Chapter 5
EMC and thermal analysis

Abstract

This chapter deals mainly with problems related with the thermal analysis for the power supply subsystem and for the whole satellite. A section about electromagnetic compatibility is also included.

5.1. Introduction

An important space in the present chapter is reserved for the thermal analysis. The mechanisms of the heat transfer are presented, as well as some methods of thermal modeling and control. It is important to have a control of the temperature inside the satellite, due to the hostile environment in which the electronic components and other parts have to function. The analysis is performed in several sections, starting with section 5.2.

Some basic knowledge about electromagnetic compatibility (EMC) is presented in section 5.5. This part contains also some recommendations to follow in order to avoid electromagnetic interferences and to minimize the parasitic emissions, due to digital circuits or power electronic circuits.

5.2. Thermal analysis

One of the necessary parts of Cubesat's design is the thermal analysis. It will provide us operating temperatures an their distribution for all device inside satellite. For decision, which temperature standard can be used for components it is necessary to know the maximum and the minimum value of temperature. In virtue of this results the position of the all device must be also optimized. Some methods for thermal control are also proposed. There are two main source of heat in Cubesat, the Sun from outside and the electrical power from inside generated by all working components

5.2.1. Conditions for Low Earth Orbit

In Chapter 2, section 2.4, the specifications for the Low Earth Orbit are described. As it has been shown in section 2.3.1 (Table 2.1), the heat in space comes from three main sources:

- ❑ The Sun – energy 1358 ± 5 [W/m^2]
- ❑ Albedo – energy 406 [W/m^2]
- ❑ Infrared – energy 237 [W/m^2]

The temperature surrounding the satellite in space is 2.7K and the pressure surrounding is very close to vacuum. In figure 5.1, are illustrated the sources of heat in space [*Sellers, p.67, 1994*].
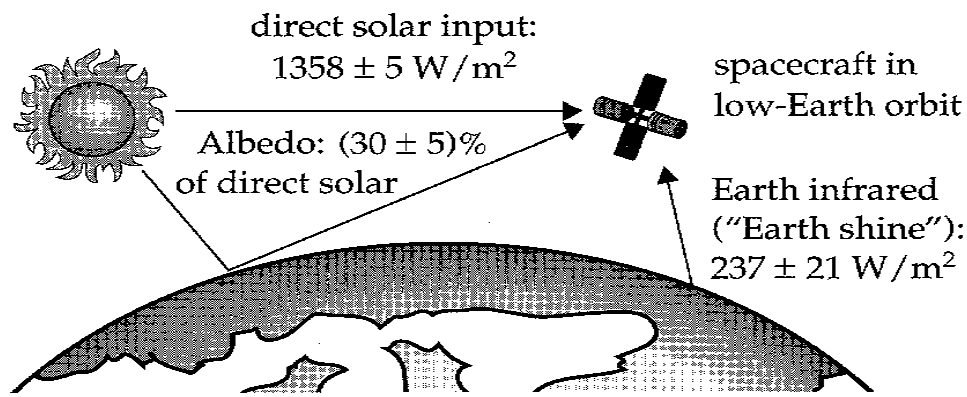
Figure 5. 1 Sources of radiation in space

5.2.2. Heat transfer

There are three mechanisms by which thermal energy is transported:

1. Convection

2. Conduction

3. Radiation

In space convection can be neglected. As said before, the surrounding temperature in space is 2.7˚K, very close to absolute zero. Then there is no transfer between hot and cold air as on the Earth. The vacuum is also cause for this problem, because there is no difference in density of gasses.

Conduction

In definition of heat transferred through conduction, the following formula is used:

$$P_{cond} = \frac{\lambda \cdot A \cdot \Delta T}{L}$$ (5.1)

where λ is thermal conductivity [J/s·m·K]

A is a cross section area [m²]

L represents the length of the conduction path [m]

ΔT is difference temperatures between the two bodies, T_1 and T_2

In figure 5.2 is shown an illustration of the heat conduction mechanism.

Thermal resistance is defined by formula:

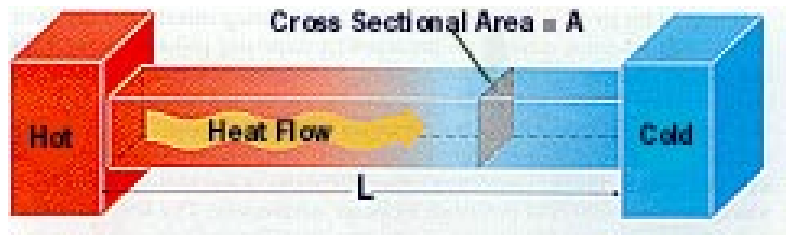$$R_{th\_cond} = \frac{\Delta T}{P_{cond}} \left[K/W \right]$$ (5.2)

Figure 5.2 Illustration of heat conduction mechanism
[http://sol.sci.uop.edu/~jfalward/heattransfer/heattransfer.html]

Replacing the expression of P_{cond} from equation (5.1), it yields:

$$R_{th\_cond} = \frac{L}{\lambda \cdot A} [\text{K/W}]$$ (5.3)

Conduction will apply only for components on the same board and R_{jc} (thermal resistance junction case) can be assumed as a thermal resistance for this transfer.

Radiation

All matter and space contains electromagnetic radiation. A particle of electromagnetic energy is a photon, and heat transfer by radiation can be viewed either in terms of electromagnetic waves or in terms of photons.

For calculation of the amount of heat transferred through radiation is valid Stefan-Boltzmann law:

$$P_{rad} = \varepsilon \cdot \sigma \cdot A \cdot T^4$$ (5.4)

where, ε = emissivity (value between $0 \div 1$)

σ = Stefan-Boltzmann constant equal with $5.67 \cdot 10^{-8}$ [W/m^{2}K^4]

A = surface area of object [m^2]

T = temperature [K]

From this equation may be observed that for modifying the radiated power for an object, the only parameter which can be changed is the emissivity of radiating object, supposing that the object maintains its physical dimensions. This can be realized by modifying the color and surface of component. Figure 5.3 shows the difference between the absorbtion and emission of radiation. [http://sol.sci.uop.edu/~jfalward/heattransfer/heattransfer.html]

For a dark-color material, the absorbtion of a radiated amount of heat is higher than for a light-color material, supposing the same geometric dimensions for the two bodies.
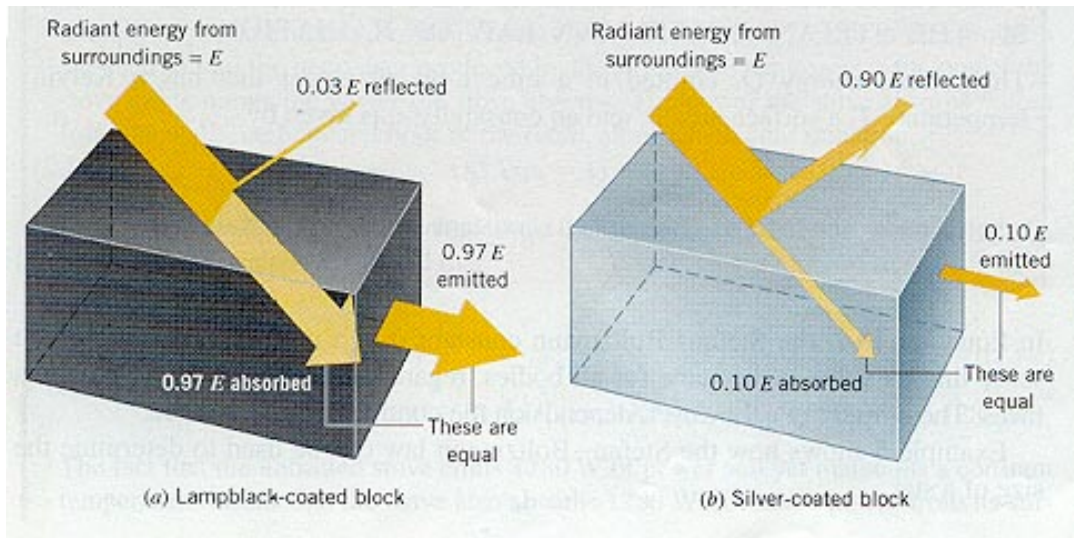
Figure 5.3 Absorption and emission of radiation

The thermal resistance for radiation can be defined as:

$$R_{th\_rad} = \frac{\Delta T}{P_{rad}} [\text{K/W}] \tag{5.5}$$

Combining equations (5.4) and (5.5), the thermal resistance may be written in the following form:

$$R_{th\_rad} = \frac{1}{h_r \cdot A} [\text{K/W}] \tag{5.6}$$

where, $h_r = 4 \cdot \varepsilon \cdot \sigma \cdot T_m^3$ is called the *radiation heat transfer coefficient* [W/m^{2}K].

For normal room temperature, 25°C (= 298K), h_r is about six times the surface emmitance. This can be easily proved, replacing in the definition relation the corresponding numbers [*Mills, p.16, 1995*]:

$$h_r = 4 \cdot \varepsilon \cdot 5.67 \cdot 10^{-8} [\text{W/m}^2\text{K}^4] \cdot (298)^3 [\text{K}] \cong 6 \cdot \varepsilon [\text{W/m}^2\text{K}] \tag{5.7}$$

5.2.3. Temperature equilibrium

A temperature equilibrium will be always reached after the solar irradiation has begun. It is helpful to know this temperature for the first idea about thermal conditions in the Cubesat. There is presented only instance without internal heat sources. The temperature equilibrium is obtained when the absorbed power Q_A is equal to emitted power by radiation Q_E. These values are given by the following equations:

$$Q_A = S_0 \cdot \alpha \cdot A_{in} \tag{5.8a}$$

$$Q_E = \varepsilon \cdot \sigma \cdot A_{out} \cdot T_e^{\,4} \tag{5.8b}$$

where the symbols in the equations have the following significances:

S_0 is solar irradiation (1353 [W/m^2], in case of sunlight, 237 [W/m^2], in case of eclipse),

α represents the absorbitivity of the material,

A_{in} is area illuminated by solar irradiation [m^2],

ε is the emissivity of the material,

σ is Stephan-Boltzmann constant, equal with 5.67 x 10^{-8} [W/m^{2}K^4],

A_{out} is the radiating area [m^2], and

T_e represents the equilibrium temperature [K].

The equilibrium temperature is obtained from condition $Q_A = Q_E$. Replacing the expressions for the two amounts of heat, from equations (5.8a, b), it yields:

$$T_e = \sqrt[4]{\frac{A_{in}}{A_{out}} \cdot \frac{\alpha}{\varepsilon} \cdot \frac{S_0}{\sigma}} \tag{5.9}$$

In the satellite are used these materials with their constants as is shown in table follows.

	Solar cells (InGaP,GaAs,Ge)	Material of sides (Carbon)	Material on side with camera (Aluminum)
α	0.75	0.96	0.55
ε	0.83	0.9	0.3
Coverage of one side (%)	57	43	100

Table 5.1 Absorbitivity and emissivity for materials used in the satellite

Case of sunlight

Solar irradiation is taken into account without respect of Albedo and infrared heat from the Earth. The illuminated sides are only the sides with solar cells (side with camera is still pointed to the Earth). For material constants can be put only values with respect of coverage of sides. It can be calculated as below:

$$\overline{\alpha} = \alpha_{cell} \cdot 0.57 + \alpha_{mat} \cdot 0.43 = 0.75 \cdot 0.57 + 0.96 \cdot 0.43 = 0.8403 \tag{5.10a}$$

$$\overline{\varepsilon} = \varepsilon_{cell} \cdot 0.57 + \varepsilon_{mat} \cdot 0.43 = 0.83 \cdot 0.57 + 0.9 \cdot 0.43 = 0.8601 \tag{5.10b}$$

Due to assumption, that the satellite will stay in position with camera side pointed to the Earth, there are these boundary conditions:

- One side illuminated
- Three sides illuminated

From equations (5.10a, b) the equilibrium temperature can be calculated as follows:

$$T_e = \sqrt[4]{\frac{\sqrt{N} \cdot A_1}{A_1} \cdot \frac{\overline{\alpha}}{5 \cdot \overline{\varepsilon} + 1 \cdot \varepsilon_{cam}} \cdot \frac{S_0}{\sigma}} = \sqrt[4]{\frac{\sqrt{N} \cdot \overline{\alpha} \cdot S_0}{(5 \cdot \overline{\varepsilon} + 1 \cdot \varepsilon_{cam}) \cdot \sigma}} \tag{5.11}$$

where A_1 is the area of one side [m^2],

N is number of illuminated sides, and

ε_{cam} represents the emissivity of material on side with camera.

The illuminated area is dependent on the angle of sunlight and its maximum is respected by $\sqrt{N}$ (section 3.3.1). That is why this value is placed in numerator.

In radiation must be taken in account that all of sides are radiating. But not all of them are the same. One side (with camera) has different conditions. This is a reason for writing such a shape of denominator as in equation (5.11).

Then by inserting these values into the equation (5.11) is obtained:

❑ One side illuminated:

$$T_e = \sqrt[4]{\frac{0.8403 \cdot 1353 \,[\mathrm{W/m^2}]}{(5 \cdot 0.8601 + 1 \cdot 0.3) \cdot 5.67 \cdot 10^{-8} \,[\mathrm{W/m^2 K^4}]}} = 256.94 \,[\mathrm{K}] = -18.19 \,[^\circ\mathrm{C}] \tag{5.12}$$

❑ Three sides illuminated:

$$T_e = \sqrt[4]{\frac{\sqrt{3} \cdot 0.8403 \cdot 1353 \,[\mathrm{W/m^2}]}{(5 \cdot 0.8601 + 1 \cdot 0.3) \cdot 5.67 \cdot 10^{-8} \,[\mathrm{W/m^2 K^4}]}} = 294.77 \,[\mathrm{K}] = 21.62 \,[^\circ\mathrm{C}] \tag{5.13}$$

❑ Three sides illuminated simultaneously by direct solar irradiation, Albedo, infrared heat of the Earth:

$$T_e = \sqrt[4]{\frac{\sqrt{3} \cdot 0.8403 \cdot (1353 + 406 + 237) \,[\mathrm{W/m^2}]}{(5 \cdot 0.8601 + 1 \cdot 0.3) \cdot 5.67 \cdot 10^{-8} \,[\mathrm{W/m^2 K^4}]}} = 327.99 \,[\mathrm{K}] = 54.84 \,[^\circ\mathrm{C}] \tag{5.14}$$

Case of eclipse

The source of power for this case is only infrared heat produced by the Earth by itself. In this case are counted all possible boundary conditions that can appear:

• One side pointed to the Earth

    o   Side with camera (case 1)

    o   Side without camera   (case 2)

• Three sides pointed to the Earth

    o   Including side with camera (case 3)

   o   Without side with camera (case 4)

In all of these cases is the denominator still the same due to radiation of all sides. Then the general equation can be written as follows:

$$T_e = \sqrt[4]{\dfrac{\dfrac{\sqrt{N_{cam} + N_{·cells}}}{N_{cam} + N_{cells}} \cdot \left(N_{cells} \cdot \overline{\alpha} + N_{cam} \cdot \alpha_{cam}\right) \cdot S_0}{\left(5 \cdot \overline{\varepsilon} + 1 \cdot \varepsilon_{cam}\right) \cdot \sigma}}$$

(5.15)

where N_{cam} = 1 if the side with camera is illuminated,

    0 if the side with camera is not illuminated,

  N_{cells} is the number of sides with cells illuminated,

  $\overline{\alpha}$ is the absorbtivity with respect of coverage,

  $\overline{\varepsilon}$ represents the emissivity with respect of coverage,

  α_{cam} is the absorbtivity of side with camera,

  ε_{cam} is the emissivity of side with camera,

  S_0 = 237 [W/m^2] represents the irradiation due to infrared heat from the Earth, and

  σ is Stephan-Boltzmann constant (5.67 x 10^{-8} [W/m^{2}K^4]).

Then by inserting these values into the equation (5.15) the following results are obtained:

case 1: $T_e = \sqrt[4]{\dfrac{\dfrac{\sqrt{1+0}}{1+0} \cdot \left(0 \cdot 0.8403 + 1 \cdot 0.55\right) \cdot 237\,[\text{W/m}^2]}{\left(5 \cdot 0.8601 + 1 \cdot 0.3\right) \cdot 5.67 \cdot 10^{-8}\,[\text{W/m}^2\text{K}^4]}} = 149.51\,[\text{K}] = -123.64\,[^\circ\text{C}]$ (5.16)

case 2: $T_e = \sqrt[4]{\dfrac{\dfrac{\sqrt{0+1}}{0+1} \cdot \left(1 \cdot 0.8403 + 0 \cdot 0.55\right) \cdot 237\,[\text{W/m}^2]}{\left(5 \cdot 0.8601 + 1 \cdot 0.3\right) \cdot 5.67 \cdot 10^{-8}\,[\text{W/m}^2\text{K}^4]}} = 166.23\,[\text{K}] = -106.92\,[^\circ\text{C}]$ (5.17)

Case 3: $T_e = \sqrt[4]{\dfrac{\dfrac{\sqrt{1+2}}{1+2} \cdot \left(2 \cdot 0.8403 + 1 \cdot 0.55\right) \cdot 237\,[\text{W/m}^2]}{\left(5 \cdot 0.8601 + 1 \cdot 0.3\right) \cdot 5.67 \cdot 10^{-8}\,[\text{W/m}^2\text{K}^4]}} = 184.95\,[\text{K}] = -88.2\,[^\circ\text{C}]$ (5.18)

Case 4: $T_e = \sqrt[4]{\dfrac{\dfrac{\sqrt{0+3}}{0+3} \cdot \left(3 \cdot 0.8403 + 0 \cdot 0.55\right) \cdot 237\,[\text{W/m}^2]}{\left(5 \cdot 0.8601 + 1 \cdot 0.3\right) \cdot 5.67 \cdot 10^{-8}\,[\text{W/m}^2\text{K}^4]}} = 190.69\,[\text{K}] = -82.46\,[^\circ\text{C}]$ (5.19)

Conclusion

  The goal was to compute the equilibrium temperature for the satellite, considering no internal heat sources. If all equilibrium temperatures are compared than can be seen that the worst case for the satellite is in eclipse when only side with camera is pointed to the Earth.

Then, it is accepted the smallest amount of energy in comparison with other cases. In addition, in all cases are radiating all sides. But must be mentioned, that no internal heat made by equipments is taken into account. So temperature range according to the temperature equilibrium is:

$T_{max} = 55\ [\degree C]$

$T_{min} = -124\ [\degree C]$

From this numbers can be derived that satellite has a trend to keep lower temperature than higher one. This is advantage for us, because no internal sources of heat are included. Internal heat sources will raise temperature inside.

5.3. Methods of modeling

5.3.1. Two-dimensional model of board

In this part of analysis the method of modeling for the electrical board is suggested. Whole Cubesat will be divided into separate layers, corresponding to the number of boards and each layer will be meshed, as shown in figure 5.4.
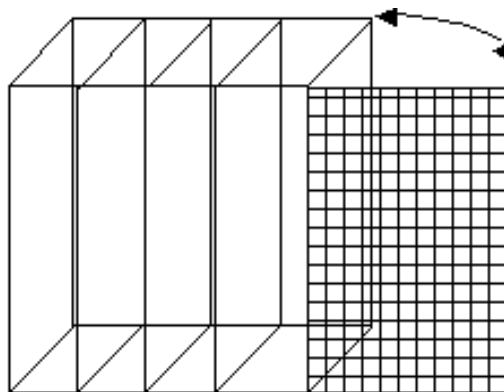

Figure 5.4 Meshed layer of the satellite

Then the components from the board will be projected into the mesh such a way, that thermal source and thermal resistances will represent each component. An example is depicted in figure 5.5. The thermal models for the components are implemented by use of Saber software. On the attached CD-ROM can be found all files concerning this simulation.
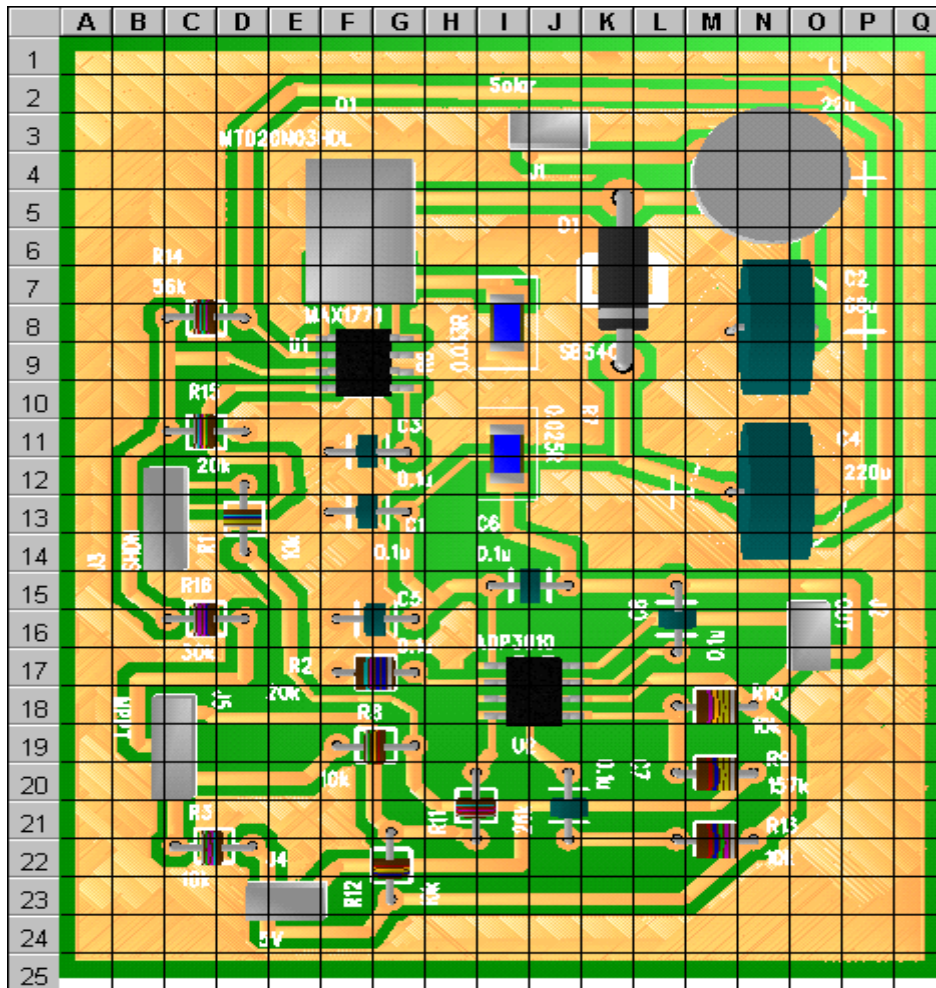
Figure 5.5 Meshed surfaces for the board

From figure 5.6 can be seen the thermal model for a power MOSFET (MTD20N03HDL), which includes the heat source corresponding to operating values and 3 thermal resistances, which represent thermal resistance of each PIN. The library of all components was created the same way. Thermal resistances include only the junction-case resistance and radiation is neglected. The thermal resistance of PCB is not considered.

Table 5.2, which includes operating values of power and thermal resistance is shown further, Thermal resistances R_{thjc} are not known for some components (in tab they are written in italic) so some of them were estimated. The estimation is based on type of package, it is assumed that if the same technology is used, then the thermal resistances will be the same.
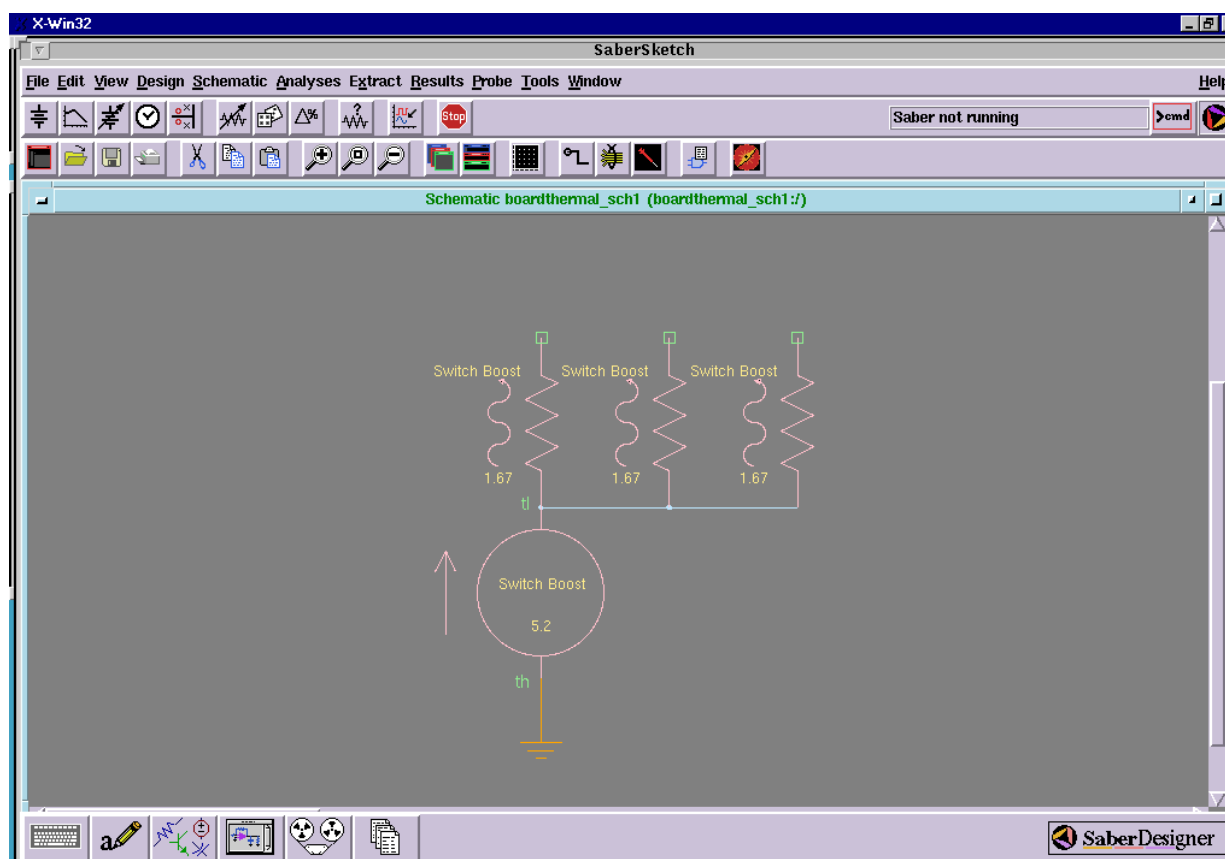
Figure 5.6 Thermal model for a power transistor

Component name	Function	Number of pieces	Number of legs	$R_{th\,j\text{-}c}$ (K/W)	Working conditions			Included in model?
					Current (A)	Voltage (V)	Power (W)	
MTD20N03HDL	switch for step-up convertor	1	3	1.67	0.58	5.23	3	yes
NDT 456P	switch for step-down convertor	1	3	12	2	3.4	6.8	yes
TPS2034	protection for transmitter	1	8	*10*	1.8	5	9	yes
TPS2030	protection for ACS,CAM, MCU, OBC	4	8	*10*	0.05; 0.06; 0.003; 0.092	5	0.25; 0.3; 0.015; 0.46	yes
MAX1771	step-up convertor	1	8	*10*	110μ	5	0.55m	yes
MAX1744	step-down convertor	1	8	*10*	221μ	8.4	1.86m	yes

UCC3911	protection for 2 batteries in series	2	16	*12*	0.92	8.4	7.728	yes
SB540	diodes for convertors	2	2	*2*	0.5	0.43	0.215	yes
PRLL5817	string diodes for solarcells	5	2	*5*	0.5	0.35	0.175	yes
MAX4372	current-sence amplifier	10	5	*7*	30μ	5	0.15m	no
LM78L05	terminal positive regulator	1	8	*7*	0.1	5	0.5	yes
MAX835	latching voltage monitor	4	5	*7*	15μ	5	0.075m	no

Table 5.2 Operating values of components

From these components MAX4372 and MAX835 were neglected.

The restrictions of 2D model are stated as follows:

- The thermal resistance of PCB is not considered.

- Number of nodes is directly connected to the accuracy of the model. The more nodes we have the higher accurate model we obtain.

- In our case only main sources of heat will be taken in account.

- Radiation is not included in this model; it is supposed that the conduction through the copper is main way for heat transfer.

- Distances between components are not included.

- The model is only two-dimensional and it is a problem to transfer into 3D.

- The thermal resistances for radiation (R_{thca} case-ambient) are not included in datasheets and must be computed for each component.

- Saber software is not optimal for this type of analysis.

- Creating of the model is elaborate and requires a large amount of work.

- Thermal resistances R_{thjc} are not known for all device.

5.3.2 Implementation of the model and results

The whole thermal model of the PSU board is depicted in figure 5.7. In model there are included only main sources of heat. Position of components is respecting the electrical layout, because final board wasn't at disposal. It is assumed that the copper on a board is conducting the most of the heat, because its thermal conductivity is thousand times higher then for the board. Pins, which are not connected to other components and have no function have zero value. If it is not like this, the Saber software will assume them as a nonfinite value and it will alter the results.
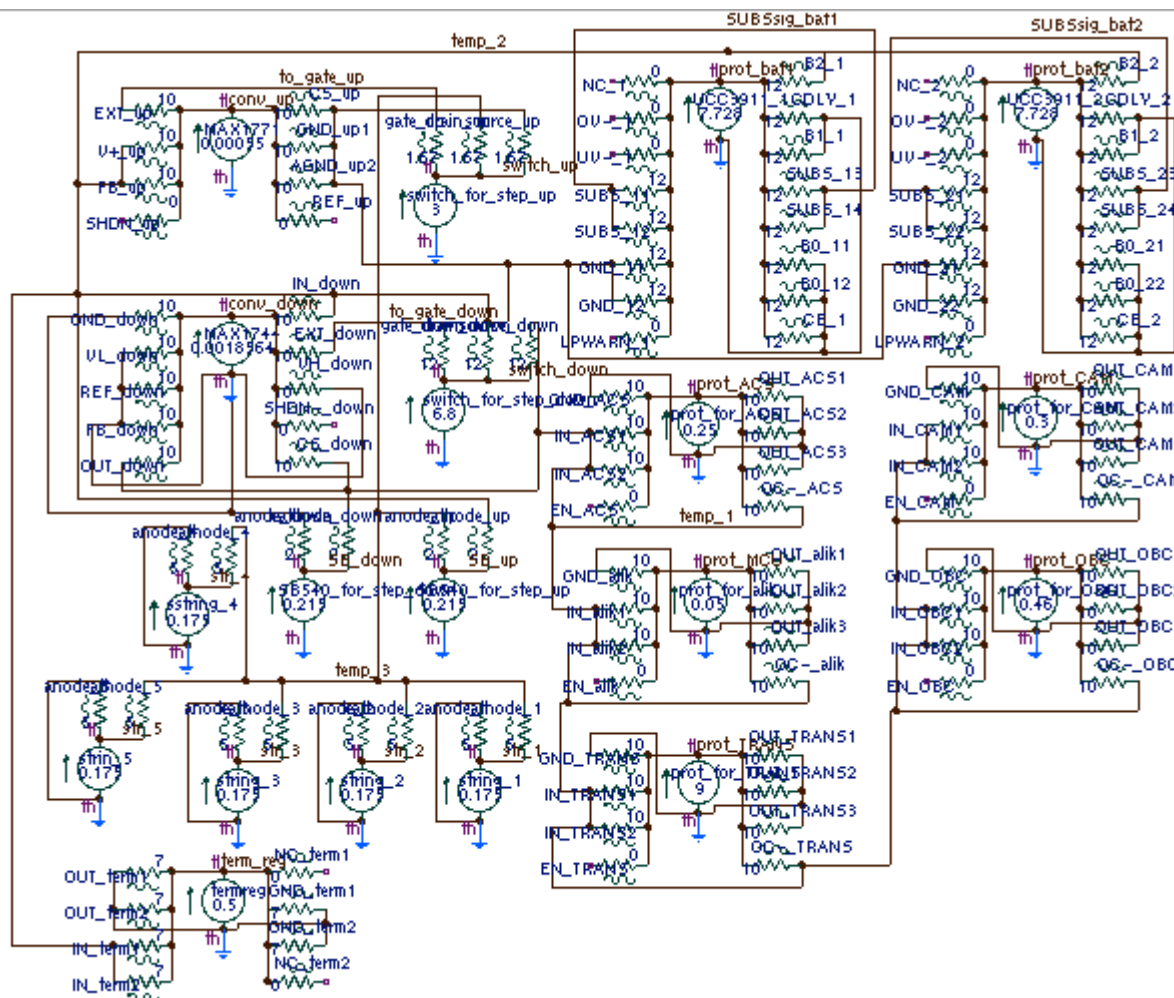

Figure 5.7 Final layout for thermal model

The results are presented in table 5.3 and in figure 5.8.

All temperatures are acceptable and are following the industrial standard. The highest temperature is on the switch of step-down converter (40.9˚C). It is exactly according to the expectances, because of the highest power. Also protections for batteries and for communication module will have temperatures near to 20˚C.

	Device	Temperature (^{o}C)
Convertors	Step-up	13.3
	Step-down	5.3
Protections	ACS	3.1
	Batteries	16.6
	CAM	3.2
	MCU	2.8
	OBC	3.4
	Transmitter	15.6
Diodes	String	4.9
	SB540 for step-up	11.3
	SB540 for step-down	3.4
Switches	For step-up	13.6
	For step-down	**40.9**
	Terminal positive regulator	5.0

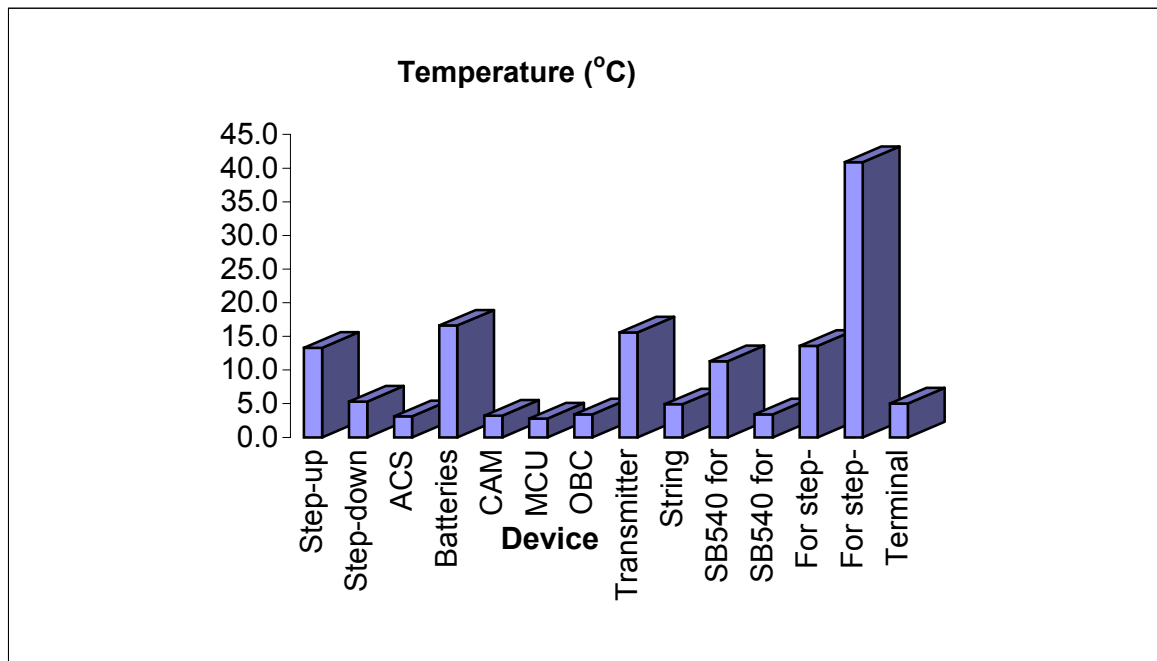*Table 5.3 temperatures of main components*

Figure 5.8 Temperatures of main components

Conclusion

Sequent model is not the final one, because it does not consider the geometrical distribution of components. For successful completion of it, the final board is necessary. The method for it, is shown in figure 5.5. The model has many restrictions and imperfections. The main problem is that the material properties of the board are not included and if two components are very close and their electrical connection is far distant then the conduction by board can apply more than by copper.

Anyway, this model gives the basic idea about thermal conditions on a PSU board. The main sources of heat and the temperature amount are known. The problem is with verifying values of resulting temperatures in our laboratory. For this it is necessary to eliminate convection so vacuum chamber is needed. It is also clear that the temperatures are strongly dependent on thermal resistances, which were just estimated.

5.3.4. Three-dimensional model of satellite

In reference to mentioned restrictions of previous model, another solution for 3D model needed to be found. In this case, a software using method of finite elements have to be used. ANSYS software has been chosen as a most suitable for our application. Its biggest advantage is that it consider the material properties and it works in three dimensions. On the other hand it is very sophisticated tool and it requires a lot of time to learn it.

To simplify the realization of model it will include only main parts of the satellite:

- Side walls

- Solar cells

- It is assumed steady state for all the computations

For proper function of this software, it is necessary to choose a proper element. As was mentioned before, between heat conduction mechanisms, only radiation and conduction are applicable in a space application. For a 3D analysis only LINK31, SHELL57 and SURF152 elements can work in ANSYS software with respect to radiation.

LINK31 element can be used only for calculating the heat flow between two nodes. It only has these two nodes and cannot be meshed. SHELL57 has four nodes and capability to define in each node different thickness. There is not problem with meshing of this element.

SURF152 (also called superelement) may be used for various load and surface effect applications.

If a radiation simulation between some surfaces and surroundings has to be performed, then the SHELL57 element must be chosen. After setting the thickness, the geometry of the satellite can be done by creating key points, from them lines and finally from lines can be constructed areas of each hand side. Figure 5.9 shows an example of a meshed surfaces for the satellite.
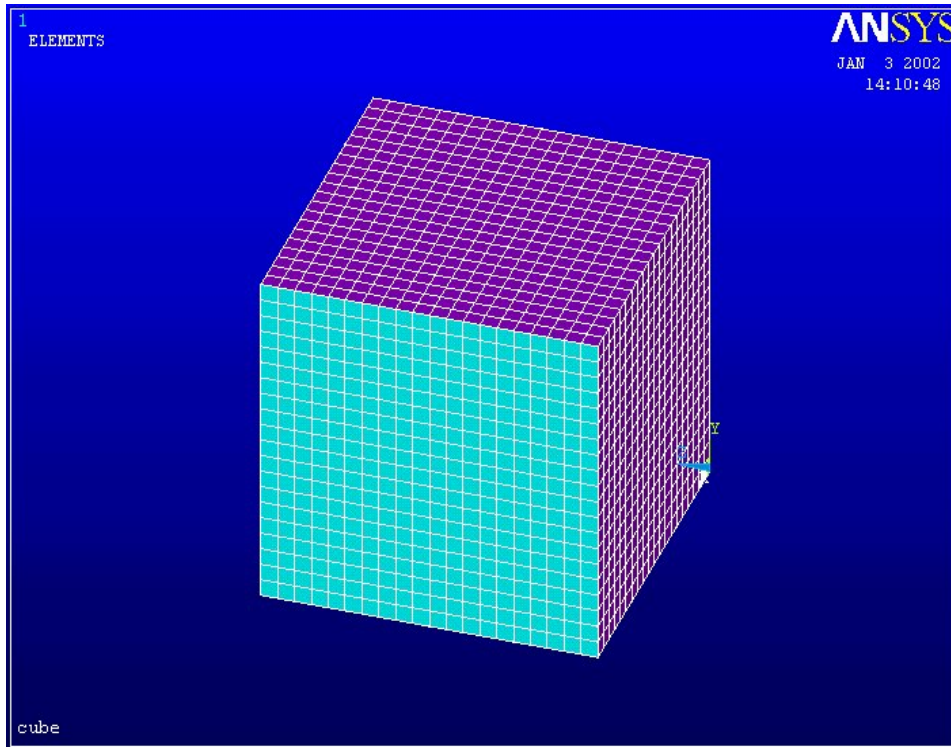
Figure 5.9 Example of meshed structure for the satellite

Following, there are two methods of doing simulation with reference to radiation problem:

- AUX12 Radiation Matrix Method
- Radiosity Solver Method.

For the AUX12 method must be SHELL57 superimposed by superelement on which must be defined conditions for radiation.

Assigning edge conditions for the model

Because there was not possible to establish temperature distribution only from heat flux and material properties, boundary conditions had to be calculated.

For calculation the edge temperature on the sun side (T_1), can be used Stefan-Boltzmann law:

$$S_{rad} = \sigma \cdot T^4 \cdot \varepsilon \qquad (5.20)$$

From this, the expression of temperature resides:

$$T = \sqrt[4]{\frac{S_{rad}}{\sigma \cdot \varepsilon}} \qquad (5.21)$$

where the symbols in the equations have the following significances:

S_{rad} is the solar heat flux, equal with 1353 [W/m^2]

ε is the emissivity of the material, and

σ is Stephan-Boltzmann constant, equal with 5.67 x 10^{-8} [W/m^{2}K^4].

Assuming the emissivity ε equal with 1, and replacing the numbers in equation (5.21), it yields:

$$T_1 = \sqrt[4]{\frac{1353[\text{W/m}^2]}{1 \cdot 5.67 \cdot 10^{-8}[\text{W/m}^2\text{K}^4]}} = 393[\text{K}] = 120[^\circ\text{C}] \tag{5.22}$$

A similar value can be obtained also by computing thermal equilibrium for solar cells. The same equation can be used for infra radiation from the side of the Earth, only now the heat flux for infrared is 237 [W/m²].

$$T_2 = \sqrt[4]{\frac{237[\text{W/m}^2]}{1 \cdot 5.67 \cdot 10^{-8}[\text{W/m}^2\text{K}^4]}} = 254[\text{K}] = -19[^\circ\text{C}] \tag{5.23}$$

By using these edge conditions it has been obtained the picture shown in figure 5.10 (using SHELL57 element), which shows temperature distribution in Cubesat, but this model is including only conduction. It is necessary to build similar model for radiation, but this was not possible at the time of doing the analysis.
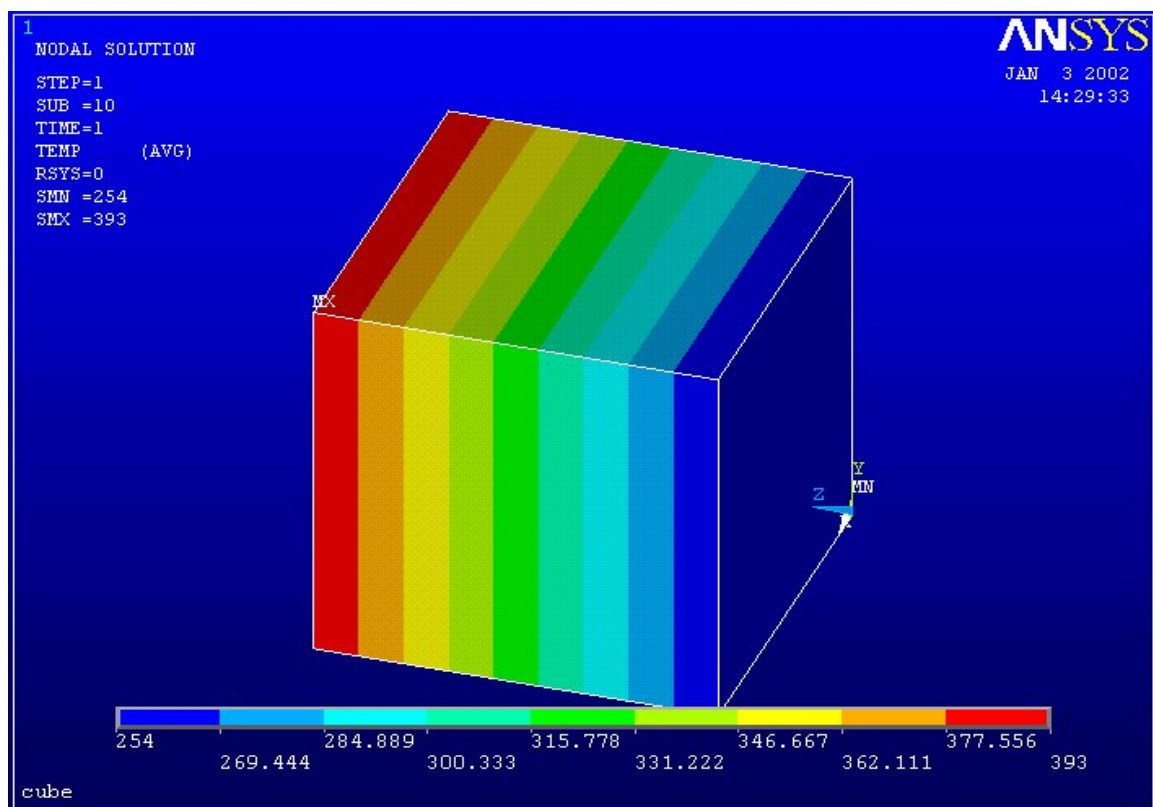

Figure 5.10 Distribution of temperature on the satellite surface

Conclusion

The built model is very simple and couldn't satisfy our recommendations. It is necessary to find a solution for radiation element. And connect both models together.

5.4. Thermal control

It is necessary to keep the temperature in Cubesat during the mission in the industrial standard, because all electronic devices are designed to operate in this temperature range. The methods of realizing this goal are described in the following.

The methods of thermal control can be split into two categories, passive methods and active methods. In respect to the size of the satellite, passive methods will be preferred.

Heat insulation is needed to keep an instrument sufficiently warm or to prevent heat from body-mounted solar panels from propagating into the spacecraft or for separation the heat-sensitive parts. Used material is MLI (multilayer insulation), with a structure like the one depicted in figure 5.11 [*Hansen, 2001*].
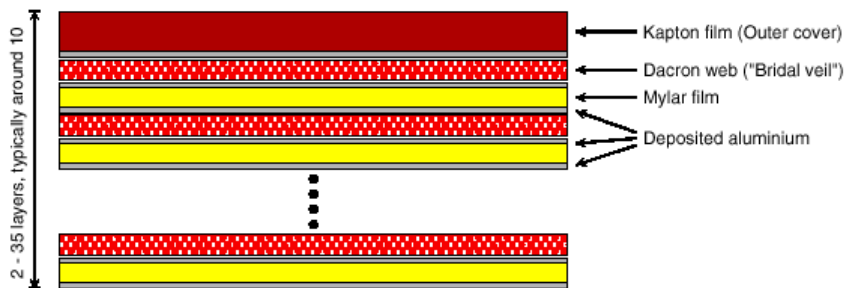

Figure 5.11 Thermal insulating material

This material is very light and thin and can be simple used for a small satellite. This material will be probably used as a thermal shielding for our batteries. This can help us to avoid fast temperature changes.

Another passive form is *changing value of α/ε factor*. This can be realized by changing the color or surface materials. This method is very easy to implement and is also reliable. Temperature equilibriums for different values of α/ε factor can be seen in a table 5.4 [*Hansen, 2001*].

No.	Material	Measure-ment temp.(K)	Surface condition	Solar absorbitivity α	Infrared emissivity ε	α/ε ratio	Equili-brium temp.(^{o}C)
1	Aluminum (6061-T6)	294	As received	0.379	0.0346	10.95	450
2	Aluminum (6061-T6)	422	As received	0.379	0.0393	9.64	428
3	Aluminum (6061-T6)	294	Polished	0.2	0.031	6.45	361
4	Aluminum (6061-T6)	422	Polished	0.2	0.034	5.88	346
5	Gold	294	As rolled	0.299	0.023	13.00	482

6	Titanium (6AL-4V)	294	As received	0.766	0.472	1.62	176
7	Titanium (6AL-4V)	422	As received	0.766	0.513	1.49	166
8	Titanium (6AL-4V)	294	Polished	0.448	0.129	3.47	270
9	Titanium (6AL-4V)	422	Polished	0.488	0.148	3.30	251
10	White enamel	294	Al. substrate	0.252	0.853	0.30	20
11	White epoxy	294	Al. substrate	0.248	0.924	0.27	13
12	White epoxy	422	Al. substrate	0.248	0.888	0.28	16
13	Black paint	294	Al. substrate	0.975	0.874	1.12	136
14	Silvered Teflon	295		0.08	0.66	0.12	-39
15	Aluminized Teflon	295		0.163	0.8	0.20	-6
16	Quartz Over Silver	295		0.077	0.79	0.10	-51
17	Sol.Cell-Fused Silica Cover			0.805	0.825	0.98	122
18	Crushed Carbon Graphit			0.88	0.96	0.92	

Table 5.4 Temperature equilibrium for different materials

From the active methods of thermal control, the *rotating method* can be mentioned. If large amounts of heat are located on a board the satellite, this can start slowly to rotate. There exists a critical value of temperature, which can be measured by temperature sensors and this signal can be used as a control signal for the attitude control system to rotate the satellite. This method is dependent on speed of rotation, which is connected to the induced current into the magnetotorquers. We cannot rotate very fast or very slow, the speed of rotation must be optimized in transient thermal analysis. And it is a task for thermal stabilization.

Also h*eaters* are used to avoid low temperatures. They can be realized as electrical blankets or as small resistances. For our application they seem to be so inefficient, because of power problems. Only one possible application can be realized for heating batteries. The necessary amount of the heat has to be computed.

Heat pipes are the last active method. Heat pipes can transfer much higher powers for a given temperature gradient than even the best metallic conductors. They are hollow tubes closed on both ends filled with some fluid like ammonia, as shown in figure 5.12. As one end of the pipe is exposed to a heat source, the ammonia absorbs this heat and vaporizes. The ammonia vapor then flows through

the pipe and carries the heat away to the cold end. There the ammonia losses its heat and recondenses as a liquid. It then flows back to the other end. This is a form of convection in which the work is being done not by gravity but by the wicking effect. This system can be effective for higher temperatures, depends on boiling point of inner fluid. (But in case of our system the problem is to avoid low temperatures during the eclipse). Its light weight (generally less than 40 grams), small, compact profile, and its passive operation, allow it to meet the demanding requirements of mini satellites. Their application needs deeper analysis. They can be used for transporting heat from hot (illuminated) sides to cold one.
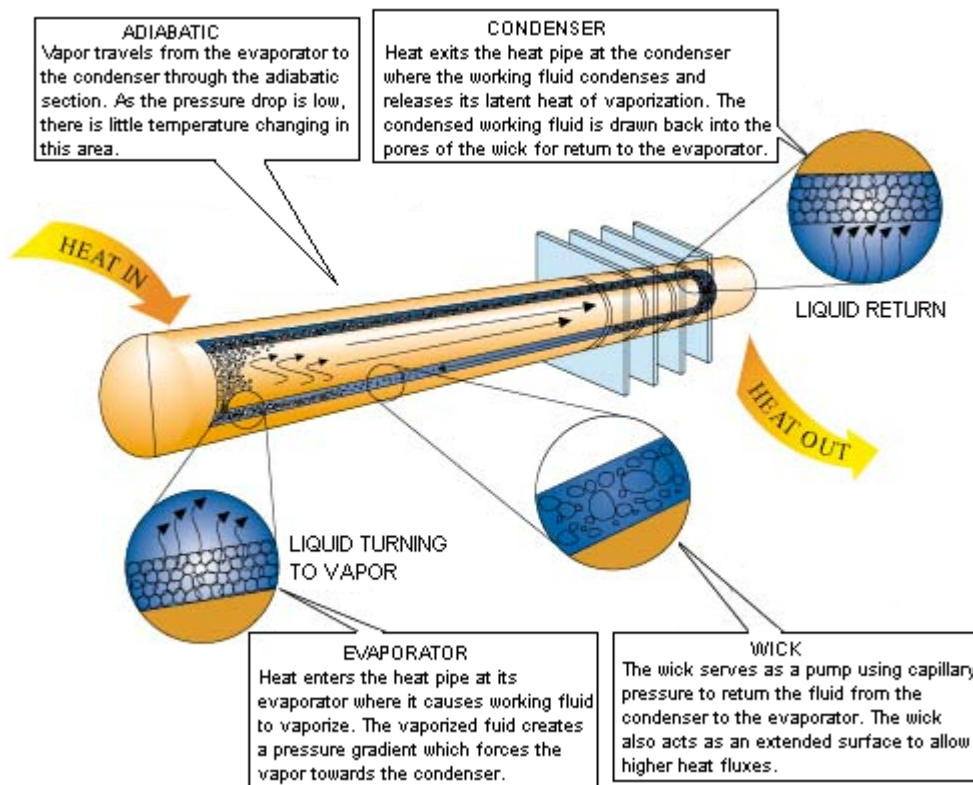

Figure 5.12 Heat pipes – principle of operation
[http://www.electronics-cooling.com/Resources/EC_Articles/SEP96/sep96_02.htm]

5.5. EMC considerations

Power supply must also fulfill requirements for EMC. It means that the level of the electromagnetic noise of our device should be below admissible value for other parts of Cubesat. And on the other hand our device must be resistant enough against foreign sources of noise [http://www.its.bldrdoc.gov/fs-1037/dir-013/_1932.htm].

Definitions

Electromagnetic compatibility (EMC):

1. Electromagnetic compatibility is the condition, which prevails when equipment is performing its individually designed function in a common electromagnetic environment without causing or suffering unacceptable degradation due to unintentional electromagnetic interference to or from other equipment in the same environment.

2. The ability of systems, equipment, and devices that utilize the electromagnetic spectrum to operate in their intended operational environments without suffering unacceptable degradation or causing unintentional degradation because of electromagnetic radiation or response. It involves the application of sound electromagnetic spectrum management; system, equipment, and device design configuration that ensures interference-free operation; and clear concepts and doctrines that maximize operational effectiveness.

Electromagnetic environment (EME):

1. For a telecommunications system, the spatial distribution of electromagnetic fields surrounding a given site. The electromagnetic environment may be expressed in terms of the spatial and temporal distribution of electric field strength [V/m], irradiance [W/m^2], or energy density [J/m^3].

2. The resulting product of the power and time distribution, in various frequency ranges, of the radiated or conducted electromagnetic emission levels that may be encountered by a military force, system, or platform when performing its assigned mission in its intended operational environment. It is the sum of electromagnetic interference; electromagnetic pulse; hazards of electromagnetic radiation to personnel, ordnance, and volatile materials; and natural phenomena effects of lightning.

Electromagnetic interference (EMI):

1. Any electromagnetic disturbance that interrupts, obstructs, or otherwise degrades or limits the effective performance of electronics/electrical equipment. It can be induced intentionally, as in some forms of electronic warfare, or unintentionally, as a result of spurious emissions and responses, intermodulation products

2. An engineering term used to designate interference in a piece of electronic equipment caused by another piece of electronic or other equipment. EMI sometimes refers to interference caused by nuclear explosion [JP 1-02].

Level of noise

*   High frequencies >1MHz

*   Low frequencies our case <1MHz

Digital circuits as a noise sources

Digital circuits generate mainly narrow-band noise, that means energy is concentrated on single frequency. The biggest emission is normally between 50 and 500 MHz depends on clock frequency. The highest energy appears normally as a harmonic of clock frequency. Our microcontroller works on 1MHz. There is also direct emission from the PCB, which works as a magnetic loop antenna. The emission level depends on the current in the loop. From this is obvious that the board must be as small as possible. It is also important to use a PCB with ground plan (gridded ground system).

The emission from PCB loop (figure 5.13), which has diameter much smaller than a wavelength (λ), can be described as:

$$H_{max} = \frac{A}{2\pi \cdot r^3} \cdot i \ , \ \left(r < \frac{\lambda}{6} \right)$$ (5.24)

where, H is magnetic field strength [A/m]

E represents the electric field strength [V/m]

A is area of the loop [m^2], and

r is the distance from the current loop to measure point [m]
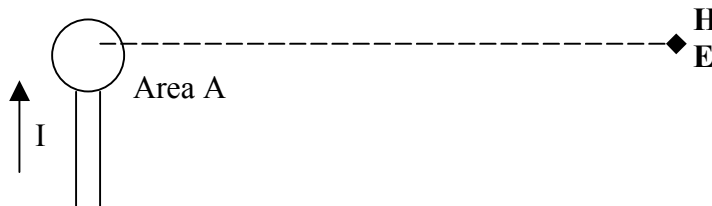

Figure 5.13 Emission from a PCB loop

Recommendations for minimizing emission of digital circuits:

- Use the lowest possible clock frequency.

- Do not use digital circuit with faster rise time than it is necessary.

- Use parallel power supply for 0 V and for V_{cc}.

- Minimize the area of all printed circuit loops. Especially for clock and bus circuit. The best place is in the middle of the board.

- Make the connection to PCB on the same side, the smaller impedance will be obtained.

- Make HF filters on all connection to the PCB. All filter capacitors should have reference to one ground plane.

Noise from power electronics

If it is made a comparison between the power electronic circuits and digital circuits, it might be observed that the rise times are higher in digital circuits, but the current is higher in power

electronics. This can lead to emission of high levels of noise and electromagnetic interferences, if proper methods to avoid this are not considered.

Recommendations to prevent noise:

- Loops in circuit as short as possible: long loops works by certain frequencies as magnetic loop antenna.

- Shielding: It reduces or absorbs the coupling between noise source and the victim. The cause of this effect is, that the conductive shield hit by electromagnetic field will induce current in the plate, which transform the field energy into the heat.

The damping ability of a shield depends on:

- The frequency of the field

- The field impedance

- The shield material

- The dimensions and the placing of the shield

Absorption loss in shield are given by the following formula:

$$A = 131\sqrt{f \cdot \mu_r \cdot \sigma_r} \cdot t \qquad (5.25)$$

where, f represents the frequency of electromagnetic signal [Hz]

μ_r is the relative permeability of shield material

σ_r is the material relative conductivity in relation to copper, and

t represents the shield thickness.

Reflection loss are given as:

$$R = 168 + 10\log\left(\frac{\sigma_r}{\mu_r} \cdot \frac{1}{f}\right)[\text{dB}] \qquad (5.26)$$

where, f is the frequency of the perturbing signal [Hz],

σ_r is the material relative conductivity in relation to copper, and

μ_r represents the relative permeability of shield material

5.6. Summary

The goal of thermal analysis developed in this chapter, is to have basic idea about temperature distribution in Cubesat and suggest some methods for thermal control. For this different approaches were used. First of all was computed the temperature equilibrium for the satellite, considering no

internal heat sources. If all equilibrium temperatures are compared than can be seen that the worst case for Cubesat is in eclipse when only side with camera is pointed to the Earth. So temperature range according to the temperature equilibrium is:

$T_{max} = 55$ [˚C]

$T_{min} = -124$ [˚C]

From this numbers can be derived that satellite has a trend to keep lower temperature than higher one. This is advantage for us, because no internal sources of heat are included and they will raise temperature inside.

Second part was model of the board in Saber , which gives us basic idea about temperatures on a board. Highest obtained temperature for switch of step-down converter is 40.9˚C, which is far away from maximum for industrial standard. Of course, this temperatures will add up with the temperatures of surroundings and they are not final.

Next most problematic part was model of whole Cubesat in ANSYS: The built model is very simple and couldn't satisfy our recommendations. It is necessary to find a solution for radiation element. And connect both models together.

From thermal control shielding for batteries is suggested (as the most temperature sensitive part of power subsystem). MLI can be easily used for this. Also heat pipes seem to be relevant for the current application.

Some basic considerations about electromagnetic compatibility problems are presented in section 5.5. Potential sources of noise are analyzed and a comparison between them is made. Measurement of noise for final board on spectrum analyzer will be done.