The heat transfer features of the thin-walled shell of an inflatable aerodynamic decelerator for CubeSat nanosatellites

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Abstract. Small spacecraft, first of all, nanosatellites of a CubeSat standard have a relatively small operational life. After their operational lives have expired, they turn into space debris. Disabled spacecraft can be transferred to the disposal orbit in the dense atmosphere using inflatable decelerators in order to avoid pollution of the near-Earth space. Decelerator’s temperature state is formed under the action of thermal radiation from the Sun and the Earth and kinetic heating caused by movement in a free-molecular medium. The specific features of heat transfer of inflatable decelerator’s thin-walled spherical shell are considered. The inflatable decelerator is designed for spacecraft removal during moving in the low-earth orbit.

1. Introduction

The development of the near-Earth space is accompanied with the appearance of failed or out-of-service spacecraft in near-earth orbits. Such spacecrafts are called space debris [1-3]. High activity of enthusiasts who create small spacecraft, such as CubeSat class nanosatellites, leads to a dismal outlook of space debris problem. Various projects are proposed for the sake of the near-Earth space debris mitigation. There are projects involving collection and disposal of already accumulated debris and equipping of a new generation spacecraft with devices for individual or group disposal.

Among all these projects three directions of spacecraft removal can be distinguished: transportation to the high disposal orbits, conversion directly in the operational orbit and deorbiting to the Earth’s atmosphere. The indicated directions are based on different physical principles and require completely different technical means and energy resources. Thus, to transfer spacecraft to the high disposal orbits, rocket engines and reserves of the working fluid (fuel) or sailing systems that can be mounted directly on the spacecraft are needed. Conversion directly in the operational orbit implies the presence of special spacecraft equipped with means of collection (networks, harpoons, foams, traps) and processing (mechanical shredders, laser cutters and evaporators). In various well known projects, traps are large transformable structures [4-6]. Their designs are close to those of space antennas transformable reflectors [7–9]. Deorbiting of an individual spacecraft and those collected by the traps into the dense layers of the atmosphere can be accomplished with the assistance of rocket engines, cable systems and inflatable aerodynamic decelerator (IAD).

The usage of each removing scheme for small spacecraft of the CubeSat standard involves a large amount of researches aimed at achieving high mass-geometric perfection. The projects with the use of IAD are excel among the promising directions spacecraft removal, suitable, first of all, for
nanosatellites. Their principle of operation is based on a multiple increase in geometric dimensions to increase the drag force. Thus, IAD provides spacecraft deorbiting into the dense layers of the atmosphere, where it collapses together with the spacecraft under the action of high thermal and mechanical loads. The height of the hermiticity and carrying capacity exhaustion is of great importance in the IAD operating analysis. After this height, the dipping of the spacecraft into the atmosphere will get out of control, or it may not take place at all.

This paper is devoted to the study of external and internal heat transfer features of a CubeSat type nanosatellite IAD deorbiting system. Previously, the problems of the thermal conditions of thin-walled spherical shells space structures were considered in [10–15]. However, in the mentioned studies heating of shells by thermal radiation from the Sun and the Earth was investigated, while and contribution of kinetic heating in a significantly discharged atmosphere was not taken into account.

2. The inflatable aerodynamic decelerator design variations

An IAD shell must withstand the stresses that occur while moving in the Earth orbit for the time required for a sufficient decreasing of the spacecraft orbit. Thus, such shell must be robust enough, heat-resistant and possess high windage. Low adhesion of the shell material is necessary for trap opening at the right time.

The shape of the IAD affects the efficiency of the device. Combining simple geometry forms is a possible solution for achieving necessary aerodynamic characteristics (Figure 1). Moreover, not all elements of the structure must be inflatable, it is possible to use sailing elements.

![Alternative geometric forms of the IAD shell](image-url)

**Figure 1.** Alternative geometric forms of the IAD shell
Table 1 presents the characteristics of shells made of aluminized PET film with a thickness of 8 μm and a density of 1420 kg/m³ [16].

| IAD geometric form   | Radius, m | Mass, kg | Cross-sectional area, m² |
|----------------------|-----------|----------|--------------------------|
| Three identical spheres | R=1      | 0.42     | 9.42                     |
| Torus                | R=2, r = 0.5 | 0.87     | 19.63                    |
| Single sphere        | R=3       | 1.28     | 28.27                    |

Since the aerodynamic characteristics of spherical bodies are well studied, a spherical shell was chosen for the base-line study.

Before packing, the shell is evacuated by vacuum, but it is not possible to achieve the absolute packing density. Figure 2 shows the possible variants of the shell packaging.

The folded shell is placed in an opening container that is attached to a spacecraft (Figure 3). Inflation can occur by chemical reaction or compressed gas.

3. Formulation of the problem of the spherical decelerator heat transfer numerical simulation

The methods of thermal design should be used for choosing IAD’s design and technology solutions [17]. The IAD’s thermal conditions will be formed under the influence of kinetic heating caused by movement in a free-molecular medium and heating by thermal radiation fluxes from the Sun and the Earth.

The interaction of gas molecules with the IAD surface during movement in a discharged flow was simulated using the Free Molecular Flow module of the COMSOL Multiphysics software package. The atmosphere characteristics were taken from to reference [18]. The modeling results of the heat
flux caused by atmospheric drag for altitudes from 300 km to 125 km are presented in Table 2. Comparison of the values with the heat flux density of the solar radiation, assumed to be equal to 1400 W/m², shows that consideration of the kinetic heating becomes necessary at altitudes below 200 km.

The data on the temperature of a highly heat-conductive rotating sphere heated in space by a solar radiation flux with a density of 1400 W/m² was used to verify the model. The calculated value of the shell steady-state temperature for these conditions agree with the value of temperature 7°C given in [19].

Simulation of the shell heating by radiation fluxes from the Sun and the Earth was carried out in the Space System Thermal module of the Siemens NX software package. The shell diameter was assumed to be 6 m, the thickness was 8 μm, the thermal conductivity of the metallized film was 11.4 W/(m·K). It was supposed that the spacecraft moved in the sun-synchronous circular orbit and deorbited from 300 to 125 km. The density of a solar heat flux was assumed to be 1400 W/m². It was assumed that the shell retains its spatial orientation due to the presence of a uniaxial gravitational orientation in the spacecraft, which is a long rod with a load in the end of it. The rod is attached to the spacecraft in the folded state, and after the deployment, it orients the spacecraft.

4. The result of the numerical simulation of the spherical decelerator heat transfer

Table 2 presents the values of heat flux density and IAD shell temperature for different altitudes.

| Altitude, km | $q_k$, W/m² | Maximum temperature, °C | Minimum temperature, °C |
|--------------|--------------|-------------------------|------------------------|
| 300          | 4            | 141                     | -180                   |
| 275          | 8            | 141                     | -180                   |
| 250          | 14           | 142                     | -180                   |
| 225          | 27           | 143                     | -180                   |
| 200          | 58           | 147                     | -180                   |
| 175          | 142          | 157                     | -180                   |
| 150          | 461          | 205                     | -180                   |
| 125          | 3456         | 473                     | -180                   |

Since the melting point of PET film is 250°C, there is a chance of the shell complete destruction at an altitude of 125 km.

The simulation results indicate that radiation heating prevails at an altitude of 300 km. There is a clear-cut temperature maximum on the sunny side of the shell (Figure 4). Kinetic heating prevails at an altitude of 125 km (Figure 5). Temperature distribution in both cases is substantially non-uniform.
Figure 4. Temperature distribution pattern over the shell surface at an altitude of 300 km, with an inclination angle of 96.65°, at time 500 s; \( q_s \) – the direction of a solar heat flux, \( q_k \) – the direction of a kinetic heat flux

Figure 5. Temperature distribution pattern over the shell surface at an altitude of 125 km, with an inclination angle of 96.65°, at time 500 s; \( q_s \) – the direction of a solar heat flux, \( q_k \) – the direction of a kinetic heat flux

Conclusions
1. A methodology for simulating heat transfer of the spherical IADs for removing the CubeSat type spacecraft from the low-Earth orbits has been developed.
2. The spherical IAD’s temperature state in the process of descent from an orbit with an altitude of 300 km to 125 km was determined. The role of aerodynamic heating and heating by thermal radiation fluxes from the Sun and the Earth was highlighted. It is was that during the deorbiting from an altitude of 300 km of a spacecraft weighing 10 kg, the IAD made of PTF film may collapse
at an altitude of 125 km. At the same time, the spacecraft descent to the dense layers of the atmosphere is guaranteed.

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