CubeSat Thermal Analysis

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ABSTRACT
A complete thermal analysis on picosatellites is of most importance because it helps in the development of thermal control system that can protect the satellite's internal systems from the extreme condition of outer space. Lack of a properly designed thermal control system could potentially mean the failure of the mission. Budget constraints in the design of the NEESAT-1U picosatellite, lead the team to implement passive thermal control systems on their CubeSat. In this paper, various materials have been considered for implementation as a thermal insulator. These materials have been evaluated by numerical methods. Best performing material was then evaluated using one-dimensional heat conduction to find the appropriate thickness needed to maintain the internal components at a safe operating temperature.

Keywords
Passive thermal control, Thermal insulation, CubeSat.

NOMENCLATURE

q_s	Solar Radiation, *W/m²*
q_e	Earth's IR Radiation, *W/m²*
q_a	Albedo Radiation, *W/m²*
G_s	Solar Constant, *W/m²*
α_s	Absorbance of material, Dimensionless
φ	Angle between surface normal vector and direction of solar rays, Degrees
θ	Angle between surface normal vector and direction of solar rays, Degrees
q_e	Earth^' s IR Radiation, *W/m²*
σ	Stefan Boltzmann Constant, 5.67e8, $W/(m^2*K^4)$
T_e	Effective Black Body Temperature, *K*
F_e	View Factor
R	Resistance of the Material, $(m^2*K)/W$
L	Thickness of the Material, *m*
K	Thermal Conductivity of the Material $W/(m*K)$
A	Area, m^2
Q_{in}	Heat Flux into the System, w/m^2
T_{out}	Temperature on the Outer Surface, *K, C*
T_{in}	Temperature on the Inner Surface, *K, C*

1. INTRODUCTION
A 1U CubeSat is a small satellite measuring 10cm x 10cm x 10cm with a maximum weight of 1.33kg, these satellites have gained popularity among the researchers, universities, and schools across the world due to their short development time and low cost [1]. The CubeSat project began as a collaborative effort between Prof. Jordi Puig-Suari at California Polytechnic State University (Cal Poly), San Luis Obispo, and Prof. Bob Twiggs at Stanford University and it was intended to standardize the development and construction of microsatellites [2]. There are many different sub sections involved in the development of a CubeSat. The RoarSat team at Florida International University (FIU), have already completed a study on the development of an attitude control system used in their microsatellite [3]. Following their steps and aiming to assist future teams in the development of CubeSat, the NEESAT-1U team conducted this study on the thermal control system of a CubeSat. Micro and Nano-satellites with their low thermal capacitance are vulnerable to rapid temperature fluctuations [4], which creates the need for a thermal control system that can protect the internal components of the satellite from the extreme conditions of the Lower Earth Orbit (LEO). This issue has been approached by many researchers in the past from different angles [5,6,7], for instance, by development of numerical methods capable of analyzing the thermal behavior of a nanosatellite in LEO [5], or by creating new panel configuration capable of managing the radiation energy coming into the CubeSat Systems [7]

2. THERMAL CONTROL SYSTEM
A thermal analysis on our CubeSat is of most importance because it helps in the development of thermal insulation that can protect the satellite's internal systems from the extreme condition of outer space. The lack of a property designed thermal layer, could potentially mean the failure of the mission since there is an elevated risk of damaging the internal components. Due to the budget constraint, it was decided to come up with a passive thermal control that can satisfy the mission requirements. In this section, various materials will be considered using analytical methods and simulations.

2.1 Environment
For analytical thermal insulation calculations, it is important to state the operation conditions of a CubeSat. One of the most common orbits where nanosatellites are being launched is at a reference altitude of 600km, 97.8° inclination Sun Synchronous

Low Earth Orbit [8], for simplification of these calculations in this study, an angle of 0º inclination is assumed.

Thermal control is a process of energy management in which environmental heating plays a key role [1]. The first step in obtaining a proper thermal layer was to compute the different fluxes coming into the systems. Due to the lack of a medium, the primary mode of heat transfer in LEO is radiation. Equations 1 to 3 were used to obtain the heat flux value for the primary sources of radiation.

Equation 1 represents, direct solar radiation flux absorbed by a spacecraft surface [9].

$$q_s = G_s \alpha_s \cos\varphi \quad (1)$$

Equation 2 represents the direct Earth IR radiation, T_e is the effective blackbody temperature of the Earth (255 K on average) [9], and Fe is the view Factor from the Space craft Surface to the Earth's disk. Due to the huge size difference between the NEESAT-1U and Earth, the View factors was assumed to be 1.

$$q_e = \sigma T_e^4 \alpha_{IR} Fe \quad (2)$$

Finally, Equation 3 details the radiation flux absorbed by the spacecraft surface due to albedo [9].

$$q_a = G_s (AF) \alpha_s Fe * \cos\theta \quad (3)$$

Using the previous equations following heat flux values were obtained.

Table 1. Sources of heat flux

Source	*Heat Flux (W/m)*
Solar Radiation	1366
Albedo	237
Earth's IR Radiation	368

2.2 Analytical Design

After researching multiple possible materials that could be used as thermal insulators, Cryogel insulating blankets were selected as a possible insulation for current work. This product is made from Aerogel, a material which has a thermal conductivity of .014 W/m*k and an extremely low density of 13 g/m^3. Cryogel has an operating temperature of -200 ºC to 200 º C [10] making it a very light and affordable selection.

The next step was to use the concept of one-dimensional conduction through a wall to calculate the appropriate insulation layer thickness.

Equation 4 is used to calculate the thermal resistance (R) of each one of the walls using the thickness of the material (L). The thermal conductivity of the material (K), and area (A), Equation 5 is the heat transfer between the wall form point $T_{s,1}$ to T_{s4}.

$$R = \frac{L}{KA} \quad (4)$$

$$q_x = \frac{T_{s1} - T_{s4}}{\Sigma R_t} \quad (5)$$

$$Q_{in} = \frac{T_{out} - T_{in}}{\frac{L_{in}}{K_{in} * A_a}} \quad (6)$$

Using equation 6 an appropriate thickness of Aerogel was found for each one of the three radiation sources.

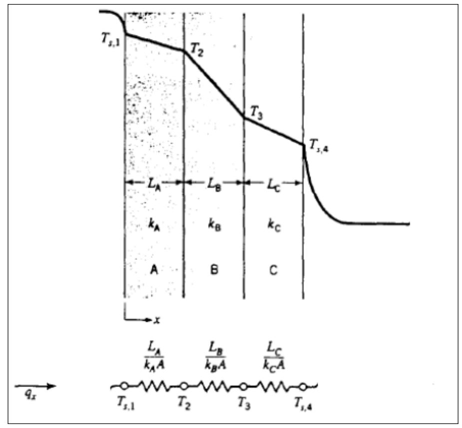


Figure 1. Thermal Resistance Across Multiple Layers

3. NUMERICAL APPROACH

3.1 Simulation Scenarios

To select a suitable insulation material that could satisfy the thermal requirement of mission at LEO, a selection of three materials was compiled for a finite element analysis. Table 1 displays the materials selected and their properties.

Table 2. Material Properties

Material	*K (W/mk)*	*ρ (kg/m^3)*	*Cp (J/kg.K)*	*Max service temp (C)*	*Source*
Aerogel	0.014	1100	Not Available	200	buyaerogel.com
Polyurethane	0.19	130	1760	100	Matweb.com
Polyimide	0.0657	596	Not Available	300	Matweb.com

To simplify the analysis and with the requirement that a thermal control system should be able to maintain an appropriate temperature inside a CubeSat, even when exposed to a large heat flux, a single insulation panel was modeled. Such panel, simulates the surface of a 1U CubeSat wall, an arbitrary thickness of 2 mm was used for this model. Next, a material from table 1 was added to the model, and an initial temperature of 20ºC was applied to inner surface. Finally, a heat flux of 1366 W/m was applied to the outside surface simulating a 100% exposure to solar radiation.

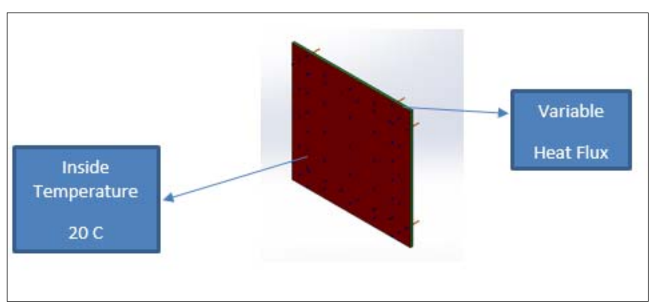
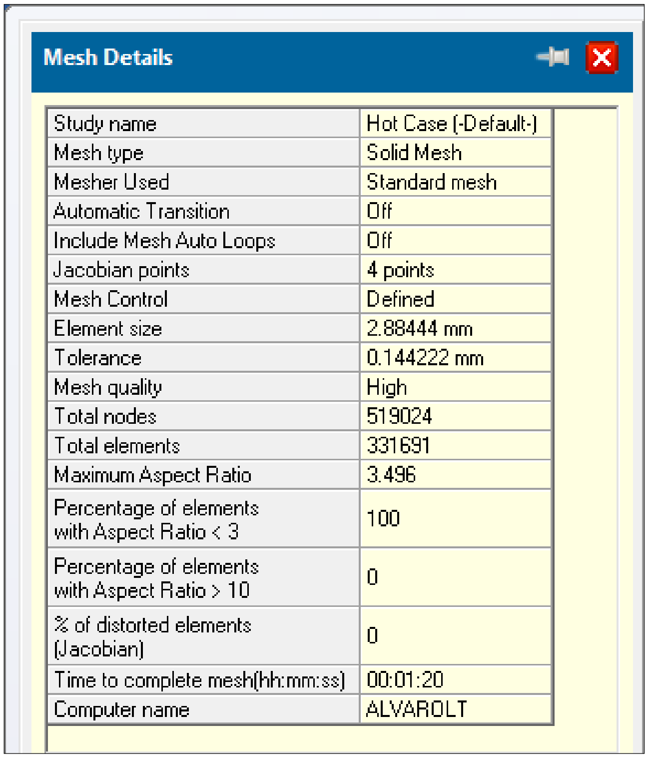


Figure 2. General Set Up for Steady State Simulation

The best performing material was then, put through a different study, where the thickness obtained using analytical methods for the highest heat flux, was compared to a larger and a smaller thickness, to analyze their response to an incoming heat flux.

3.2 Computational Details

SolidWorks 2016 software was used to complete the thermal study for the materials and appropriate thickness for insulation layer. To increase the result's accuracy from the study, the following mesh controls were applied to the simulation. A solid fine mesh was used with an element size of 2.44 mm with a tolerance of 1.44 mm. The under-relaxation factor was set as automatic and the convergence tolerance was set to $10x^{-6}$. Other parameter used in this simulation are listed in figure 3.



Mesh Details

Study name	Hot Case (-Default-)
Mesh type	Solid Mesh
Mesher Used	Standard mesh
Automatic Transition	Off
Include Mesh Auto Loops	Off
Jacobian points	4 points
Mesh Control	Defined
Element size	2.88444 mm
Tolerance	0.144222 mm
Mesh quality	High
Total nodes	519024
Total elements	331691
Maximum Aspect Ratio	3.496
Percentage of elements with Aspect Ratio < 3	100
Percentage of elements with Aspect Ratio > 10	0
% of distorted elements (Jacobian)	0
Time to complete mesh(hh:mm:ss)	00:01:20
Computer name	ALVAROLT

Figure 3. Mesh Details

4. RESULTS AND DISCUSSION

After completing all analytical calculation for the different scenarios, the values obtained are shown in Table 3, they represent the appropriate thermal insulation thickness for a 1U CubeSat at various heat fluxes. Since the primary concern is an elevated temperature damaging the inside components inside the satellite, the insulation for the largest heat flux solar radiation has been chosen because it protects the satellite at the worst-case scenario.

Table 3. Calculated Insulation Thicknesses

Source (W/m)	*Insulation Thickness(mm)*
Solar Radiation	1.84
Albedo	10.6
Earth's IR	6.85

The results from the steady state simulation demonstrated that Aerogel material was a suitable candidate as the thermal insulator, it was evident that it dissipated energy better than any the other three materials as shown in Table 4 and Figure 3.

Table 4. Numerical Solutions Results

Material	*T_{in} (K)*	*Flux (W/m^2)*	*Thickness (mm)*	*T_{out} (K)*	*T_{out} (C)*
Aerogel	293	1366	2.0	488.1	214.95
Polyurethane	293	1366	2.0	307.4	34.25
Polyimide	293	1366	2.0	334.6	61.45

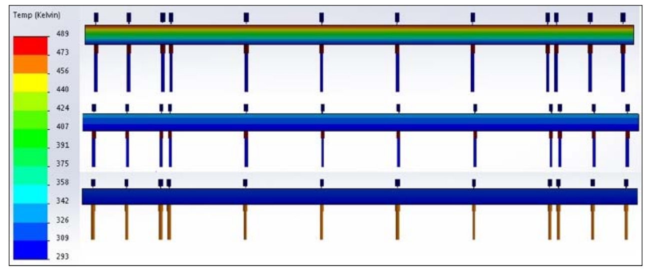


Figure 4. Thermal Dissipation Across Insulation Material: Top – Aerogel, Middle – Polyimide, Bottom – Polyurethane

Finally, the thicknesses found by analytical solution and the best performing material form the simulation were combined to verify how the different thicknesses responded to an incoming flux. Table 5 shows how larger thickness increases the outside temperature to a value greater than the maximum operation temperature of an Aerogel material. This table also shows how a smaller thickness has a lower outside temperature meaning that it does not provide thermal barrier better than the analytical thickness and therefore allowing the external radiative flux to raise the internal temperature of the satellite.

Table 5. Aerogel Thickness Performance

Flux (w/m^2)	*Thickness (mm)*	*T_{in} (K)*	*T_{out} (K)*	*T_{out} (C)*
1366	5	293	781	507.85
1366	1.84	293	472.7	199.55
1366	1	293	390.7	117.55

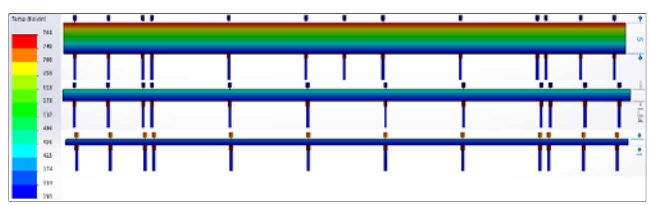


Figure 5. Thermal Dissipation across Different Thicknesses: Top – 5mm, Middle – 1.84 mm, Bottom – 1 mm

It is recommended to further validate these results through a vacuum chamber test, where a 1U CubeSat prototype can be exposed to the conditions prescribed in this paper and the results for such test should be compared to those presented in this study.

5. CONCLUSION

In this study, a thermal analysis was conducted for the development of a passive thermal control system that could satisfy the requirement for a CubeSat mission in the LEO. To accomplish this, the study first, establishes the environmental conditions to which a CubeSat might be exposed to. Next, one-dimensional thermal resistance equation was solved to find an appropriate thermal insulation layer thickness.

Different materials were analyzed using finite element methods, and the best candidate as an insulator for a 1U CubeSat was selected. Later, the thickness of the best performing material was optimized using the results obtained from the analytical calculations. It was demonstrated that a thickness larger than the 1.84 mm, would provide better thermal resistance raising the temperature of the outside surface of the insulation. Whereas, a smaller thickness than the optimum, could not provide the required thermal barrier and allow to raise the internal satellite temperature resulting in the mission failure.

It is also important to study the effect of the infiltrating external radiation on the satellites internal component to ensure the mission success for the satellite lifetime. Vacuum thermal bake studies will be suggested to study the outgassing of the components.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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