Thermal analysis and simulation of the ChemiX instrument

Urszula Z. Kaszubkiewicz,
Space Research Centre Polish Academy of Sciences, Solar Physics Division

ABSTRACT

ChemiX is a new generation Bragg crystal spectrometer intended to measure X-ray spectra from solar corona. The instrument is under development, and will be attached as one of the scientific equipment to Russian space solar observatory Interhelioprobe. The final heliocentric orbit will be reached after cruise phase which involves exposing the observatory to varying thermal conditions during the whole mission. Final scientific orbit is highly eccentric which results in substantial changes of solar heat flux. The power dissipated inside the instrument itself has also significant impact on thermal conditions. Furthermore ChemiX, as a component of whole spacecraft, will receive and give back some heat due to conduction to the main structure.

Proper evaluation of temperatures and heat fluxes in this case is not only important for correct performance of ChemiX but also for success of whole Interhelioprobe mission. To evaluate those parameters a steady state analysis in satellite crucial position was provided as well as computer simulation.

Keywords: ChemiX, satellite thermals, Thermal analysis, Heat balance

1. INTRODUCTION

ChemiX instrument is a project of Polish Academy of Sciences, Center of Space Research, Solar Physics Division. It is going to be attached to Russian space solar observatory Interhelioprobe as a one of the research instruments. Scientific goal of this project is to observe the solar corona in X ray with use of new generation Bragg crystal spectrometer.

1.1 Influence of orbit shape on heat dissipation

Interhelioprobe will start mission from Earth orbit, then on the Venus orbit a series of gravity assisted maneuvers will be performed[10]. With help of engines and planets, spacecraft will be placed on operational orbit. Final orbit period will be 88 days. With perihelion equal to 0.044 AU and aphelion 0.73 AU, which means that the lowest distance will be smaller than Mercury's orbit and the biggest one higher than Venus orbit[8]. The orbit visualization is presented in the figure 1.

Interhelioprobe is a Sun oriented mission which means that while moving on the final orbit only one side of satellite is going to be illuminated. ChemiX will be protected from the major sun heat input by the spacecraft heat shield. During the cruise phase satellite's orientation is going to vary and there will be moment when ChemiX won't be under the shield and the instrument will be directly illuminated. Heat loads during this phase will be the biggest. After the cruise phase Interhelioprobe is going to move in highly eccentric orbit, and that will also result in significant flux changes. Additionally in both phases, there will be heat conduction between spacecraft and instrument.

Since ChemiX have no active cooling nor heating it is essential to conduct research to verify if achieved temperatures will allow for proper work of equipment installed inside. To estimate temperatures thermal analysis in both steady state and orbital steady state was carried out. The results from both cases were compared with simulations conducted with use of Solid Works program.

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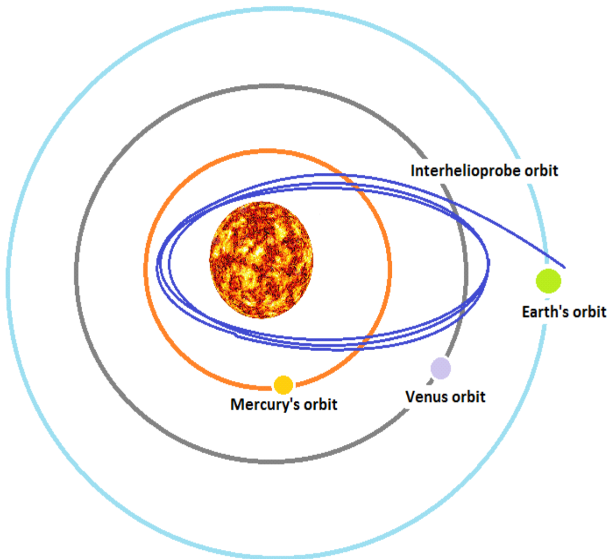

Figure 1. Interhelioprobe orbit shape.

1.2 ChemiX construction

ChemiX has a simple cuboid shape. Its walls are going to be made of 7075 aluminum alloy. On front the side a radiator is going to be attached. As a radiator material aluminum P1020 was chosen because of its low absorptivity value[7]. A simplify model of ChemiX is presented in the figure 2. In the picture numbers identify the walls. Wall number 5 is the one with radiator, wall number 1is directly connected to Interhelioprobe structure. On the final orbit wall number 4 (top) will be constantly Sun oriented while wall number 3 (bottom) in the same orbit will not be illuminated by the Sun.

In this article it is assumed that all the internal generated heat comes from one element. In the cross section in the figure 2 the element is shown on the wall number 1. Inside structure of the instrument will be of course more complex. The assumption was made for simulation purposes. In Solid Works program too complicated shape of the elements prevent from creating a mesh on them.

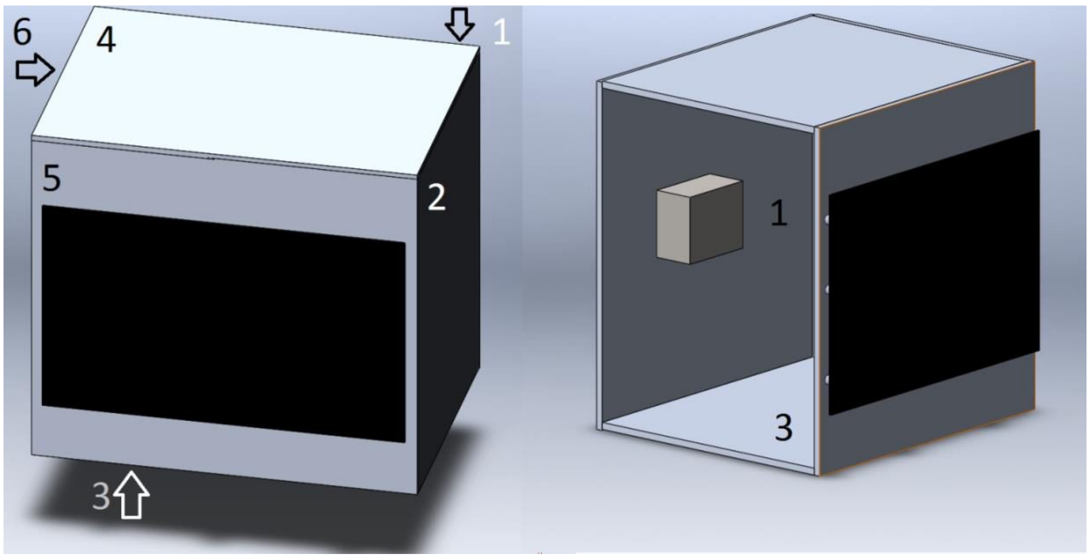

Figure 2. On the left ChemiX model with labeled walls, on the right ChemiX cross section.

2. GENERAL THERMAL ANALYSIS

In order to conduct full thermal analysis it is required to solve a heat balance equation[1,3], shown below:

$$\rho c_p \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) = Q \tag{1}$$

In the equation ρ states for density, c_p is a specific heat, k is a thermal conductivity, T is a temperature and t states for time. Heat balance equation consists of three components. The first one from the left describes energy stored and is dependent from material properties. The second is amount of heat conducted. The sum of those two components should be equal to sum of external and internal heat loads[5] marked in the equation as Q.

3. STEADY STATE ANALYSIS

The first assumption of heat balance equation is a steady state analysis[2]. In this case equation turns into the form shown below:

$$\sum_{i=1}^{n} Q_i = 0 \tag{2}$$

It is assumed that sum of incoming and out coming heat is equal to zero. In this equation i is a heating component number depending on considered model. In steady state analysis heat is only temperature dependent. The result of this analysis is one temperature which is an estimation of temperature of whole the structure.

As ChemiX is a part of bigger mission amount of heat received on each flight phase is already known. Apart from that it was necessary to consider heat radiated, internal heat sources, and illumination changes. Values of heat received are presented in the table 1.

Table 1. Heat received by walls in subsequent mission phase.

	Top [W] (wall number 4)	**Bottom and side walls [W]** (wall number 2,3,6)	**Wall with radiator [W]** (wall number 5)
Intake	8,37	142,23	0,60
The shortest distance Q_{max}	33,85	47,12	2,43
The longest distance Q_{min}	1,57	1,32	0,11

3.1 Estimation of heat received by each wall

In order to sum up all the incoming and out coming heating components analysis on each wall was provided. Then heat on each wall was summed up giving steady state analysis equation.

Wall attached to the spacecraft structure won't receive and emit any heat due to radiation. It doesn't see cosmic space that is why the sum of heat on this wall is equal to 0. Heat balance on the other walls is equal to given amount of heat minus amount of heat radiated into space[2,3]. Apart from that into to summation a 20 W of internal heat should be considered. Internal heat isn't turned on during whole orbit period. It is switched off and on depending on executed task. To estimate temperature in both cases two equations needs to be solved. In the following equations exact calculations are presented.

$$Q_1 = 0 \tag{3}$$

$$Q_i = Q_g - Q_{i\,space} \tag{4}$$

$$Q_{space}(T) = \varepsilon AF\sigma(T^4 - T_s^4) \tag{5}$$

$$Q(T) = Q_1(T) + 3Q_2(T) + Q_4(T) + Q_5(T) + P \tag{6}$$

Where Q_i is a heat generated on a specific wall and i is a number of the wall according to the figure 2. As Q_g a given amount of heat, according to the table 1 was used. $Q_{i\ space}$ describes amount of heat radiated depending on the wall number. In the equation T_s is temperature of the space estimated at 3 K, ε is an emissivity value, A states for surface area, σ is a Stefan-Boltzmann constant, and F is a view factor. View factor describes part of radiation emitted by one surface and intercepted by the other. It depends on distance between surfaces and their orientation. It can vary between 0 to 1 [6]. In the equation (6) Q_2 is multiplied by factor of three because heat generated on walls 2,3 and 6 is equal. In the same equation P stands for optional 20 watts of internal heating.

4. ORBITAL STEADY STATE ANALYSIS

In orbital steady state analysis material properties and position change is taken into account[3,4]. Here heat balance equation is approximated to form presented in the equation 7.

$$\rho c_p \frac{\partial T}{\partial t} = Q(t, T) \tag{7}$$

Energy stored inside the structure is equal to the sum of external and internal heat. Amount of heat received depends on in orbit position[10]. A good approximation is assumption that heat received changes with sinus function.

$$\omega = \frac{2\pi}{K} \tag{8}$$

$$Q_{sun}(t) = Q_{min} + q_a \cdot \alpha \cdot \left|\sin\left(\frac{\omega t}{2}\right)\right| \tag{9}$$

$$q_a = Q_{max} - Q_{min} \tag{10}$$

$$Q_i(t, T) = Q_{sun}(t) - Q_{space}(T) \tag{11}$$

To the minimum value of heat received per wall sinus faction, multiplied by the q_a factor, is added. q_a is a difference between maximum and minimum heat received per wall, ω is an angular velocity and t states for time. In the calculations it is assumed that when satellite is in the farthest position from the Sun value of sinus function is equal to zero however when satellite is the closest to the Sun sinus function is equal to one. The result of orbital steady state analysis is time-temperature dependence.

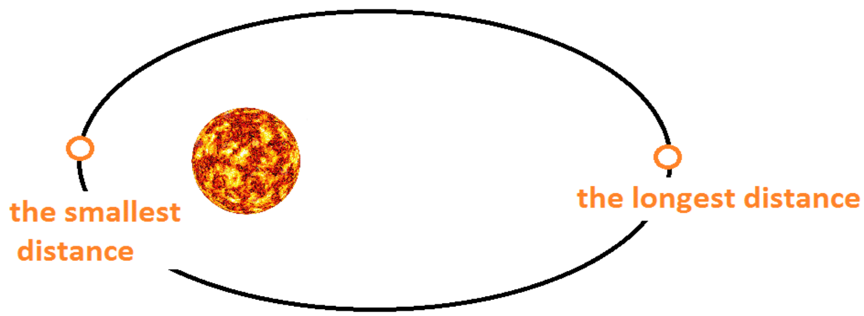

Figure 3. Satellite's positions on final orbit.

5. SOLIDWORKS SIMULATIONS

Simulations of ChemiX temperature distribution, in both steady state and orbital steady state, were conducted in SolidWorks program. SolidWorks assess results with use of finite element method which means that model of a satellite is divided into smaller elements and temperatures are calculated only in nodes. Mean value of temperature in nodes was assumed to be a temperature of whole device.

In SolidWorks several heat loads were set. According to the table. Six simulations were conducted. Heat loads were set according to the table 1. Apart from that radiation on each unveiled wall was added. For a case with internal heating a 20 Watts heat was added inside.

6. RESULTS

6.1 Steady state analysis

The same analysis parameters and assumptions for the steady state calculations were used to evaluate temperatures in Solid Works simulations.

Figures 4 and 5 are illustrations of temperature distribution simulated with use of Solid Works program. The show both cases: with and without internal heating. Each figure show comparison between different flight phases. Temperature scales presented in the pictures are the same (from 200 Kelvins – marked in blue, up to 580 Kelvin which corresponds to red color).

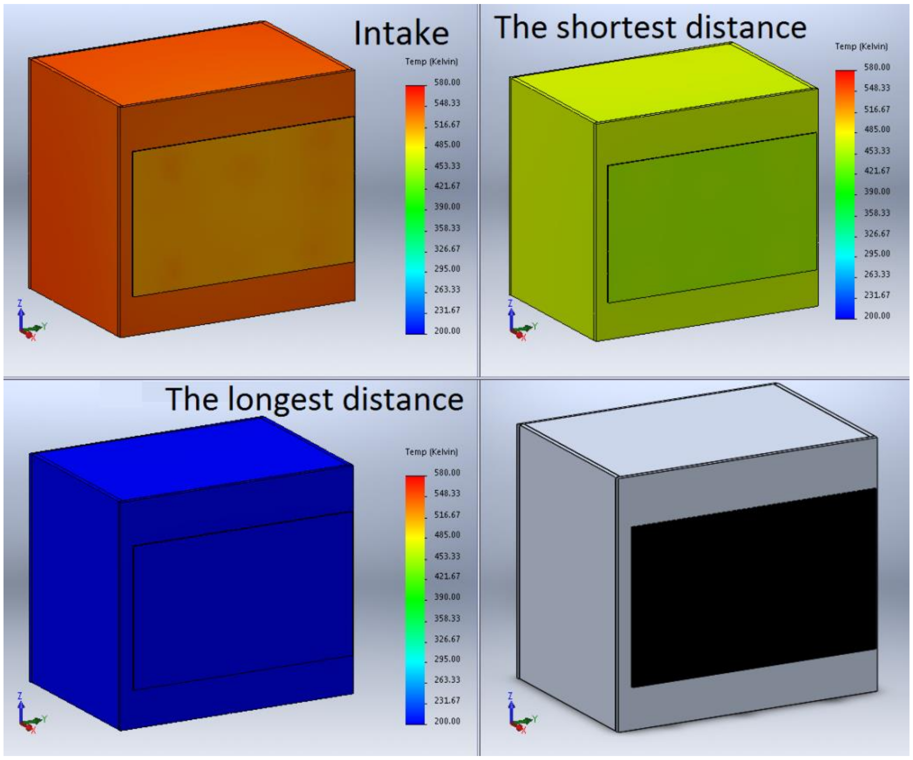

Figure 4. Results of simulations in SolidWorks programme Case without internal heating

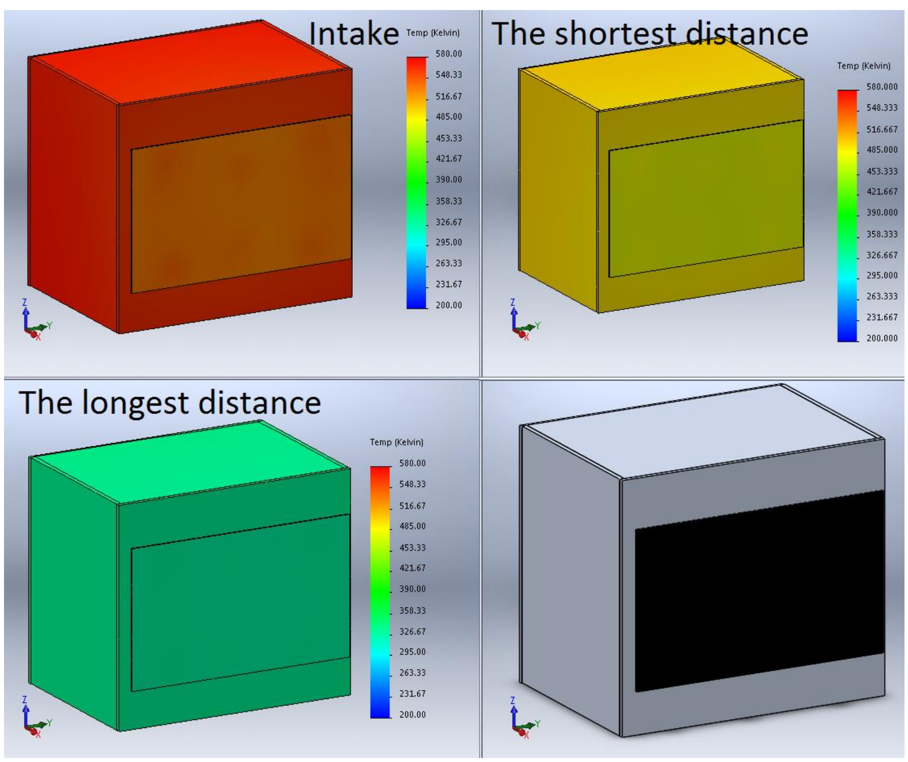

Figure 5. Results of simulations in SolidWorks programme Case with internal heating.

The result of calculations, with use of equation 2, is one temperature. In order to compare those results with simulation outcome a mean temperature, based on temperatures in nodes and nodes number in the model, was calculated. Comparison of calculated temperatures and temperatures assessed in simulations is presented in tables 2 and 3.

Table 2. Comparison between calculated values and results of simulations in SolidWorks for case without internal heating.

	Calculations [K]	SolidWorks [K]
Intake phase	541,22	537,38
The closest distance	467,48	464
The longest distance	203,59	201,47

Table 3. Comparison between calculated values and results of simulations in SolidWorks for case with internal heating.

	Calculations [K]	SolidWorks [K]
Intake phase	558,29	553,87
The closest distance	493,28	489,53
The longest distance	338,77	333,33

According to the tables calculated temperatures and those resulting from the simulations differ in less than 2%.

6.2 Orbital steady state

In the orbital steady state a temperature-time dependence was obtained. Partial differential equation was solved with use of Mathcad program. Simulations were conducted for two cases with and without internal heating. In the following figures the diagrams of temperature in Kelvins as a function of time in days for both cases are presented.

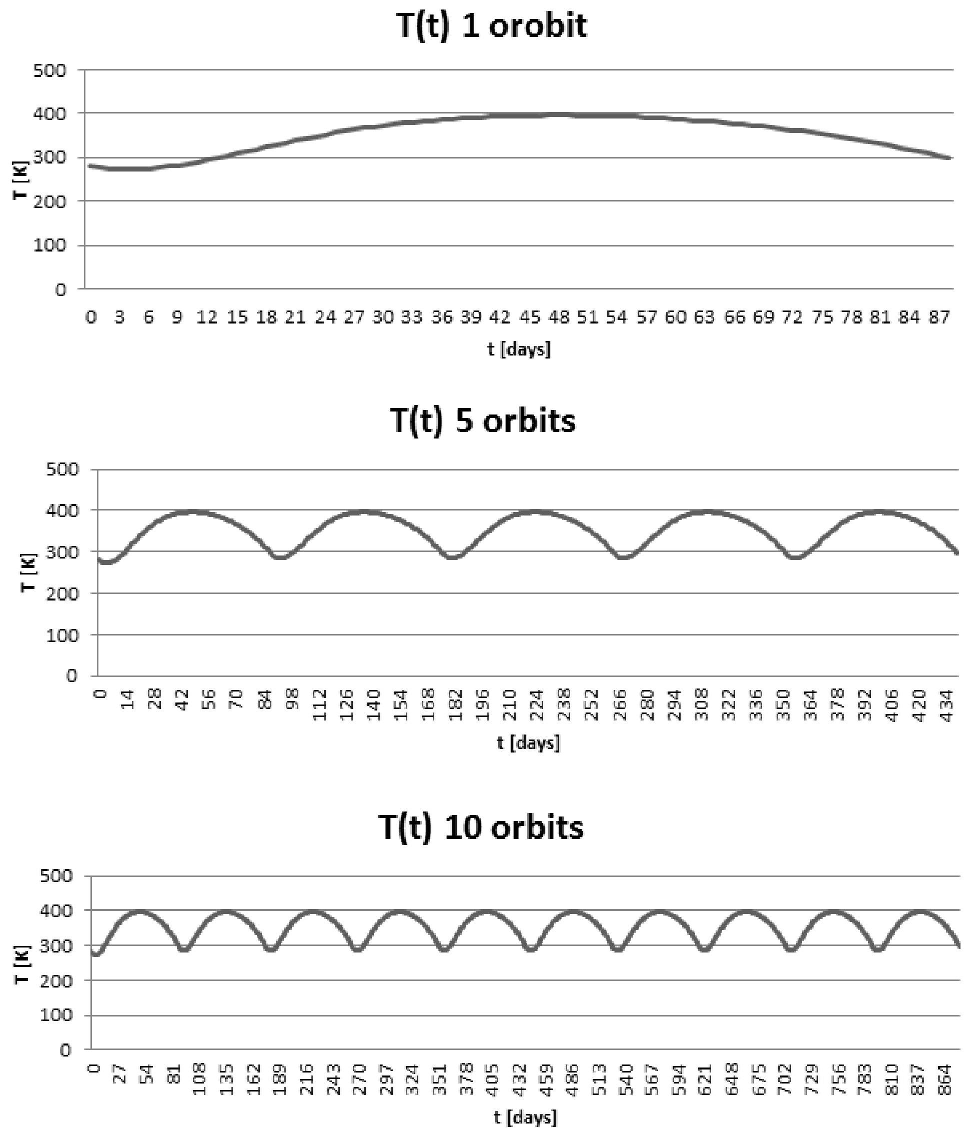

Figure 6. From the top of a figure: the temperature value during one orbit period, five orbit periods and ten orbit periods for a case without internal heating.

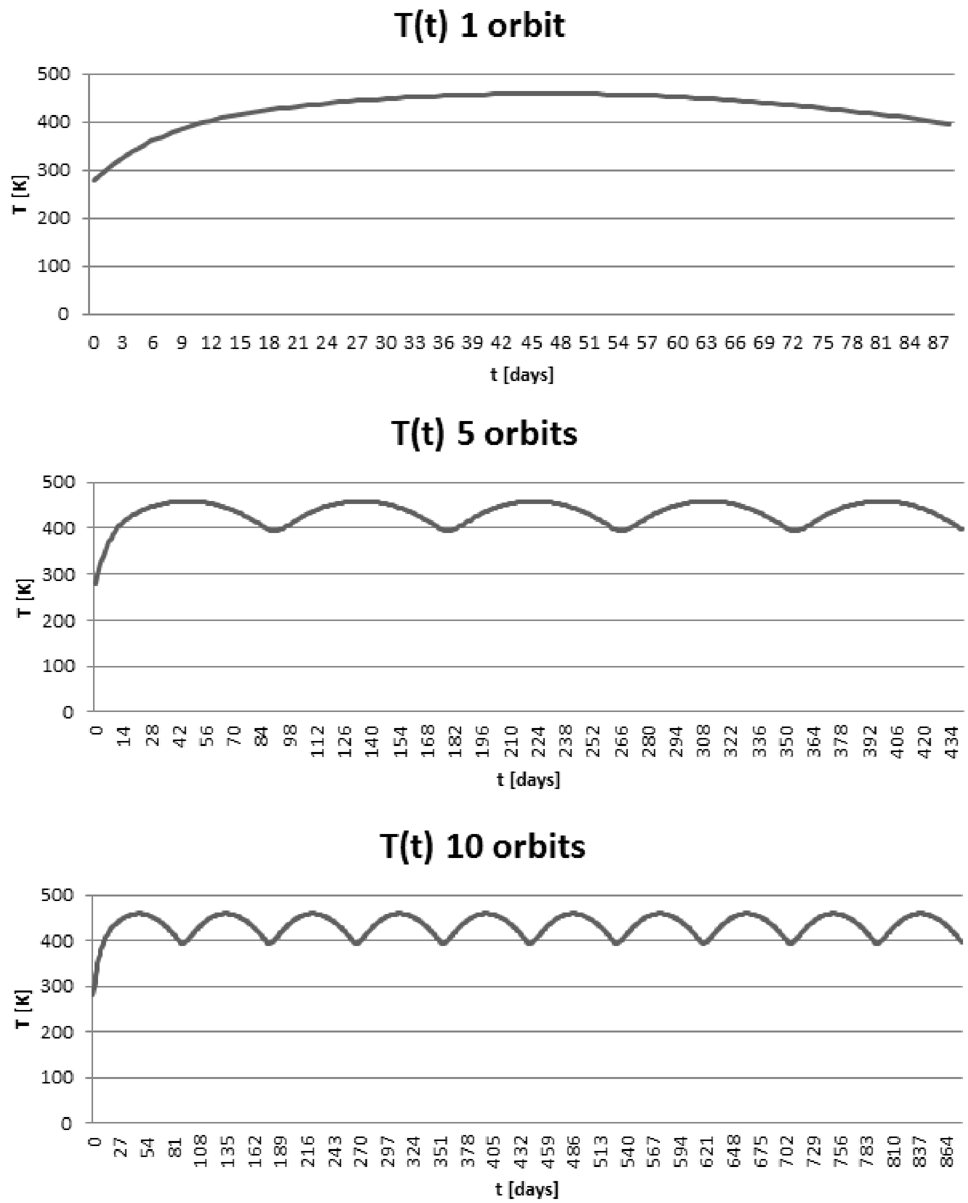

Figure 7. From the top of a figure: the temperature value during one orbit period, five orbit periods and ten orbit periods for a case with internal heating.

A distinction of number of orbits was made in order to check the period of time after which temperature is stabilized. According to the diagrams since third cycle temperature underwent the same changes.

7. CONCLUSIONS

Calculated temperatures are average temperatures of the structure. In the reality temperature on specific wall will vary depending on Sun's illumination. Inhomogeneity of temperature distribution will be increased by equipment installed inside structure.

In the above thermal analysis it is assumed that internal heating sources are concentrated in one point, in the real model power will be generated on several devices which would have influence on temperature values and distribution too. Another reason of temperature difference between real one and calculated will be conduction, between satellite's and ChemiX walls, which wasn't taken into account in calculations.

Preliminary steady state calculations shown that temperature on the radiator might be too high. It might be necessary to replace material of the radiator in the one with higher emissivity value.

Small differences between calculated values and those from Solid Works simulation might be the result of model design. In the Solid Works model walls have some thickness which causes a heat dissipation over this length, calculated model assumes that walls are infinitely thin.

Comparison of the results shown that temperatures calculated in orbital steady state analysis vary from those in steady state. The difference comes from taking into account material properties. Results from such analysis should be more accurate.

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