УДК 629.7.054.847
Doi: 10.31772/2712-8970-2023-24-3-550-557

Для цитирования: Шатров А. К., Фисенко Е. Н., Рабецкая О. И. Обеспечение теплового режима конструкций космического аппарата // Сибирский аэрокосмический журнал. 2023. Т. 24, № 3. С. 550–557. Doi: 10.31772/2712-8970-2023-24-3-550-557.

For citation: Shatrov A. K., Fisenko E. N., Rabetskaya O. I. [Ensuring the thermal regime of spacecraft structures]. *Siberian Aerospace Journal.* 2023, Vol. 24, No. 3, P. 550–557. Doi: 10.31772/2712-8970-2023-24-3-550-557.

Обеспечение теплового режима конструкций космического аппарата

А. К. Шатров, Е. Н. Фисенко*, О. И. Рабецкая

Сибирский государственный университет науки и технологий имени академика М. Ф. Решетнева
Российская Федерация, 660037, г. Красноярск, просп. им. газ. «Красноярский Рабочий», 31
*E-mail: fisenkoen@sibsau.ru

Основное требование для бесперебойной работы космического аппарата – это его стабильный тепловой режим. Особо сложная задача – обеспечение стабильной системы терморегулирования аппарата с учетом жестких ограничений по энергетическим и массовым затратам на устройства терморегулирования. Эти задачи необходимо решать на каждом этапе создания спутников. На каждом этапе проводятся тепловые расчеты с выбором оптимальных теплофизических параметров. Такой объем работ составляет примерно десятую часть от всех работ со спутником. Необходимость теоретическо-экспериментального уточнения расчетных методик является актуальной задачей, которая позволит существенно снизить материальные и временные затраты на проектирование, испытания и доводку аппарата. Поэтому расчет и анализ тепловых режимов космических аппаратов является важным этапом при проектировании спутников. Наземные тепловакуумные испытания очень затратны как по времени, так и финансово. Суть концепции заключается в проведении только стационарных тепловых режимов в условиях максимальных и минимальных тепловых нагрузок на спутник в целом и его отдельные внешние элементы с последующим обеспечением сходимости результатов испытаний с расчетными результатами. А подтверждение промежуточных требований по обеспечению заданных тепловых режимов осуществляют расчетным путем.

В статье рассмотрены задачи по обеспечению теплового режима конструкций космического аппарата; классификация устройств, применяемых для обеспечения теплового режима; наземная отработка теплового режима спутников связи при тепловакуумных испытаниях; обеспечение теплового режима космического аппарата связи при наземных электрических испытаниях; тепловой режим конструкций космического аппарата при транспортировании с завода-изготовителя на техническую позицию.

Ключевые слова: космический аппарат, тепловакуумные испытания, тепловой режим, система терморегулирования.

Ensuring the thermal regime of spacecraft structures

A. K. Shatrov, E. N. Fisenko*, O. I. Rabetskaya

Reshetnev Siberian State University of Science and Technology
31, Krasnoyarskii Rabochii prospekt, Krasnoyarsk, 660037, Russian Federation
*E-mail: fisenkoen@sibsau.ru

The main requirement for the smooth operation of the spacecraft is its stable thermal regime. A particularly difficult task is to ensure a stable temperature control system of the device, taking into account *strict restrictions on energy and mass costs for temperature control devices. These tasks need to be solved at every stage of the creation of satellites. At each stage, thermal calculations are carried out with the choice of optimal thermophysical parameters. This amount of work is about a tenth of all work with the satellite. The need for theoretical and experimental refinement of calculation methods is an urgent task that will significantly reduce the material and time costs of designing, testing and fine-tuning the device. Therefore, the calculation and analysis of the thermal regimes of spacecraft is an important stage in the design of satellites. Ground thermal vacuum tests are very costly, both in time and financially. The essence of the concept is to conduct only stationary thermal modes under conditions of maximum and minimum thermal loads on the satellite as a whole and its individual external elements, followed by ensuring convergence of test results with calculated results. And the confirmation of intermediate requirements to ensure the specified thermal conditions is carried out by calculation.*

The article considers the tasks of ensuring the thermal regime of spacecraft structures. Classification of devices used to ensure the thermal regime. Ground-based testing of the thermal regime of communication satellites during thermal vacuum tests. Ensuring the thermal regime of the communication spacecraft during ground-based electrical tests. Thermal regime of spacecraft structures during transportation from the manufacturer to the technical position.

Keywords: spacecraft, thermal vacuum tests, thermal regime, temperature control system.

Introduction

Ensuring the thermal regime of a spacecraft consists of maintaining the temperatures of the main structural elements, instruments, assemblies, radio elements, gas and liquid media in sealed containers and systems in specified ranges.

Violation of the thermal regime leads, as a rule, to equipment failures and the inability to perform the tasks assigned to the communications spacecraft for its intended purpose.

Due to the increase in the duration of the active life, the consumed electrical power, while simultaneously increasing the requirements for reducing the relative mass, the requirements for the temperature control system also increase, which complicates the tasks that need to be solved at all stages of the creation of new communication satellites. In this case, it is necessary to take into account the degradation of the thermophysical parameters of materials under the influence of outer space factors (radiation, vacuum, high and low temperatures, the cyclicity of their changes).

In order to design a temperature control system for a communications spacecraft that meets the requirements for it, one of the most important conditions is the ability to carry out, using modern computer tools, a large volume of calculations of temperature fields for conditions of variable effects of internal and external thermal loads on the components of the satellite and the satellite as a whole under conditions operation in orbit [11].

No less complex are the tasks of ensuring the thermal regime of the spacecraft during ground tests and experimental ground testing of the thermal regime of both individual components and the spacecraft as a whole, simulating conditions as close as possible to the conditions of normal operation in orbit.

Calculations and analysis of the thermal conditions of the spacecraft are carried out from the moment of the first sketches of its appearance and continue during operation in the event of emergency situations on board. An estimate of the amount of work performed to ensure the thermal conditions of the device is approximately a tenth of all work with the satellite.

A significant amount of work to ensure the thermal conditions of communication satellites is also carried out in terms of simulating the conditions of outer space in the process of various types of tests in a thermal pressure chamber to create and use screen-vacuum thermal insulation, testing the durability of optical coatings of materials with different thermal conductivities, testing the performance of thermal control system units (hydraulic units, fans, thermostats), as well as devices and equipment for filling closed hydraulic and gas circuits, electronic equipment, etc. with coolants. [6].

Classification of devices used to ensure thermal regimes of communication spacecraft

The main difference between domestic spacecraft is that the main radio-electronic equipment is placed in a sealed container filled with gas. Foreign analogues do not have such sealed containers [13].

Placing electronic equipment in such a container provides, on the one hand, a working pressure close to atmospheric in terrestrial conditions, and on the other hand, it acts as a circulating coolant to remove excess heat from electronic equipment. The adoption of this satellite configuration was determined by the lack of on-board electronic equipment that can operate reliably in outer space when exposed to deep vacuum, high degrees of cosmic radiation, low and high temperatures, as well as sudden multi-cyclic changes therein.

This option for placing radio-electronic equipment also has its disadvantages. Since the devices are located inside a sealed container filled with a gaseous medium, the thermal conditions of the devices are ensured mainly by blowing with gas. The devices are located in a container on boards parallel to the average direction of movement of the gas flow, but since they mostly contain outer casings, the circulation of gas along the internal surfaces of the devices is insufficient and, as a consequence of this, the temperatures of individual elements of the devices are higher in conditions normal operation compared to the results of tests in ground conditions, in which additional circulation of gas inside the device is provided due to natural convection caused by gravity. The trend of compactness in the development of radio-electronic equipment leads to an increase in the mass and energy density of the layout of the instrument compartments of a spacecraft, as a result of which the named problem of using sealed containers for a communications satellite is aggravated by the fact that reproducing the conditions of normal operation taking into account weightlessness while ensuring the thermal regime of instruments placed in a gas environment, in terrestrial conditions is not possible.

Foreign communications satellites do not have sealed instrument containers. Excess heat is removed from devices only by thermal conductivity and heat radiation from the surfaces of devices and their elements into the environment. This allows us to ensure a high degree of adequacy of the results of ground-based thermal tests with full-scale ones and thereby provide a higher degree of guarantees to ensure the reliability of the operation of the spacecraft for its intended purpose .

The current trend in the development of communication satellites is characterized by an increase in the period of active existence, energy consumption, and an increase in the density of thermal loads, which complicates the tasks of ensuring the thermal conditions of satellites [12].

To ensure the thermal regime of a spacecraft with a sealed container filled with gas, a gas-liquid thermal control system is used. Excess heat from the devices is transferred to the gas circulating in a closed circuit in the container. From the gas, heat is transferred to a gas-liquid heat exchanger to a liquid coolant, which transfers it to an external radiant radiator. The radiator is a cylindrical or flat shell made of aluminum alloy with hydraulic channels. A coating with a low absorption coefficient of solar radiation and the maximum possible value of emissivity (degree of emissivity) is applied to its outer surface, illuminated by the Sun [14].

Using a closed hydraulic circuit with a coolant fluid circulating in it, which is driven by a hydraulic pump, heat is removed not only from the heat exchanger, but also from the most thermally loaded devices, for example, directly from the repeater.

For reliable operation of the thermal control system, a number of components and assemblies have been developed to ensure heat transfer from the gas circulating in the container to the liquid coolant in the line, as well as heat transfer from the coolant liquid to the ground liquid circuit during electrical tests. These include compact gas-liquid heat exchangers and liquid heat exchangers. Valves, valves and check valves have been developed and used for filling gas and liquid coolant.

Reliable thermostats, control valves, and bypass valves have been developed to actively regulate the thermal regime of a communications satellite during ground-based electrical tests and under normal operating conditions. To create pressure differences to ensure circulation in a closed gas line, fans are used; for the liquid line, hydraulic pumps are used.

One of the most important tasks in the process of designing and creating a communications spacecraft at all stages is carrying out thermal calculations with the selection of optimal thermophysical parameters. In this case, it is necessary to take into account changes in thermophysical parameters during long-term operation in orbit.

Ground testing of the thermal regime of a communications satellite

The complexity of ground-based testing of a communications satellite is associated with the difficulties of simulating real space conditions for its operation: deep vacuum, weightlessness, external heat flows from the Sun and Earth.

To test the thermal regime on a full-scale mock-up of a satellite, a thermal pressure chamber with a simulator of solar heat flow is required. Such testing equipment tens of times larger than the satellite, is complex and expensive. Such tests are called thermal vacuum tests. The ground testing stage is preceded by comprehensive thermal calculations of the individual components of the satellite and the satellite as a whole. To prepare for thermal vacuum testing, at the preliminary design stage, a plan for ground-based experimental testing of components, assemblies, systems and the satellite as a whole is drawn up. At the same time, the number and composition of full-scale development mock-ups, the necessary test equipment and a specialized testing location are determined [15].

Since many Russian satellites contain a sealed container filled with gas, the most appropriate for them was an active gas-liquid system, with specified flow characteristics for liquid and gas coolants, thermally connected to each other through a gas-liquid heat exchanger. On full-scale thermal mock-ups of satellites, appropriate standard gas-liquid thermal control systems are installed. When conducting thermal vacuum tests, along with with the testing of the thermal conditions of the satellite, its systems and external elements, the thermal control system is also being tested, the operation of its automation to regulate temperatures in given ranges under various operating conditions, the transition to backup sets of system units, checking their functionality, as well as testing the electronic control circuits of electric pumps units, fans and electric heaters. The thermobaric chamber provides low pressure, simulating what a spacecraft experiences in outer space, $1{\cdot}10^{-5}$ mmHg. Art., minimum temperatures are not higher than –180 °C, for which low-temperature nitrogen screens are used. To simulate variable heat flows from the Sun to different sides of the satellite, a special rotating device is used, with the help of which the rotation of the satellite is simulated relative to the direction of the heat flow from the solar simulator and, thus, thermal conditions are tested under conditions as close as possible to the conditions of full-scale operation of the satellite. Due to this, high quality and reliability of testing the thermal conditions of the satellite in ground conditions is achieved [11].

Thermal vacuum testing is very expensive; full testing is carried out around the clock for several months and incurs high energy costs. Modern advances in the accuracy of methods for calculating the temperature fields of large and complex satellites, in the speed of carrying out large volumes of calculations on their thermal regimes and their components using a developed fleet of modern computers, have made it possible to implement a new concept for conducting thermal vacuum tests. Its essence lies in carrying out only stationary thermal regimes under conditions of maximum and minimum thermal loads on the satellite as a whole and its individual external elements, followed by ensuring the convergence of test results with the calculated ones. And confirmation of intermediate requirements to ensure specified thermal conditions is carried out by calculation. This allows you to significantly reduce the time required for ground-based thermal satellite development and reduce financial costs.

Ensuring the thermal conditions of a communications spacecraft during ground-based electrical tests

As the active life of a spacecraft increases, ground tests make up a smaller percentage of the total service life of onboard equipment, and therefore the requirements for the quality of their conduct, including the provision of thermal conditions during testing, sharply increase .

Ensuring the thermal conditions of the on-board equipment before launching the satellite into orbit is divided into such stages as ensuring the thermal conditions at the manufacturing plant, during final control, testing of equipment installed on the instrument frame of the undocked satellite (during testing of the undocked complex), testing of a fully assembled satellite at the factory – manufacturer, during transportation to the launch site, during checks at the technical position, the launch complex, the satellite launch site into orbit before its separation from the launch vehicle and during the activation of on-board instrument systems before the start of normal operation.

The thermal conditions of the satellite for all stages are calculated during preliminary design. The versatility and complexity of calculations are determined by strict limiting requirements for energy and mass costs for thermal control devices and thermal control systems in general.

Instruments installed on the satellite's instrument frame must be operable in normal climate conditions of the workshop (at an ambient temperature of 10–35 °C) without special thermostatting by forced airflow. For devices cooled by the liquid coolant of the thermal control system, device developers supply installations that ensure the circulation of the coolant liquid in the cooled circuit of the device with a flow rate equal to or close to the flow rate of the coolant liquid provided by the thermal control system during its normal operation.

For instruments, the thermal regime of which in the satellite is ensured by natural convection using an onboard fan, technological ground fans are used with an intensity of open airflow equivalent to the airflow intensity of the onboard fan during normal operation.

During electrical testing of an undocked satellite before its final assembly, instruments cooled by a liquid coolant are, as a rule, docked with the main line by an on-board thermal control system, and for instruments that require cooling under normal conditions by blowing gas in a sealed container, a technological ventilation unit is used.

During the electrical tests of the docked satellite, the thermal regime is ensured by the on-board thermal control system, the main line of which includes a liquid heat exchanger, the outer circuit of which is connected to the liquid circuit of a special ground-based cooling unit, the need for the use of which is due to the insufficient efficiency of heat removal from the on-board radiant radiator into the environment. If the on-board thermal control system contains only a gas circuit, then the radiating on-board radiator is cooled by blowing air over it, for which a special ventilation unit is used with the required air flow and the ability to both cool and heat the radiating on-board radiator [8].

After completion of electrical tests at the technical complex during the pre-launch preparation period, technological devices are removed from the satellite.

For satellites with a gas-liquid thermal control system, the liquid heat exchanger is cut off using valves that are part of the on-board thermal control system. In this case, the liquid heat exchanger either remains on board, as on the "Molniya" satellite, or is removed from the satellite, as on the "Raduga", "Horizon" and subsequent satellites. It should be noted that the most reliable option is a non-removable process liquid heat exchanger, since this eliminates the possibility of coolant leakage from the liquid circuit of the onboard thermal control system during the process of undocking the heat exchanger, and provides a higher guarantee of the tightness of the onboard liquid circuit. However, due to the strict weight limit of the thermal control system, the liquid heat exchanger has to be removed [14].

The thermal regime of the spacecraft during transportation from the manufacturing plant to the technical position is determined and calculated at the preliminary design stage depending on the tactical and technical requirements for the satellite.

Until recently, many spacecraft could be transported by any type of transport at ambient temperatures in the range of ±50 °C. But at the same time, a large amount of work to prepare the satellite for launch into orbit fell on technical positions, which increased the time the satellite spent at the cosmodrome. In addition, complex and expensive equipment was required for the pre-launch preparation of the satellite, as well as the presence of highly qualified specialists from the manufacturing plant. It was not economically viable. Therefore, there is currently a tendency to ensure that the maximum amount of work to prepare a satellite for launch is carried out at the manufacturing plant. In this case, it is necessary to meet the conditions for ensuring the thermal regime during transportation from the manufacturer to the cosmodrome in the range of approximately 0–40 ° C, which requires the use of a special thermostatically controlled container [16].

Ensuring the thermal conditions of the spacecraft as part of the launch vehicle during transportation from the technical position to the launch complex is carried out by supplying air under the fairing. Air flow and temperature are provided by a ground-based installation depending on the season and weather. In the last hours before launch, the satellite warms up to such a level that during its insertion into orbit its temperature does not go beyond the specified range .

Conclusion

Despite the difference between domestic spacecraft and foreign analogues, which until recently consisted in the presence, as a rule, of a sealed instrument container on domestic satellites, their technical level was fully consistent with the modern world level in terms of active life, reliability and functionality. However, today the development of containerless spacecraft using honeycomb panels and heat pipes is underway.

Библиографические ссылки

1. Анкудинов А. В. Использование математических моделей и методов анализа для определения проектного облика КА связи на ранних этапах жизненного никла // Решетневские чтения : тез. докладов Всеросс.й науч.-техн. конф. Вып. 1. Красноярск, 1997. С. 74.

2. Шатров А. К. Термоструктурный анализ антенных блоков. Науч.-тех. отчет 33-1811-85. Красноярск: НПО ПМ, 1985. 80 с.

3. Шатров А. К. Расчет температурных деформаций берилиевой плиты. Технический отчет 33-3619-88.Красноярск: НПО ПМ, 1988. 62 с.

4. Шатров А. К., Пискунов В. Г., Сипетов В. С. Экспериментально-теоретическое исследование ребристых пологих оболочек в стационарном температурном поле // Прочность материалов и элементов конструкций при сложном напряженном состоянии : тез. докл. Всесоюз. симп. Киев, 1984. Ч. 11. С. 39.

5. Моделирование характеристик тепловых труб при расчете нестационарных температурных полей конструкций с тепловыми трубами / К. Г. Смирнов-Васильев. В. В. Двирный, Г. И. Овечкин, Г. И. Панов // Проблемы обеспечения качества изделий в машиностроении : сб. докл. Междунар. науч.-техн. конф. Красноярск, 1994. С. 462–468.

6. Шатров А. К., Фисенко Е. Н., Рабецкая О. И. Отработка теплового режима спутников связи // Решетневские чтения : материалы XXVI Междунар. науч.-практ. конф., псвящ. памяти генерального коструктора ракетно-космических систем академика М. Ф. Решетнева (09–11 нояб. 2022, г. Красноярск) : в 2 ч. / под общ. ред. Ю. Ю. Логинова. СибГУ им. М. Ф. Решетнева. Красноярск, 2022. Ч. 1. С.357–359.

7. Организация базы данных для численного моделирования температурных полей элементов конструкции космических аппаратов / В. Г. Бутов, Т. В. Васенина, Н. Е. Кувшинов и др. // Вестн. Томск. гос. ун-та. Матем. и мех. 2011. № 4(16). С. 49–54.

8. Быков А. П., Андросов С. В., Пиганов М. Н. Методика тепловакуумных испытаний приборов космического аппарата // НиКСС. 2019. № 3 (27). С. 78–83.

9. Теплообмен и тепловой режим космических аппаратов / под ред. Н.А. Анфимова. М. : Мир, 1974. 544 с.

10. Блох А. Г., Журавлев Ю. А., Рыжков Л. П. Теплообмен излучением. М. : Энергоатомиздат, 1991. 432 с.

11. Крушенко Г. Г., Голованова В. В. Совершенствование системы терморегулирования космических аппаратов // Вестник СибГАУ. 2014. № 3 (55). С. 185–190.

12. Бабышева Е.Е. Перспективы развития спутниковой связи // Экономика и качество систем связи. 2017. № 3 (5) [Электронный ресурс]. URL: https://cyberleninka.ru/article/n/perspektivy-razvitiya-sputnikovoy-svyazi (Дата обращения: 10.05.2023).

13. Буртыль И. В., Голиковская К. Ф. Особенности исполнения приборных отсеков космических аппаратов // Актуальные проблемы авиации и космонавтики. 2012. № 8. С. 48–49.

14. Двирный В. В., Крушенко Г. Г., Двирный Г. В., Шевчук А. А., Елфимова М. В., Кузнецова М. С. Особенности комплектующих систем терморегулирования космических аппаратов // Космические аппараты и технологии. 2019. №1 (27). С. 13–21.

15. Асланян Р. О., Анисимов Д. И., Марченко И. А., Пантелеев В. И. Имитаторы солнечного излучения для термовакуумных испытаний космического аппарата / Р. О. Асланян, Д. И. Анисимов, И. А. Марченко, В. И. Пантелеев // Сибирский журнал науки и технологий. 2017. Т. 18, № 2. С. 323–327.

16. Борисов М. В., Садыков О. Ф. Транспортная космическая система: задачи, структура, параметры // Известия Самарского научного центра РАН. 2019. № 1. С. 72–80.

References

1. Ankudinov A. V. [The use of mathematical models and analysis methods to determine the design appearance of the spacecraft at the early stages of the life cycle]. *Reshetnevskie chteniya : tez. dokladov Vseross.y nauch.-tekhn. konf*. [Abstracts of reports of the All-Russian scientific and technical conference Reshetnev readings]. Is. 1. Krasnoyarsk, 1997, P. 74 (In Russ.).

2. Shatrov A. K. *Termostrukturnyy analiz antennykh blokov. Nauch.-tekh. otchet 33-1811-85* [Thermostructural analysis of antenna blocks. Sci.-tech. report 33-1811-85]. Krasnoyarsk, NPO PM, 1985, 80 p.

3. Shatrov A. K. *Raschet temperaturnykh deformatsiy berilievoy plity. Tekhnicheskiy otchet 33-3619-88* [Calculation of temperature deformations of beryllium plate, Technical report 33-3619-88]. Krasnoyarsk, NPO PM, 1988, 62 p.

4. Shatrov A. K., Piskunov V. G., Sipetov V. S. [Experimental and theoretical study of ribbed flat shells in a stationary temperature field]. *Prochnost' materialov i elementov konstruktsiy pri slozhnom napryazhennom sostoyanii : tez. dokl. Vsesoyuz. simp* [All-Union Symposium Strength of materials and structural elements in a complex stress state]. Kiev, 1984, Part 11, P. 39.

5. Smirnov-Vasiliev K. G., Dvirny V. V., Ovechkin G. I., Panov G. I. [Modeling the characteristics of heat pipes in the calculation of non-stationary temperature fields of structures with heat pipes]. *Problemy obespecheniya kachestva izdeliy v mashinostroenii : sb. dokl. Mezhdunar. nauch.-tekhn. konf*. Krasnoyarsk, 1994, P. 462–468 (In Russ.).

6. [Testing of the thermal regime of communication satellites / A. K. Shatrov, E. N. Fisenko, O. I. Rabetskaya]. *Reshetnevskie chteniya : materialy XXVI Mezhdunar. nauch.-prakt. konf., psvyashch. pamyati general'nogo kostruktora raketno-kosmicheskikh sistem akademika M. F. Reshetneva* [Reshetnev readings: proceedings of XXVI International Scientific Conference]. Krasnoyarsk, 2022, Part 1, P. 357–359 (In Russ.).

7. Butov V. G., Vasenina T. V., Kuvshinov N. E. et al. [Organization of a database for numerical modeling of temperature fields of spacecraft structural elements]. *Vestn. Tomsk. gos. un-ta. Matem. i mekh*. 2011, No. 4(16), P. 49–54 (In Russ.).

8. Bykov A. P., Androsov S. V., Piganov M. N. [Methods of thermal vacuum tests of spacecraft instruments]. *NiKSS.* 2019, No. 3 (27), P. 78–83 (In Russ.).

9. *Teploobmen i teplovoy rezhim kosmicheskikh apparatov* [Heat exchange and thermal regime of spacecraft]. Ed. N. A. Anfimov. Moscow, Mir Publ., 1974, 544 p.

10. Bloch A. G., Zhuravlev Yu. A., Ryzhkov L. P. *Teploobmen izlucheniem* [Heat exchange by radiation]. Moscow, Energoatomizdat Publ., 1991, 432 p.

11. Krushenko G. G., Golovanova V. V. [Improving the system of thermoregulation of spacecraft]. *Vestnik SibGAU.* 2014, No. 3 (55), P. 185–190 (In Russ.).

12. Babysheva E. E. [Prospects for the development of satellite communications]. *Economics and quality of communication systems.* 2017. No. 3 (5).

13. Burtyl I. V., Golikovskaya K. F. [Features of the execution of instrument compartments of spacecraft]. *Actual problems of aviation and cosmonautics*. 2012, No. 8, P. 48–49 (In Russ.).

14. Dvirny V. V., Krushenko G. G., Dvirny G. V. et al. [Features of component systems for thermoregulation of spacecraft]. *Kosmicheskie apparaty i tekhnologii.* 2019, No. 1 (27), P. 13–21 (In Russ.).

15. Aslanyan R. O., Anisimov D. I., Marchenko I. A., Panteleev V. I. [Solar radiation simulators for thermal vacuum tests of spacecraft]. *Sibirskiy zhurnal nauki i tekhnologiy.* 2017, Vol. 18, No. 2, P. 323–327 (In Russ.).

16. Borisov M. V., Sadykov O. F. [Transport space system: tasks, structure, parameters]. *Izvestiya Samarskogo nauchnogo tsentra RAN*. 2019, No. 1, P. 72–80 (In Russ.).

Шатров Александр Константинович – доктор технических наук, профессор, профессор кафедры технической механики; Сибирский государственный университет науки и технологии имени академика М. Ф. Решетнева. E-mail: shatrov@sibsau.ru.

Рабецкая Ольга Ивановна – кандидат технических наук, доцент кафедры технической механики; Сибирский государственный университет науки и технологии имени академика М. Ф. Решетнева. E-mail: rabetskaya@sibsau.ru.

Фисенко Елена Николаевна – старший преподаватель кафедры технической механики; Сибирский государственный университет науки и технологии имени академика М. Ф. Решетнева. E-mail:fisenkoen@sibsau.ru.

Shatrov Alexander Konstantinovich – Dr. Sc., Professor, Professor of the Department of Technical Mechanics Reshetnev; Reshetnev Siberian State University of Science and Technology. E-mail: shatrov@sibsau.ru.

Rabetskaya Olga Ivanovna – Cand. Sc., Associate Professor of the Department of Technical Mechanics; Reshetnev Siberian State University of Science and Technology. E-mail: rabetskaya@sibsau.ru.

Fisenko Elena Nikolaevna – Senior Lecturer of the Department of Technical Mechanics; Reshetnev Siberian State University of Science and Technology. E-mail: fisenkoen@sibsau.ru.