THERMAL DESIGN OF PHOTOVOLTAIC SOLAR PANELS FOR SPACE APPLICATIONS

Célio Costa Vaz, celiovaz@orbital-eng.com
Orbital Engenharia Ltda,
São José dos Campos, 12240-000, São Paulo, Brazil

Bruno NunesVaz, bruno.ssv@gmail.com
São Paulo State University, Faculty of Engineering of Guaratinguetá
Guaratinguetá, 12516-410, São Paulo, Brazil

Jaqueline NunesVaz, jaqueline@orbital-eng.com
Orbital Engenharia Ltda,
São José dos Campos, 12240-000, São Paulo, Brazil

Abstract. *This paper addresses the thermal design of photovoltaic solar panels for space applications. The results of a generic mathematical model for space solar panels thermo-optical analysis are discussed aiming to provide to a solar array designer the most sensitive thermal parameters affecting the electrical energy generated by the solar cells along one satellite orbit. The in-orbit temperature of the several layers of a typical solar panel multi-layer structure is determined under steady-state and transient conditions, using uni heat transfer models for coupled conduction and radiation with non linear boundary conditions. The electrical energy generated by the solar cells is calculated by integration of the electrical power at both operation voltage and maximum power voltage along the satellite orbit considering the solar cells temperature profile along on satellite orbit.*
Keywords*: solar panels, thermo analysis, space satellites.*

1. SOLAR PANELS DESCRIPTION

Most of the modern space vehicles use solar cells as primary energy source to operate its internal equipment. Generally solar cell array constitutes the power generation equipment within the framework of a power subsystem of a satellite or other space application system that require electrical power. A solar cell panel is an array arrangement of solar cells designed to generate electricity directly from sunlight.

Since the photoconversion efficiency of solar cells is temperature and light intensity dependent, a careful thermo-optical design may be lead to improve solar array performance.

2. MATHEMATICAL MODEL OF THE SOLAR PANEL

Thermal model of the solar panel is based on the panel energy balance scheme that is depicted in Fig. 1.

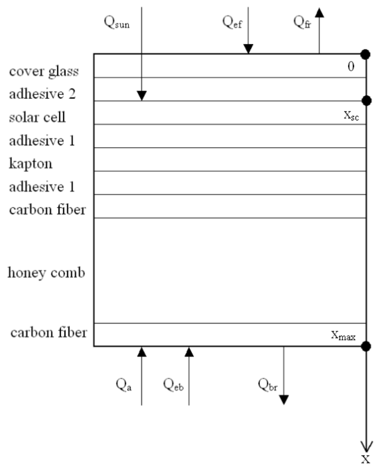

Figure 1. Scheme of solar panel energy balance

Sun and albedo radiation incident on the panel front side are absorbed by the solar panel cells and kapton gap. The absorbed heat flux is given by Eq. (1).

$$Q_{sun}^{abs} = Q_{sun}\,[F_g\,\alpha_{sc}\,(1-\eta(T))\,F_p + \alpha_k\,(1-F_p)] \tag{1}$$

Where Q_{sun} – sum of incident sun and albedo radiation, F_g – glassing factor, α_{sc} – solar cell absorptivity, η – solar cell efficiency, F_p – packing factor, α_k – kapton absorptivity. Glassing factor F_g is defined according to the optical model.

The Earth emits long-wave infrared radiation, therefore this radiation is absorbed by the cover glass because it has high value of emissivity:

$$Q_{ef}^{abs} = Q_{ef}\,[\varepsilon_{cg}\,F_p + \varepsilon_k\,(1-F_p)] \tag{2}$$

Where Q_{ef} – earth radiation incident on the panel front side, ε_{cg} – cover glass emissivity, ε_k – kapton emissivity.

Radiation of the solar panel front side Q_{fr} is in infrared part of the spectrum, too. Hence this radiation occurs from the cover glass surface:

$$Q_{fr} = [\varepsilon_{cg}\,F_p + \varepsilon_k\,(1-F_p)]\,\sigma T_{cg}^4 \tag{3}$$

Where σ – Stefan-Boltzmann constant, T_{cg} - the temperature of the cover glass surface.

Carbon fiber facesheets and honey comb core are considered as quasi-homogeneous layers, thus it is assumed that radiation incident on the panel rear side is absorbed by the carbon fiber facesheet surface and back side radiation occurs from the same surface. Therefore back side absorbed and emitted heat fluxes are:

$$Q_a^{abs} = \alpha_b\,Q_a \tag{4}$$

$$Q_{eb}^{abs} = \varepsilon_b\,Q_{eb} \tag{5}$$

$$Q_{br} = \varepsilon_b\,\sigma\,T_b^4 \tag{6}$$

Where α_b – panel back side absorptivity, Q_a – sum of sun radiation and albedo incident on the panel back side, ε_b – panel back side emissivity, Q_{eb} – earth radiation incident on the panel back side, T_b – temperature of the carbon fiber facesheet surface.

Solar panel is considered as one-dimensional multiplayer system with different thermal properties of the layers and negligible thermal resistance. Governing heat conduction equation for this system can be written as:

$$\rho c \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + S \tag{7}$$

$$\rho = \rho(x),\; c = c(x),\; k = k(x,T) \tag{8}$$

$$S = \begin{cases} Q_{sun}^{abs}/\delta x, & x_{sc} \le x \le x_{sc} + \delta x \\ 0, & x_{sc} + \delta x < x < x_{sc} \end{cases} \tag{9}$$

Boundary condition are:

$$x = 0:\; -\left(k\frac{\partial T}{\partial x}\right)_0 = Q_{ef}^{abs} - Q_{fr} \tag{10}$$

$$x = x_{max}:\; -\left(k\frac{\partial T}{\partial x}\right)_{x_{\max}} = Q_{br} - Q_a^{abs} - Q_{eb}^{abs} \tag{11}$$

2. THERMAL LOADS

The main external thermal loads interfering in the energy balance of a solar array of a low earth orbit satellite are schematically depicted in Fig. 2 . Direct sunlight radiation (solar flux) - Q_{sf}, sunlight reflected from the Earth (albedo radiation) - Q_{af} and thermal Earth radiation - Q_{ef} are falling on the front side of the solar panels. Albedo radiation - Q_{ab} and thermal Earth radiation - Q_{eb} are falling on the rear side of the solar panels.

Due to the Earth's elliptical orbit, the intensity of sunlight reaching the Earth varies approximately ±3.5 percent depending on the Earth's distance from the Sun - from 1309W/m^2 to 1399W/m^2.

Sunlight radiation incident on the front side of the panel is

$$Q_{sf} = Q_s \cos(\phi) \tag{12}$$

Where:

Q_s - sunlight intensity (1309 ÷ 1399W/m^2),

ϕ - angle between the sunlight vector and the normal to the solar panel.

Angle ϕ varies during a year and depends on the satellite crossing equator time for sun synchronous orbit.

Taking into account varying values of Q_s and ϕ, two variants of external heat fluxes must be considered - so named "cold case" (SOLMIN) and "hot case" (SOLMAX). The difference between cold case and hot case is in the solar flux and albedo incident on the front and rear side of the panel. Results of these calculations for the hot case are presented in Fig.2. In this graph and below in this report we use:

$$Q_{sun} = Q_{sf} + Q_{af} \tag{13}$$

$$Q_a = Q_{ab} \tag{14}$$

Heat flux, absorbed by the solar panel surface depends on the optical properties of the surface, in particularly emissivity - ε and absorptivity - α. These properties are changing during the orbital flight. Therefore real thermal loads will be different in the beginning of the spacecraft mission (BOL) and in the end of the mission (EOL). As a result thermo-optical analysis of the solar panels must be performed at least for four cases : cold case - BOL, cold case - EOL, hot case - BOL, hot case - EOL.

In addition to the described above external thermal loads there are radiation heat exchange between solar array and satellite main body and some heat flux from the diode board of the solar panel.

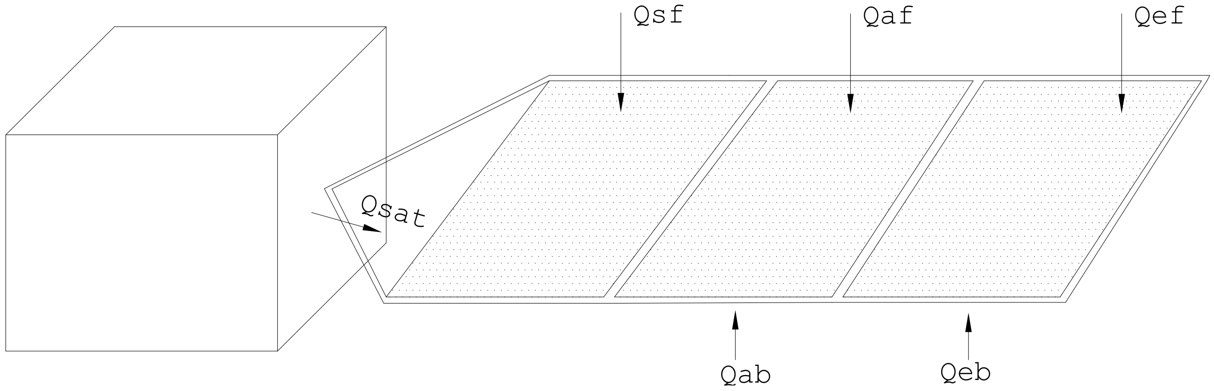

Figure 2. Solar array thermal load

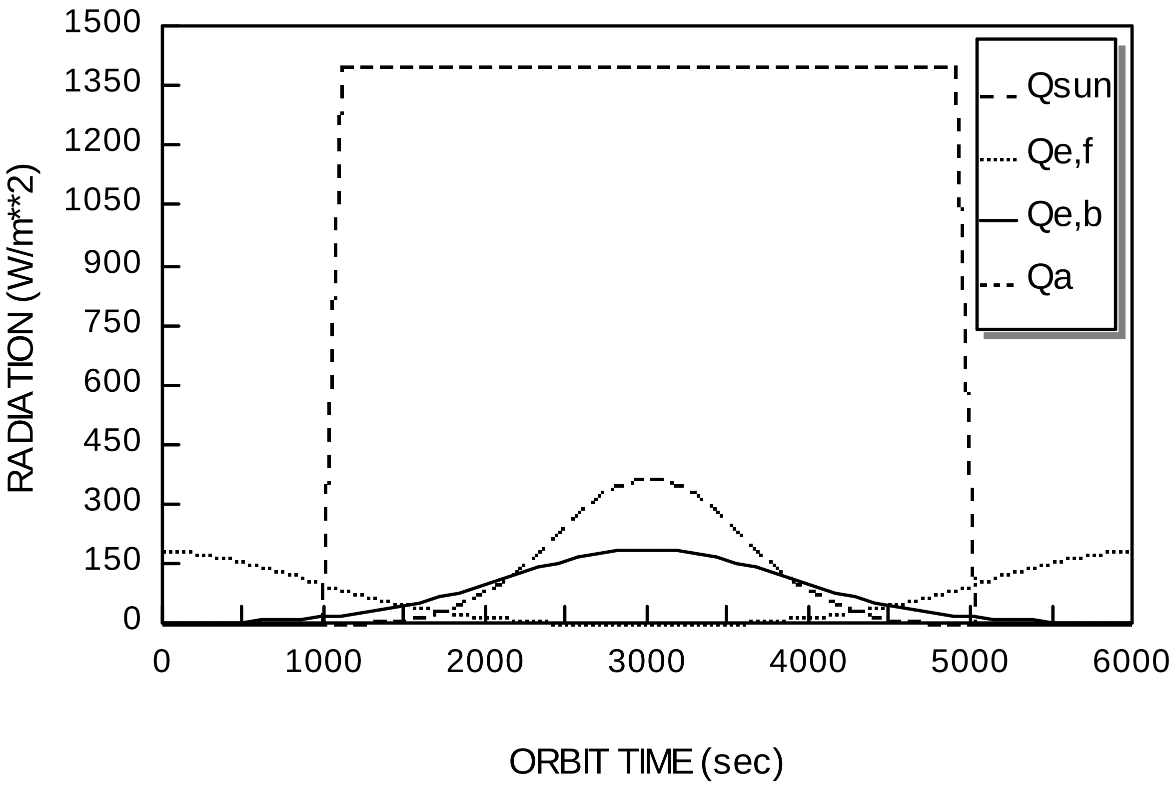

Figure 3. Hot case thermal loads for one orbit

3. SOLAR ARRAY IN –ORBIT PERFORMANCE

Graphs of solar panel temperature during one orbit are shown in Fig. 4. One dimensional and lumped models were used. Temperature of the solar cells and panel rear side predicted by one dimensional model are depicted by Graphs 1 and 3 respectively. Difference between their temperature is significant (up to 41.2°C at orbit time equal to 4970 sec). It can be explained by high thermal resistance of the solar panel cross section which is determined first of all by high thermal resistance of honey comb core. As a result lumped model gives not negligible error of solar cell temperature. Temperature of the panel solar cells obtained by the lumped model is depicted by Graph 2 in Fig. 4. Difference between solar cell temperature predicted by one dimensional and lumped models is shown in Fig. 5. It achieves 38.4°C at orbit time 1450 sec, the average value of the difference is 15.4°C.

Graphs of electrical power generated by the solar array at the operation voltage are presented in Fig. 6. For Graph1 temperature was predicted by one dimensional model. For Graph2 temperature was predicted by lumped model.

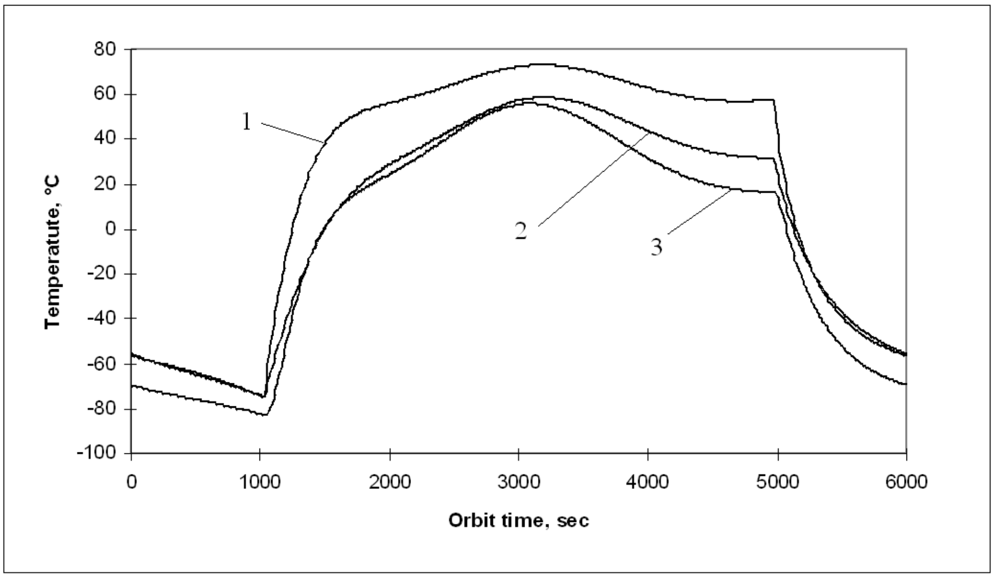

Figure 4. Solar panel temperature. 1 - solar cell temperature (one dimensional model), 2 - solar cell temperature (lumped model), 3 - rear side temperature (one dimensional model).

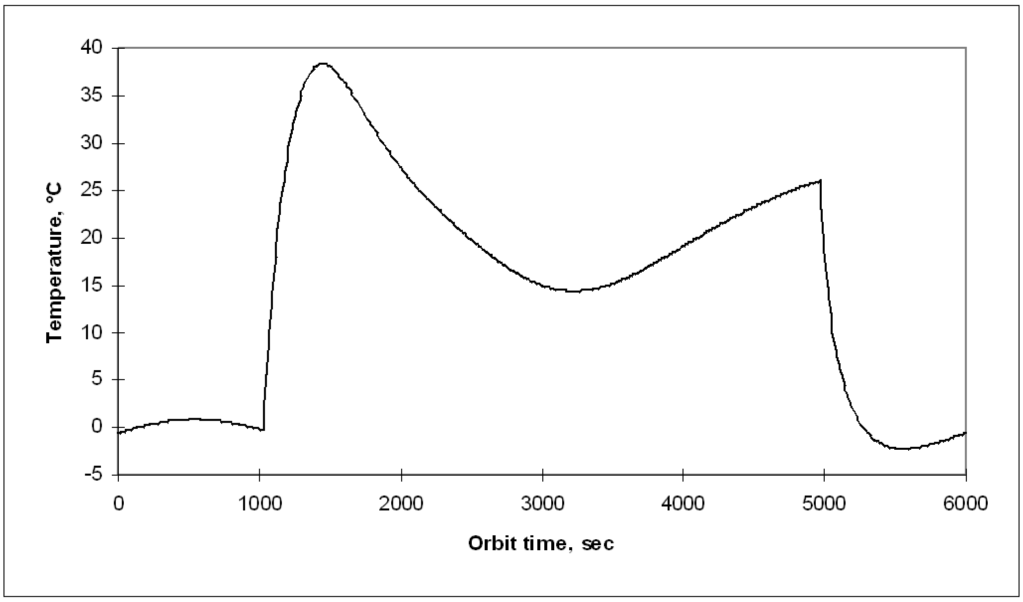

Figure 5. Difference of solar cell temperature predicted by one dimensional and lumped models.

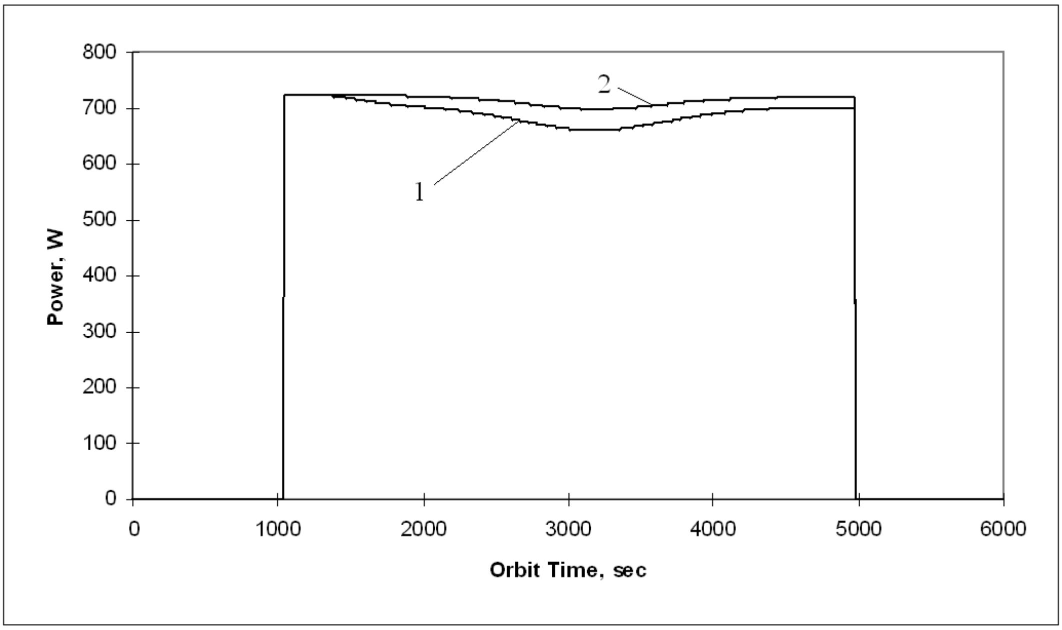

Figure 6. Solar array generated electrical power. 1 - one dimensional model, 2 - lumped model.

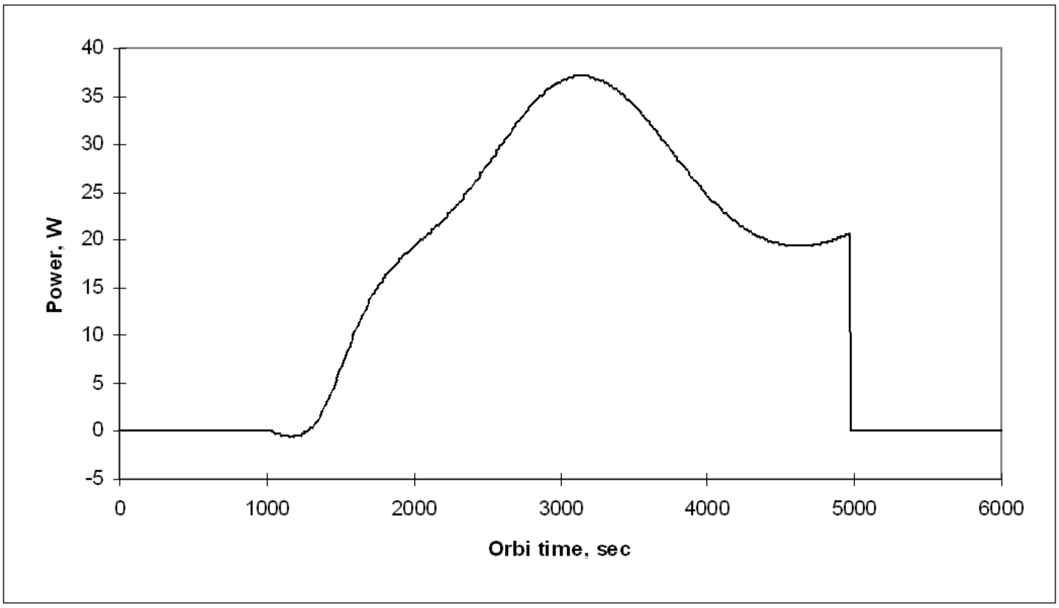

Figure 7. Difference of solar array generated electrical power predicted by one dimensional and lumped models.

Energy generated during one orbit is 2727 KJoules if one dimensional model is used and 2815 KJoules for the lumped model. Thus the difference is 88 KJoules or 3.2 %.

Results of the thermal and electrical simulation of the solar array show that developed mathematical model allows to do more accurate prediction of solar array in-orbit performance and to analyze more complex thermal processes in solar panels.

Dependence of solar array performance on solar cell temperature is illustrated in Fig. 6. At orbit time 1210 sec, when solar cell temperature is -8.9 C, generated power is 724.1 W. When solar cell temperature gets maximum (73.1 C) at orbit time 3170 sec, the power drops to 660.8 W. That is about 9 % less than power generated just after eclipse when solar cells are still cold. Hence the purpose of solar array thermal designing is to decrease solar cell maximum temperature and as a result to achieve higher electrical power and generated in one orbit energy.

Available thermo-optical model of the space solar panel allows to analyze photoconversion, electrical and thermal processes in the solar panel and to find ways to improve solar array in-orbit performance.

4. SENSITIVITY ANALYSIS

To improve solar array performance it is important to know influence of different design parameters on the work of solar panels. Solar array in-orbit performance can be characterized by solar cell maximum and minimum temperature, maximum and minimum electrical power generated during an orbit, etc. Probably the most important factor is energy generated by solar array in one orbit.

Influence of some design parameters on the solar array generated energy is relatively clear. In case of this study infrared radiation incident on the solar panel front side is small compared with the radiation in the visible range of the spectrum, hence increase of cover glass emissivity (ε_{cg}) leads to the increase of generated power and energy because of the drop of solar cell temperature. Similar situation is with kapton emissivity and absorptivity (ε_k and α_k). To reduce cell temperature and to improve solar array performance kapton emissivity must be increased and kapton absorptivity must be decreased.

Influence of glassing factor (F_g) and solar cell absorptivity (α_{sc}) is more complicated. Their increase causes increase of generated power, but on the other hand it leads to higher solar cell temperature and more low efficiency of photoconversion.

Simulation of solar array performance with different values of glassing factor shows that influence of glassing factor increase on generated power and energy is positive. Results of this simulation are presented in Table 1.

Table 1. Glassing factor influence on solar array performance.

	Glassing factor	Max solar cell temperature,°C	Min solar cell temperature,°C	Max power,W	Min power,W	Energy in one orbit,KJ
+5 %	0.965	76.6	-74.9	760.3	681.0	2833
current value	0.919	73.1	-74.9	724.1	660.8	2727
-5 %	0.872	69.4	-75.0	687.2	637.4	2611
-10 %	0.826	65.8	-75.0	650.9	612.0	2491
-20 %	0.735	58.2	-75.1	579.3	556.1	2241

The best (and practically the only) way to decrease solar panel thermal resistance is to decrease thermal resistance of honey comb core. Higher thermal conductivity (k_{hc}) or less thickness (Δx_{hc}) can lead to it. Decrease of the thermal resistance means that more heat from the panel front side will reach the rear side, thus temperature of the solar cells will be lower and solar panel performance will be better.

Albedo and Earth infrared radiation on the panel rear side are not negligible. Therefore decrease of the back side absorptivity (α_b) leads to decrease of solar cell temperature, but influence of back side emissivity (ε_b) has more complex character. More high value of ε_b increases absorbed infrared Earth radiation and heat flux from the panel back side simultaneously. Solar array performance was simulated with different values of back side emissivity. Results of this simulation are presented in Table 2.

Table 2. Back side emissivity influence on solar array performance.

	Back side emissivity	Max solar cell temperature,°C	Min solar cell temperature,°C	Max power,W	Min power,W	Energy in one orbit,KJ
+5 %	0.926	72.1	-75.9	724.1	664.3	2734
current value	0.882	73.1	-74.9	724.1	660.8	2727
-5 %	0.838	74.1	-74.0	724.1	656.9	2719
-10 %	0.794	75.2	-73.0	724.1	652.6	2710
-20 %	0.706	77.5	-70.9	724.1	642.3	2689

The conclusion is that higher value of back side emissivity leads to more quantity of generated energy and lower solar cell temperature.

Summarized information about influence of the design parameters on solar array in-orbit performance is presented in Table 3. In every case one of the parameters was changed in 5 %, thus Table 3 allows to compare influence of different parameters on solar array performance.

Table 3. Design parameters influence on solar array performance.

Parameter	Current value	New value (±5%)	Max solar cell temperature, °C	Min solar cell temperature, °C	Max power, W	Min power, W	Energy in one orbit, KJ
Current value			73.1	-74.9	724.1	660.8	2727
ε_{cq}	0.854	0.897	70.3	-74.6	724.1	670.3	2746
F_g	0.919	0.965	76.6	-74.9	760.3	681.0	2833
ε_k	0.868	0.911	72.9	-74.9	724.1	661.6	2728
α_k	0.380	0.361	72.9	-74.9	724.1	661.4	2919
Δx_{hc}	21.70	20.60	72.8	-75.2	724.1	661.9	2730
ε_b	0.882	0.926	72.1	-75.9	724.1	664.3	2734
α_b	0.750	0.713	72.4	-74.9	724.1	663.1	2729

5. CONCLUSION

In the framework of this research thermal mathematical model of space solar panel was developed and realized in a computer code.

Thermal balance test of a solar panel test coupon was performed. Results of the experiment were used for model calibration and verification.

Developed thermal model together with optical and electrical models of the solar panel were used for mathematical simulation of the solar array in-orbit performance. Solar panel sensitivity to the change of panel design parameters was found in the result of this simulation.

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7. RESPONSIBILITY NOTICE