Contemporary Engineering Sciences, Vol. 9, 2016, no. 26, 1273 - 1281
HIKARI Ltd, www.m-hikari.com
http://dx.doi.org/10.12988/ces.2016.67123

Thermal State Simulation of Radioelectronic Components as a Part of Space Vehicle with Regard to Internal Heat and External Heat Exchange

Andrey V. Paleshkin, Vadim V. Terentyev and Sergey O. Firsyuk

Moscow Aviation Institute (National Research University)
4 Volokolamskoe shosse, GSP-3, A-80, Moscow, 125993, Russia

Abstract

This article describes the conditions of the spacecraft (SC) heat transfer at the stages of its operation. A methodical approach is developed, and algorithm for calculation of external and internal heat transfer of spacecraft is proposed. The calculations of the thermal modes and computer experiment to assess the possibility of placing electronic components on the surface of the plate inside non-hermetic SC are carried out. Modeling was carried out taking into account heat liberation of functioning equipment and requirements for the maintenance of a specified temperature range with passive temperature control means. Obtained using a mathematical model results could be used as input parameters for reproducing the calculated external heat loads on the SS irradiated surface during the thermal vacuum tests. The methods of model verification and confirmation of the adequacy of ground tests during the flight test are proposed.

Keywords: Small spacecraft, Radiation heat transfer, Heat balance, Simulation experiment

Introduction

Maintenance of the desired temperature of devices and equipment is one of the main tasks of a spacecraft (SC) operation in orbit under the influence of external factors. Since SC devices have increased requirements for reliability that is why intermittent output from temperature range can leads to the loss of the SC. At the present time the majority of SC have non-hermetic performance, so in the conditions of space vacuum there are only radiative and conductive heat transfer, which efficiency is lower than the convective one used for thermostat control of equipment placed in SC pressurized container or at working in ground conditions. Other important factors lead to hypothermia or overheating of devices and equipment are cold and blackness of outer space, as well as an external heat exchange depending on the SC location and orientation relative to the Sun and the planets.

Rely to the requirements for units of electronic equipment and thermal condition of structure elements in real conditions of operation the SC developers pay particular attention to the accuracy of SC temperature modes modeling [2], as well as to reducing the costs of ground tests. Note that the accuracy of the numerical and natural experiment and simulation of SC with high accuracy could be confirmed only by experiments in outer space. At the same time, it should be noted a significant increase in the number of university launched satellites including CubeSat format, which can be used for flight tests and scientific experiments for verification of mathematical models and methods for ground tests of space technology products.

The methodical approach to the calculation of the SC thermal mode

In general, the process of storing the working temperature of the equipment installed on SC board reduces to maintenance of the required level of heat balance between the emitted heat flow and total heat capacity of devices. For small SC of non-hermetic version (for example, the standard «CubeSat») and passive thermal control system it is necessary to take into account the external heat to determine the thermal state of the internal electronics. Since the SC frame is a scattering heat conductor, when the properly selected radiation and optical characteristics of the surface these parameters will be essential for the maintenance of internal given temperature. The general heat balance equation can be written as follows:

$$m_i c_i \frac{dT_i}{d\tau} = Q_{si} + Q_{condi} + Q_{refi} + Q_{\text{int}i} + Q_{ri} \quad (1)$$

Included in the equation heat flows can be expressed as follows:

$$Q_{si} = A_{si} \cdot S \cdot \frac{(\vec{n}_{di} \cdot \vec{\rho}_{di-S}) + \left|(\vec{n}_{di} \cdot \vec{\rho}_{di-S})\right|}{2} \quad (2)$$

The average density of solar radiation reflected from the Earth absorbed by SC surface is determined by the following relationship:

$$Q_{refi} = A_{si} \cdot a_{\mathrm{E}} \cdot S \cdot \frac{(\vec{n}_{di} \cdot \vec{\rho}_{di-S}) + \left|(\vec{n}_{di} \cdot \vec{\rho}_{di-S})\right|}{2} \phi_{i-pl}, \tag{3}$$

The use of such ratio based on the assumption of a uniform distribution of the flux density reflected from the visible area of the planet, which is equal to the reflected radiation flux outgoing from the Earth's surface area over which is currently the SC.

The average density of the absorbed flow of own Earth's radiation by homogeneous surface F_i:

$$\mathrm{Q}_{\mathrm{int\,i}} = \frac{\varepsilon_i \cdot S \cdot (1 - a_E) \cdot \varphi_{i-pl}}{4}, \tag{4}$$

The radiation flux from the element of surface into space:

$$Q_{ri} = \varepsilon_i \cdot \sigma \cdot T_i^4 \cdot F_i, \tag{5}$$

Taking into account the overall heat balance equation, as well as the methodological approach to the determination of the thermal state at a point on the surface of the insulated element of small spacecraft described in [1], we obtained the effective density of heat flows coming from each face. These densities allow to calculate the temperature distribution Ti (i = 1, 2, ..., N) on the faces of the object under study.

Examine internal heat exchange and define the temperature distribution over the plate surface, wherein the electronics module is installed based on the heat flux from the source. This requires a solution to two-dimensional heat conduction problem:

$$\rho \cdot c \cdot \frac{\partial T}{\partial \tau} = \lambda \left(\frac{\partial^2 T}{\partial x^2} \right) + \lambda \left(\frac{\partial^2 T}{\partial y^2} \right), \tag{6}$$

taking into account initial $T\big|_{t=0} = T_0(x, y)$

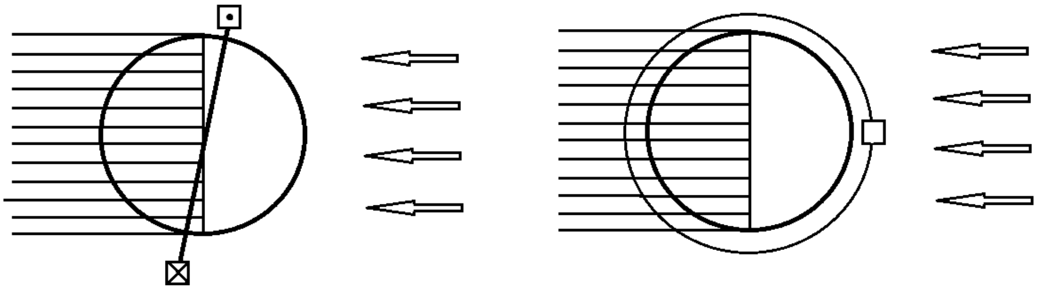
and boundary conditions $-\lambda \frac{\partial T}{\partial n}\Big|_F = q_{\mathrm{int}} + q_{ext} - q_r$,

as well as conductivity conditions between elements $q_{con} = R(T_1 - T_2)$.

In order to understand how equipment will behave in a space condition it is necessary to take into account that in the course of the annual motion of the SC along with the Earth around the Sun, the angle between the plane of the orbit and the direction of the Sun can vary over a wide range. Therefore, the calculation of the SC thermal mode for further analysis of the equipment work in a given temperature range should be carried out on two calculation cases: "hot" and "cold."

1. "Hot" case - the orbit of the apparatus is in the terminator plane (Fig.1a). A constant flare from the Sun and maximum heat emission of equipment characterizes it.

2. "Cold" case - the orbit of the apparatus is perpendicular to the plane of the terminator. (Fig.1b). The main parameters are the maximum stay in the shade and irregular thermal load.



a b

Figure 1. Calculated cases of external heat exchange

Statement of the problem and calculation results

The original formulation of the problem comes from the need to performance adjusted check of magnetic executive body control unit, which can be installed on the non-hermetic spacecraft discussed in [1]. However, taking into account the concept of a model experiment described in [5], it is necessary to simplify the investigated element to the sample or model, which could be produced and tested on the available research bench. Currently, MAI is being involved in preparation of CubeSat format satellite, in which radio-electronic magnetic executive body controls units and electronic indicator of the thermal state are installed. Accordingly for this calculation the geometric parameters are selected both for spacecraft and payload with respect to power emitted by electronic elements.

SC motion occurs in an oriented mode. SC x-axis is directed to the Earth. In the vicinity of the Earth the average solar irradiance is 1396 W/m^2, but depending on the season this value ranges from 1445 W/m^2 to 1347 W/m^2. The average radiation flow density reflected from the Earth is 265 W/m^2 and intrinsic radiation density is 220 W/m^2. The attitude of the sun synchronous orbit is 550km, orbital period T is equal to 95,57 minutes. Radiation-optical characteristics of the device surface was taken as As = 0,85, ε = 0,77. The albedo of the Earth for the first case is 0.39 for the first case and 0,35 for the second.

Consider Figure 1b. Since the stay period in the shadow is 28,88 minutes, then the bulk temperature reaches 94°C and 2,26°C in subsolar point. The average temperature of the satellite in orbit is 34,10°C.

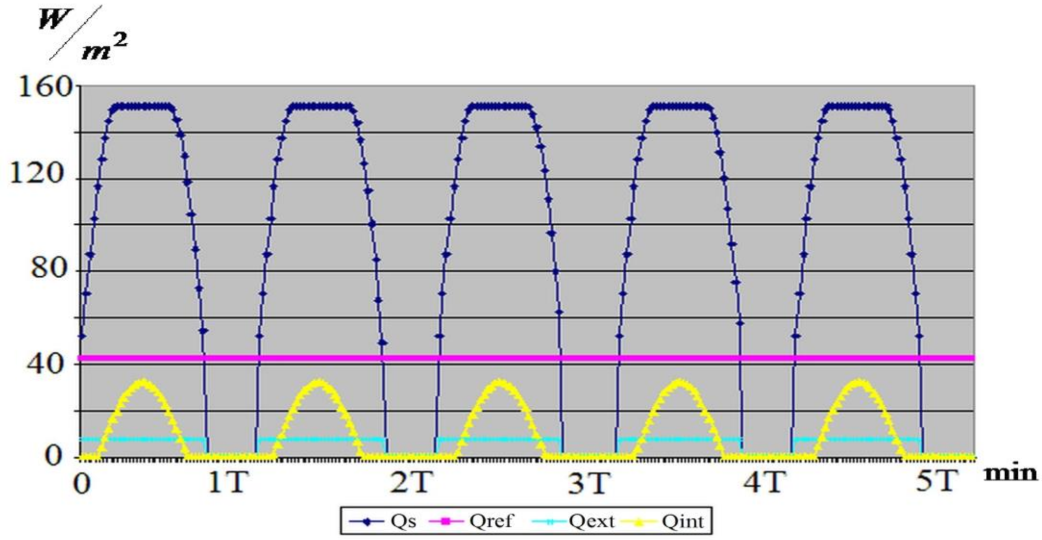


Figure 2. Density of external heat fluxes acting on the spacecraft.

The graph for the numerical solution to the differential equation spacecraft thermal state for 5 single passes is presented in Fig.3.

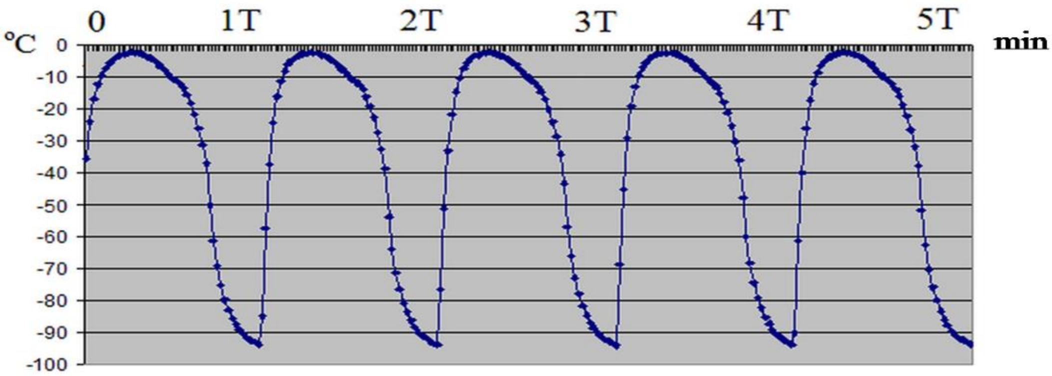


Figure 3. Temperature dependence on time during the spacecraft orbital motion.

Analyzing obtained data and Fig.2-3 we can say that the passive thermal control system for such type of satellites is only possible when the orbits are perpendicular to the terminator. Due to the irregular internal and external heat sources the required temperature in a given range of the target and service equipment is not possible.

Consider the case shown in Fig.1a. Since there is no shadow the bulk temperature of satellite was 12^{o}C. Therefore, the results of calculations for the polar orbit taking into account the data of external influencing factors and the thermal state of the electronics unit located on the aluminum plate are presented on Fig. 4. Flight direction occurs on the axis OZ.

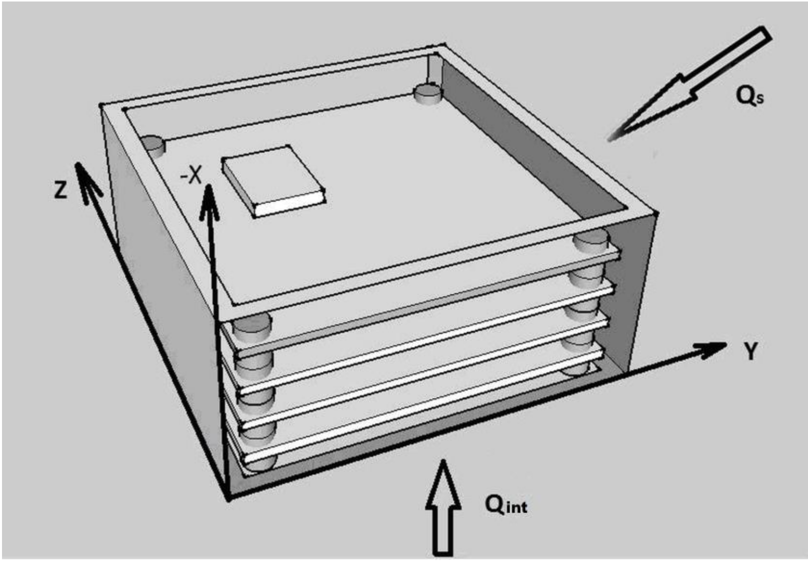


Figure 4. The geometric model for SC calculating

Calculation of the thermal mode was carried out for non-stationary case with the help of implicit finite-difference scheme with the heat balance equations linearization. Plate 9x9 cm was divided into 12 units on each side. The initial temperature T_0 = 273°K, T_1 = 233°K, T_2 = 323°K, ρ = 2700 kg/m^3, λ = 237 W/m°C, the heat emission of the block is equal to 5W. Heat sink on the takedown screw of plate is not taken into account. The temperature distribution on the plate surface after 100, 600 and 6000 seconds is shown in Figures 5a, b and c, respectively.

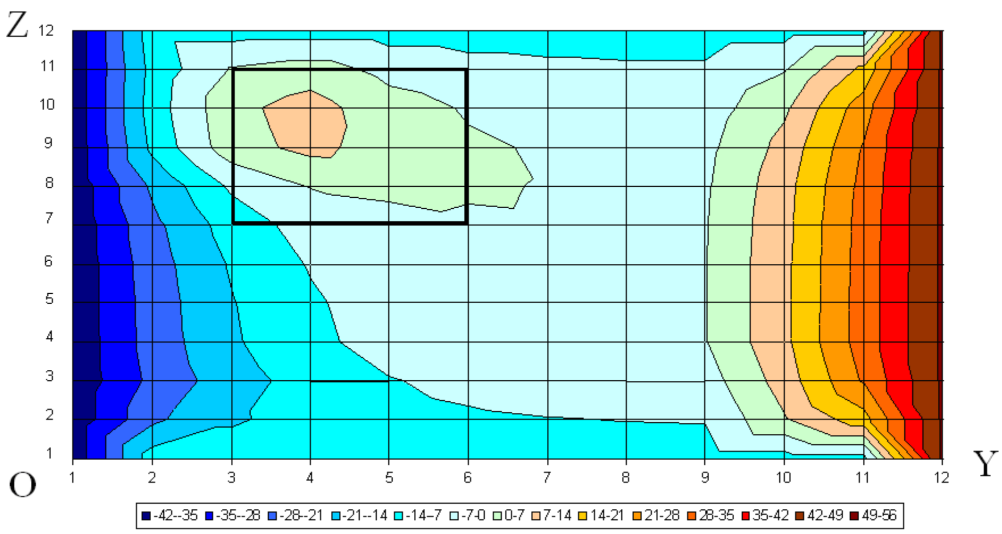


Figure 5-a. Temperature distribution [°C] on the plate surface 100 sec.

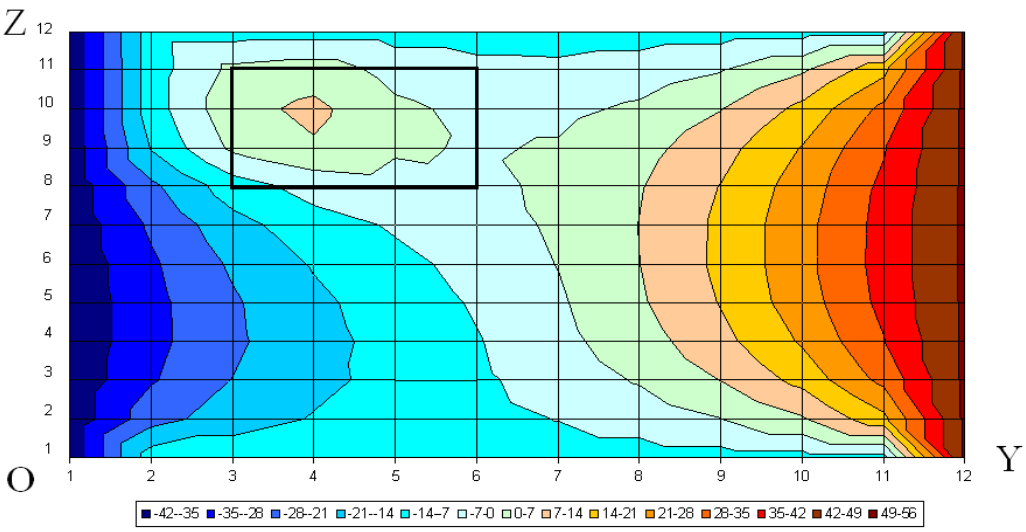


Figure 5-b. Temperature distribution [^{o}C] on the plate surface 600 sec.

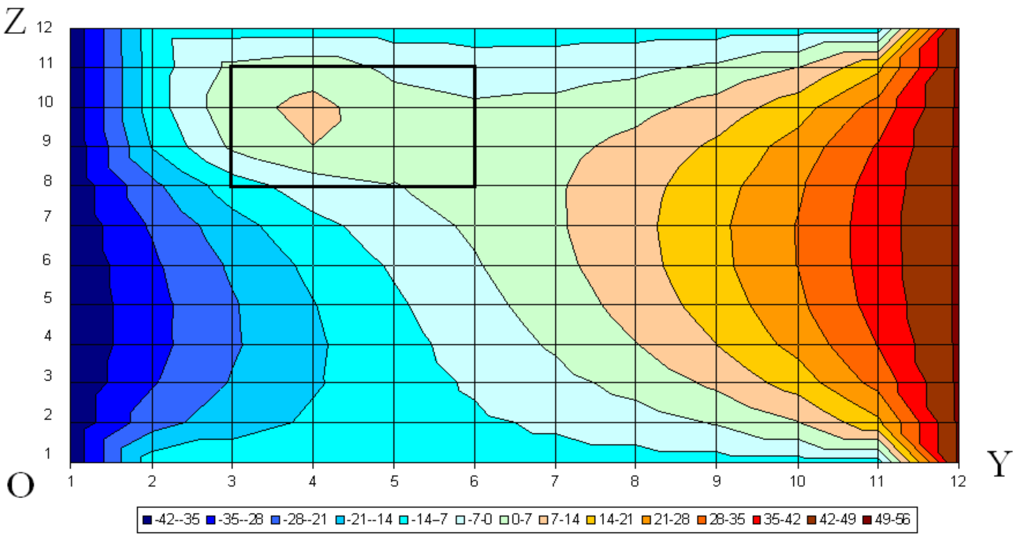


Figure 5-c. Temperature distribution [^{o}C] on the plate surface 6000 sec.

As it can be seen from Fig.5 the temperature range of the plate is from 35 to 50^{o}C if not consider extreme boundaries end faces. Therefore, this factor should be considered during the SC preliminary thermal design when placing the temperature sensing elements allocated between 0 to 40^{o}C, because by increasing the number of heat sources the plate temperature will arise, which may affect the operation of electronics. To verify the model it is necessary to carry out the further laboratory tests in a vacuum chamber to detect the actual spectral and integral characteristics of the spacecraft and the distribution of temperature fields on the plate. Tests should be carried out in a vacuum of not more than 10^{-2}Pa and camera must be equipped with a nitrogen-screen to simulate a "cold" and "blackness" of outer space and the infrared emitters to simulate the calculated external heat loads produced by means of mathematical model. These results can be used as input parameters. Methods and tools for simulating operating conditions, as well as an approximate simulation of spacecraft external heat with the help of infrared radiation sources are discussed in [3]. Also, it should be considered the accompanying problem for selection of infrared energy simulator modes [4]. This follows from the need to calculate the distribution of flux density outgoing from the radiant heat source and determine the value of input electric power to the irradiator, with which the required law of distribution of thermal load on the irradiated surface is implemented.

Conclusion

This article describes the SC heat transfer conditions on the stages of its operation. A generalized mathematical model of internal and external heat transfer is proposed. On the basis of the developed algorithm a program for calculations of two cases of external heat exchange was developed. Computer experiment to assess the possibility of placing electronic components on the surface of the plate inside the spacecraft for equipment operation in a comfortable environment was carried out with regard to the selected optical and radiation characteristics of the outer surface. In the calculations the average temperature of the unit for one single pass is 5 °C. Recommendations for testing in the experimental stand are given for further research and refinement of mathematical models. The calculation results were used during the preparation of the flight experiment on developed at MAI satellite "Iskra-MAI-85."

Acknowledgements. This research was financially supported by the state in the person of the Ministry of Education and Science of the Russian Federation in the frame work of the project RFMEFI57414X0103.

Nomenclature

m_i, c_i, T_i – mass, specific heat and temperature of the *I* elements, respectively; τ - time; Q_{si} – heat flux of direct solar radiation absorbed by the *i* element; Q_{cond} - conduction heat flow; Q_{refi} – the heat flux of the reflected solar radiation from the Earth absorbed by the *i* element; Q_{inti} – heat flux of Earth's intrinsic radiation absorbed by the *i* element; Q_{ri} – heat flux emitted by the surface of the *i* element; *S* – density of the direct solar heat flow incident on the *i* element; A_{si} – solar radiation absorption coefficient by the surface of the *i* element; $\vec{n}_{di}$ – the normal vector of the elementary area; $\vec{\rho}_{di-S}$ vector aimed at the center of the sun; a_E – albedo of the Earth; f_{i-pl} – the average angular surface factor Fi and the planet; ε_i – emissivity of surface of the *i* element; T_i – temperature of the *i* element; σ – Stefan-Boltzmann constant; F_i – the surface area of the *i* element radiating into the environment; q_{ext}, q_{int}, q_r – external, internal and outgoing heat flow acting on the surface; λ – thermal conductivity of the element; T – temperature; ρ – plate density.

References

[1] O.M. Alifanov, A.V. Paleshkin, V.V. Terentev, S.O. Firsyuk, Mathematical modeling of the thermal state of an isothermal element with account of the radiant heat transfer between parts of a spacecraft, *Journal of Engineering Physics and Thermophysics*, **1** (2016), 179-185. http://dx.doi.org/10.1007/s10891-016-1365-0

[2] A.V. Delkov, A.A. Khodenkov, Yu,N. Shevchenko, Comparison of direct and reverse cycle in thermal control systems of non-hermetic spacecraf (in Russian), *Vestnik SibGAU*, **4** (2014), 154–159.

[3] A.A. Galeev, A.V. Kolesnikov, A.V. Paleshkin, V.V. Rodchenko, *Design of Test Benches for Thermal Vacuum tests of Spacecraft*, MAI Publishing, Moscow, 2015.

[4] K.I. Mamedova, A.V. Paleshkin, Simulation of calculated external heat loads to the surface of the spacecraft with the help of infrared heaters, *Trudi MAI On-Line Journal*, **85** (2016).

[5] A.A. Matushkin, V.V. Terentev, S.O. Firsyuk, Modern features of model experiment and its role in aircraft elements design (in Russian)., *Herald of the Bauman Moscow State Technical University. Series Mechanical Engineering*, **1** (2016), 29-43. http://dx.doi.org/10.18698/0236-3941-2016-1-29-43

Received: July 25, 2016; Published: September 19, 2016