Temperature state of the housing and shell for an inflatable aerodynamic decelerator

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Abstract. Space debris is a growing concern that becomes more urgent with the increase in space exploration. This is the reason for equipping spacecraft with disposal systems. One of the methods for space debris removal is deorbiting a small spacecraft by using a decelerator. This paper presents issue analysis related to a selection of design and technology solutions and temperature analysis for inflatable aerodynamic decelerator of small spacecraft.

1. Introduction
The space debris is a growing concern that becomes more urgent with increase of space application. In near future every satellite should be required to have a certain measure to de-orbit at the end of its lifetime [1-2]. One of the methods for space debris removal is deorbiting a small spacecraft re-entry by using a decelerator.

Operating satellites this is only the proportion of moving objects in near-Earth space. After its mission is complete, a satellite continues its motion orbiting, increasing space debris population. As a result, the near-earth space is becoming increasingly polluted. In near future space junk will make launching spacecraft into orbit more difficult. At the same time, the motion small spacecraft will have to be adjusted. Therefore, a debris removal system for space and rocket equipment, especially for satellites [3], should be considered.

To remove space debris from orbits the different methods can be applied including the satellite deorbiting with subsequent complete and safe destruction. For instance, towing vehicles or extra engine modules can be used for deorbiting. However, such removal methods are not always applicable for small spacecraft due to mass and energy limitations. Inflatable aerodynamic decelerator (IAD) that decreases the orbit height of a redundant satellite by using of a lightweight braking device with a large cross-section area is preferable.

The main element of IAD is ultra-lightweight and thin, inflatable envelope. Shell shape and size must be appropriate for the purpose of the brake device. The shell must withstand the load for the time necessary to sufficiently reduce the orbit. The report presents the results of the design of the body of an IAD. The results of heating the hull and shell in near-Earth orbit are considered. Design deployment options are proposed.

2. The inflatable aerodynamic decelerator design variations
The satellite TNS-0 №2 [4], which was launched on August 17, 2017 has been chosen for the IAD development. Initially, it was planned that the service time of the device will last 5-7 months, but the satellite work time was extended, and its operation is planned until 2021. The main purpose of the
The shape of the IAD housing was determined based on the spacecraft for which it has been intended, so the housing intended for use on TNS-0 №2 (figure 1) should have the shape of a hexagonal prism.

Since the development has been carried out for a nanosatellite, special attention has been paid to the mass perfection of the design. Topological optimization of the structure has been carried out to reduce the housing weight. A thin-walled hexagonal prism has been chosen as the optimized design. Carbon fiber has been chosen as the body material because it combines such properties as high specific strength, stiffness, thermal conductivity and a low coefficient of linear thermal expansion. The goal function of optimization was to minimize flexibility, and the restriction was the mass reduction by more than 50%. The following boundary conditions have been set for analysis: sealing of the bottom edge and compressive axial load for the element of side surface and sealing the perimeter of the element and distributed pressure over the surface for the triangular parts of the base and lid. These loads are caused by housing injection into Earth orbit using a launch vehicle. As a result, the shape of the structural elements has been determined (figure 2). Thus, the resulting design is a topologically optimized power part of the housing, covered with thin plates.

The IAD concept is so that at the moment when the satellite finishes its work at an orbit, the shell opens, increasing the cross-section area of the vehicle, which, in turn, causes an increase of the drag force. Under the influence of this force, the vehicle with an open IAD reduces the height of its orbit and burns up in the dense layers of the atmosphere. A number of research activities have been conducted to determine the shape and characteristics of the shell [5-16]. According to [17], a spherical device with a diameter of 2 m allows to take a satellite weighing 5 kg into the dense layers of the atmosphere in 18 hours. The supercharging system of the IAD shell must ensure the structure opening when the satellite finishes its work in orbit. It is assumed that the supercharging and opening of the housing should occur simultaneously. The use of loop connections allows the housing to be laid out in a flat structure, which minimizes the possibility of shell damage during deployment.
One method of deployment is the shell inflation with compressed gas. This method is often used in structures, including rocket and space ones. For this method of supercharging, the main task of an engineer is to determine the necessary minimum of system elements and to calculate the amount of compressed gas, as well as to ensure the safety of the entire structure in space operating conditions. The study of structures deployed in the outer space allows to make a conclusion about the following minimum set of elements of the boost system: attachment to the shell (fitting), flexible pipeline, valve, pressure regulator and compressed gas cylinder.

Another way of deployment is the shell inflation with sublimating chemical. Paper [18] describes an experiment on supercharging a thin-film structure with benzoic acid in a thermal vacuum chamber. The main purpose of the test was to evaluate the dynamics of the process and determine the feasibility of using this substance as a gas generator. In addition, the expansion processes that can occur with residual air after vacuuming and determining their influence on the dynamics of the supercharging process were of interest. Preliminary tests have been conducted in the Cascade TEK high-vacuum furnace located at the Langley Research center, NASA. This high-vacuum furnace is usually used for baking or drying parts, but provides a pressure in the range of 0.1-0.00001 Pa. The test has been carried out in two stages: first for the evacuated shell without a sublimating substance at room temperature (to study the effect of the gas remaining in the shell after vacuuming), then using benzoic acid and heating from 20⁰C to 127⁰C. The shell with a diameter of 42 cm was tested, and as a result of the tests, the effectiveness of the sublimation boost system was confirmed.

3. The inflatable aerodynamic decelerator thermal state

When the vehicle moves along the orbit, the main heating of the structure occurs due to radiation flows coming from the Sun and the Earth [19-21]. To reduce the heat load, it is possible to use surface metallization, which makes the surface reflectivity much greater than the radiative one (figure 3). This allows to reduce the temperature ratio during the orbital flight significantly.

A study of the thermal state of the IAD hull was conducted. An orbit with shadow sections was considered to estimate the temperature difference. In one case, the optical properties of carbon fiber plates were used. In another case, the properties of plates covered with a thin layer of aluminum were used.

One of the research tasks is to determine whether it is necessary to use a metallized coating of the shell. It allows to reduce the maximum temperature and temperature difference, which helps to extend the life of the structure. But if the method of deployment with a sublimating substance is used, then the use of metallization does not allow heating the substance inside the shell. In this case, additional heaters are required, which weigh down the final design of the IAD. It is necessary to designate possibility of heating sublimating chemical without the heaters.
Metallized plates are used

Uncoated plates are used

Figure 3. Comparison of the temperature fall on the surface of the housing at a point on the top of the base: (1) Above the edge; (2) A point on the top of the base; (3) A point on the side surface.

Heating simulation was performed in the Siemens NX software package using the Space System Thermal module. The orbit parameters correspond to the parameters of the TNS-0 No. 2 satellite. Solar heating, own and reflected, Earth radiation, and free molecular heating were taken into account. The results (table 1) show that the sublimating substance is heated to the temperature necessary to start the sublimation process. However, the shell is heated to a critically high temperature. Therefore, it is more rational to use a shell with a reflective coating. In this case, the chemical reaches the desired temperature using heaters. This will be considered in further research.

4. Discussion
Creating an IAD is a complex interdisciplinary task. It includes the design of the shell, supercharging system, and housing. Also, during the research process, auxiliary systems (for example, protection or heating/cooling) may be necessary.

One of the main assumptions made in this study is that the shell is considered as a sphere. But at the time of opening, the shell is compactly folded into a container and has an arbitrary shape before the
chemical is sublimated. In further research, this assumption must be rejected or justified. A deployment shell study is required, which includes the process of opening the shell.

Polyethylene terephthalate was chosen as the shell material. It is assumed that the shell will be folded all the time the satellite is running. This may take several years. It is expected to conduct research that will reduce the adherence of the shell material.

The temperature state of housing and shell was studied separately. In future research, it is necessary to conduct simulations for a model that will include all the main parts and take into account the influence of the satellite.

| Table 1. The results of the heat shell |
|--------------------------------------|
| Shell without a coating | Shell with metallized coating |
| Maximum shell heating temperature | 250°C | 70°C |
| Minimum shell heating temperature | -40°C | -70°C |
| Maximum temperature of the sublimating chemical | 100°C | Does not exceed the initial temperature |
| Time required for sufficient heating of the chemical | 6 hours | – |

5. Conclusion
This paper discusses the general issues of creating an inflatable brake device, its appearance and possible methods of supercharging. The temperature state of housing during an orbital flight is investigated. The use of metallized plates reduces the temperature difference.

The temperature state of the shell with the chemical inside is investigated. The use of a metallized film reduces the temperature difference on the surface of the shell, but in this case the chemical does not heat up. Using an uncoated film allows the chemical to be heated to the temperature necessary to start the sublimation process. At the same time, the surface temperature of the shell exceeds the operating temperature of the film. Therefore, it is necessary to use a metallized shell. Heater design will be the subject of further research.

References
[1] Mrusek B M 2019 Satellite maintenance: an opportunity to minimize the Kessler effect. *Int. J. Aviat. Aeronaut. Aerosp.* 6(2) DOI: 10.15394/ijaaa.2019.1323
[2] Drmola J and Hubik T 2018 Kessler syndrome: system dynamics model *Space Policy* 44-45 29-39 DOI: 10.1016/j.spacepol.2018.03.003
[3] Straub J, Marsh R and Whalen D J 2017 *Small spacecraft development project-based learning* (Switzerland: Springer International Publishing) pp. 53-63 DOI:10.1007/978-3-319-23645-2
[4] Ivanov D S 2017 TNS-0 No. 2 Nanosatellite Orientation System *Preprinty IPM im. M.V. Keldysha* No. 118 DOI: 10.20948/prepr-2017-118
[5] Voinov S I, Zhelezina G F, Solovyova N A, Yamshikova G A and Timoshina L N 2015 Influence of the external environment on the properties of carbon fiber obtained by pressure impregnation (RTM) *Electronic scientific journal "PROCEEDINGS of VIAM"* No. 2
[6] Antonov F K, Golubev M V, Khaziev A R and Azarov A V 2004 Method of manufacturing products from composite materials by 3D printing and device for its implementation RU2674138C1
[7] Mikhailovskii K V, Reznik S V and Prosuntsov P V 2019 Method for modeling the interaction between transformable shells of spacecrafts and small space debris objects *AIP Conference Proceedings* 2171 030017 DOI: 10.1063/1.5133183
[8] Abramova E N and Reznik S V 2019 Small spacecraft’s inflatable aerodynamic decelerator design issues analysis *AIP Conference Proceedings* 2171 040002 DOI: 10.1063/1.5133188
[9] Golomazov M and Ivankov A 2017 Software package for the development of thermal protection systems for space vehicles descended in the atmospheres of the planets *Vestnik NPO im. S.A.*
Lavochkina 3, 41–53

[10] Nesterin L M, Pichhadze K M, Sysoev V K, Finchenco V S, Firsyuk S O and Yudin A D 2017 Proposal for the creature device to deorbit nanosatellites CubeSat in low earth orbit Vestnik NPO im. S.A. Lavochkina 3, 20–6

[11] Koryanov V V, Oriat F, Griselin H 2019 Use of autonomous inflatable devices for optimal landing of transportation systems The 2nd Int. Conf. Robot Systems and Applications DOI:10.1145/3378899.3378893

[12] Koryanov V V, Toropkov A, Kazakovtsev V P and Nedogarok A 2019 Study of the possibility of using the mechanics of inflatable braking devices to remove the spacecraft J. Phys.: Conf. Ser. 1215 012031 DOI: 10.1088/1742-6596/1215/1/012031

[13] Zarubin V S, Zimin V N and Kuvyrkin G N 2017 Temperature distribution in the spherical shell of a gauge-alignment spacecraft J. Appl. Mech. Tech. Phys. 58 1083–90 DOI: 10.1134/S0021894417060141

[14] Zarubin V S and Kuvyrkin G N 2019 Thermal state of a polymer dielectric layer with dielectric characteristics that depend significantly on temperature J. Eng. Phys. Thermophys. 92 1109–16 DOI: 10.1007/s10891-019-02026-1

[15] Hrycak P 1963 Influence of conduction on spacecraft skin temperatures AIAA J. 1 11 2619-2621

[16] Horn A C 2017 A low cost inflatable CubeSat drag brake utilizing sublimation MS, thesis, Old Dominion University DOI: 10.25777/1xaw-be17

[17] Reznik S V, Smirnov G K and Varlamov S A 2020 On the way to the optimal design of an inflatable aerodynamic decelerator of space debris removal system for CubeSat nanosatellites IOP Conf. Ser.: Mater. Sci. Eng. 709 044105 DOI: 10.1088/1757-899X/709/4/044105

[18] Nakasuka S, Senda K, Watanabe A, Yajima T and Sahara H 2007 Simple and small de-orbiting package for nano-satellites using an inflatable balloon. Trans. Jpn. Soc. Aeronaut. Space Sci. 7 26 31–36 DOI: 10.2322/tstj.7.Tf_31

[19] Reznik S V 2018 Thermal regimes of space composite structures. Part I MATEC Web of Conferences 194 01048

[20] Reznik S V 2018 Thermal regimes of space composite structures. Part II MATEC Web of Conferences 194 01049

[21] Reznik S V, Prosuntsov P V and Mikhailovskii K V 2018 Thermal regime of large space structure with transformable elements from hybrid composite J. Phys.: Conf. Ser. 1134 012048