructions made of high-strength and high-modulus carbon fiber reinforced plastic.

The analysis of the literature [10-17] indicates that the use of a two-layer shell made of flexible CM is promising for creation a reliable and effective ballistic protection in terms of weight. In this case, the outer layer of the shell, the thickness of which is from 60 to 80% of the total thickness, is intended to destroy the particle mechanically, but will be punched under its influence. Passed through the first layer SSD finely dispersed fragments will be caught by a second layer, which will ensure the safety of the protected spacecraft. Fabrics based on aramid fibers, such as «Kevlar», «Armos» and «Vektram» are promising for a flexible composite trap, production. In the proposed constructive-layout scheme of the trap, the principle of the inverse angle of inclination of the protective screen is used in relation to the probable direction of the SSD exposure. With this orientation of the shielding screen, the SSD particles falling onto it deflect towards the normal and, thus, are diverted from the protected space vehicle.

The trap was considered in the form of a tetrahedral pyramid with sides of each face 6.3; 5.0 and 5.0 m, oriented with open base area of 6.3 x 6.3 m² in the direction of flight. The elements of space debris should fall in the formed horn.

To deploy the trap from the transport position, 4 telescopic mesh arms with 6 m total length and 200x100 mm² cross section at the base will be used. To trap debris particles, trap walls have to withstand applied shock. According to the engineers, the flaps of the trap with a total thickness of 200 mm consist of two separate screens. The top layer of each screen includes a layer of screen-vacuum heat insulation (SVHI) of 3ВТИ-II type (in Russian), 20 mm thick, coated with aramid metallized fabric art. 5397-92. SVHI is formed from layers of a polyimide film with a thickness of 20 μm, separated by a fiberglass canvas. The second layer of the screen is the part of the ballistic protection and is a fabric package of 20 layers of synthetical high-strength material (SHSM) fabric CM art. 8601 type (in Russian) with 4 mm thickness, 0.19 kg/m² overall fabric density, having a cloth weaving of 15 threads 58 tex per filling and basis. The back layer of the screen is another SVHI layer 20 mm thick. The distance between the screens is 102 mm.

3. The thermal regime of the debris trap

When specifying thermal loads, it was considered that the direction of the flight of the trap along the geostationary orbit coincides with its axis of symmetry, and the transverse axis is oriented to the Earth. Under these conditions, the trap will be unevenly illuminated by the Sun (figure 2), that will cause significant temperature changes along its surface (figure 3). With the help of numerical simulation, it is established that the temperature on the outer surface of the trap can vary within wide limits from minus 165 °C to plus 80 °C. That exceeds the recommended temperature range for aramid fabric of SHSM fabric CM art. 8601 type. However, the use of double-sided thermal insulation made of SVHI allows to low the temperature fluctuations of the fabric to acceptable values and at the end of the first loop of the trap around the Earth it is in the range from plus 6 to plus 12 °C.

Due to the extremely low thermal conductivity of screen-vacuum thermal insulation, the output to the stationary thermal regime of ballistic protection is extremely slow, from 50 to 100 days. Simulation of the three-dimensional temperature state of the entire trap construction for such a period of time is connected with huge cost of computing resources, since the calculation time for one cycle of the trap flight along the geostationary orbit is more than 20 hours for Intel i7-5960X computer. Therefore, the temperature state simulation was carried out for a representative element of the volume of a CM flexible shell.

The calculation was carried out for two elements - for the upper and lower (relative to the Earth) parts of the trap. The representative element was an element of a flexible shell with an area of 10 × 10 mm², which was cut along the normal to the outer surface of the trap in its central zone. In this case, the cyclic loading of both surfaces of the representative element by direct solar radiation and solar radiation reflected from the Earth, the Earth's thermal radiation and also radiation heat exchange in the gap between the screens was taken into account. As the result, the temperature distribution in the layers of ballistic protection (figure 4) was obtained. It can be seen that the ballistic protection is
gradually settling down, but its temperature does not drop below minus 25 °C which is acceptable for aramid fabrics.

Figure 2. The flux density of direct solar radiation on the trap surface at its position on the Earth-Sun line, W/m².
**Figure 3.** The temperature state of the trap at its position on the Earth-Sun line after the first circle of flight, °C.

**Figure 4.** Temperature of space debris protection aramid fabric:
1 – first layer in the upper (relative to Earth) part of the trap; 2 – second layer of the upper part; 3 – first fabric layer of the lower (relative to Earth) part of the trap; 4 – second layer of the lower part.
The analysis of the temperature state of mesh arms has shown that the temperature drops in them reach a value of about 150 °C but neither the level itself nor the temperature gradients give cause for concern (figure 5).

![Temperature field of the trap frame](image)

**Figure 5.** The temperature field of the trap frame (the angle between the directions the trap - Earth and Earth - the Sun is 150 degrees), °C.

4. Conclusion
The possibility of ensuring the thermal regime of a large-sized space structure of a small space debris trap is shown. In this regime the stability of the structural materials of the hybrid composite panels and the mesh arms of the deployment system is maintained.

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