Steady State Internal Thermal Analysis of a 2U CubeSat

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1. Overview

OreSat is an open source 2U CubeSat nanosatellite project. OreSat has been sponsored via the CubeSat Launch Initiative (CSLI) and will be orbiting earth in low earth orbit (LEO) along the same path as the ISS in late 2020. OreSat's missions are to 1) collect data on cirrus cloud formation to be used in furthering climate studies and 2) to promote STEM outreach in Oregon grade, middle and high schools. However, thermal studies must be done on OreSat to ensure that the worst case hot and cold scenarios do not dramatically affect its operation and lifespan. Figure 1 depicts the current physical model of OreSat.

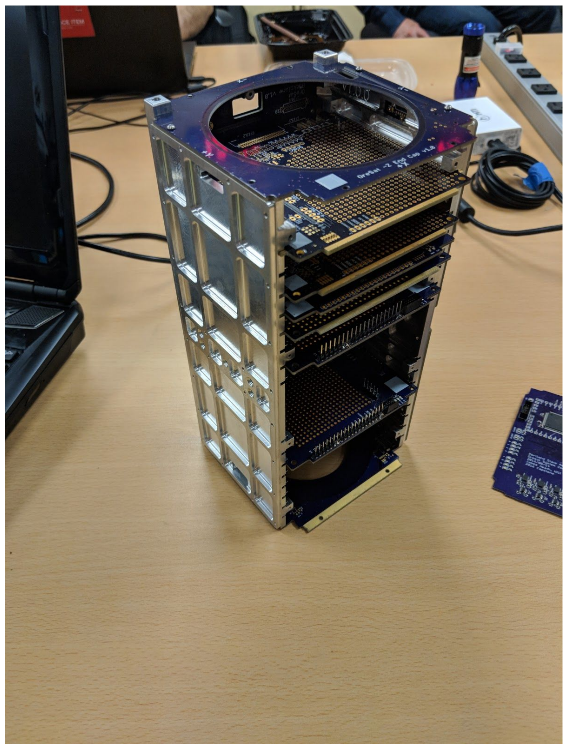

Figure 1 - Physical image of an OreSat prototype. Items of interest include the aluminum wall and the printed circuit boards (PCBs) inside of the satellite.

Conductive heat transfer will play a role via the onboard CPUs dissipating large quantities of heat, especially the dx-wifi hardware when it is switched to *active* mode. During active mode, the dx-wifi CPU will be dissipating 7.5 W of heat via conduction. There are several other boards that will be dissipating heat as well, but severely less at 1 W. The CPUs will be conducting to the silicon base PCBs, which will then be dumping heat to the aluminum frame to radiate out to space.

2. Physical Model and Boundary Conditions

The geometry of this model has been simplified to focus on three separate components: The aluminum walls that encase the satellite, three silicon based PCBs and three CPUs made of FR-4 found on three separate PCBs. Two of these CPUs will be dissipating 1 W of heat, each one on two separate PCBs, and the other will be dissipating 7.5 W of heat. These CPUs will be referred to as heaters for the remainder of the paper. Figure 2 displays the geometric model used in STAR-CCM+. The aluminum frame is modelled by the outermost rectangular prisms. The PCBs are modelled by three 10x10x0.5 cm figures found in the center. The heaters are modelled by three 3x3x0.2 cm figures found on top of each PCB. Imprints were made at the PCB/Aluminum wall and the Heater/PCB interfaces. The geometry was modelled in SolidWorks and the assembly was exported as a parasolid. This model, overall, was solved at steady state.

Table 1 - Dimensions of the parts used for this model, displayed in figure 2.

	Length (cm)	Width (cm)	Height (cm)	Description
Aluminum wall	20	10	0.5	Main frame of the satellite. Encases hardware.
PCB	10	10	0.5	Generalized circuit board hardware found in satellite.
Heater	3	3	0.2	CPUs found driving PCB hardware.

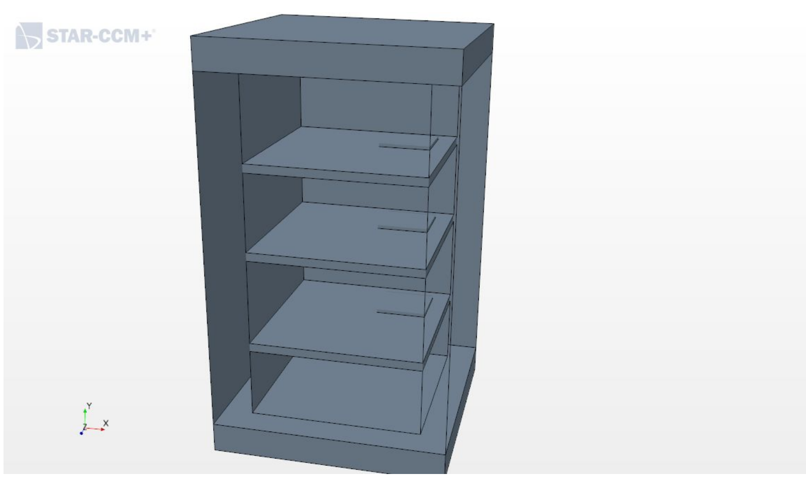

Figure 2 - Geometry used in STAR-CCM+ model. This geometry contains the simplified aluminum frame, PCBs and heaters.

Table 2 - A table depiction of OreSat's primary heat sources, the CPUs found on the PCBs, and the environment that OreSat will lose heat to via radiation: empty space.

Object	Value	Description
Power Dissipation - Low power	1 W	Two 1 W heaters are used in this model to simulate other notable sources of heat generation in the hardware.
Power Dissipation - High power	7.5 W	One 7.5 W heater is used in this model to simulate the dx-wifi borad's heat dissipation while in active mode.
Temperature of Space - Heat sink	4 K	This denotes the environment's temperature surrounding OreSat's aluminum frame. It is the primary heat sink for the model.
Heat flux - High power heater to PCB	8,333.3 W/m^2	The theoretical conductive heat flux from the 7.5 W of heat dissipated by the heater to its adjacent PCB.
Heat flux - Low power heater to PCB	1,111.1 W/m^2	The theoretical conductive heat flux from the 1 W of heat dissipated by the heater to its adjacent PCB.

Environmental boundary conditions were assigned to the vast majority of the surfaces in the satellite itself. This is especially critical for the exterior surfaces of the aluminum wall to model radiating towards empty space. If radiating to empty space did not exist in this model, there would be no purpose in creating this as the temperatures of this model would become unimaginably hot.

3. CFD Software Features

The primary material properties associated with this model are: density, specific heat and thermal conductivity. Density affects conductivity such that the denser an object, the greater the rate of conduction. Specific heat is related to the structure of a material, such that a perfect crystal structure of a solid will have a low specific heat. Larger specific heats are due to imperfect structures. As the specific heat value of a material increases, the rate of heat transfer decreases due to the increased difficulty of particles interacting with each other. Finally, thermal conductivity is the material's ability to transfer heat. It's important to get these values right as they play a critical role in conduction, overall.

Table 3 - Material properties assigned to the three materials found in this simulation. Each of the mentioned material properties are critical for thermal conduction. FR-4 information found in *Azar, K et al* [1].

Material	Density (kg/m^3)	Specific Heat (J/kg-K)	Thermal Conductivity (W/m-K)
Aluminum	2,702.0	903.0	237.0
Silicon	2,329.0	702.0	124.0
FR-4	1,850.0	950.0	0.29

For each of the physics continua, I elected to use Gray Thermal Radiation, Surface to Surface Radiation (S2S radiation), and Coupled Solid Energy models to solve this model. The S2S radiation model allowed for each surface, with an environment boundary, to interact with each other via radiation, and the variables associated with radiation (radiosity included). The Gray Thermal Radiation allowed for simulating the thermal environments that surrounded the model. Specifically, it allowed for modelling radiation out towards space. Finally, the Coupled Solid Energy model was selected over Segregated Solid Energy to reduce computation time.

4. Mesh

A simple meshing scheme was applied to the model due to the nature of the simplistic geometry of the model. Surface Remesher and Thin Mesher models were applied to the mesh continua. The Thin Mesher model was used as the bulk of the geometry was determined to be thin wall, thus a mesh to really capture the thinness of the wall was required. Four thin mesher layers were used in this model. The Surface Remesher allows for automatic mesh refinement during mesh generation. The base size of the cells was 3 mm.

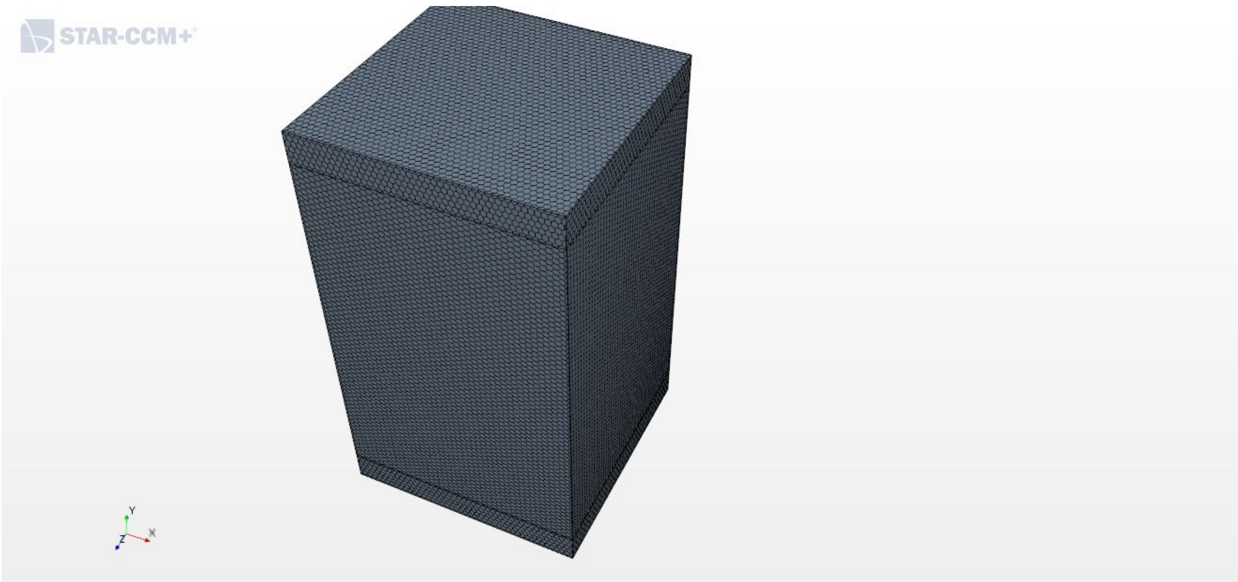

Figure 3 - The outside mesh of the CubeSat.

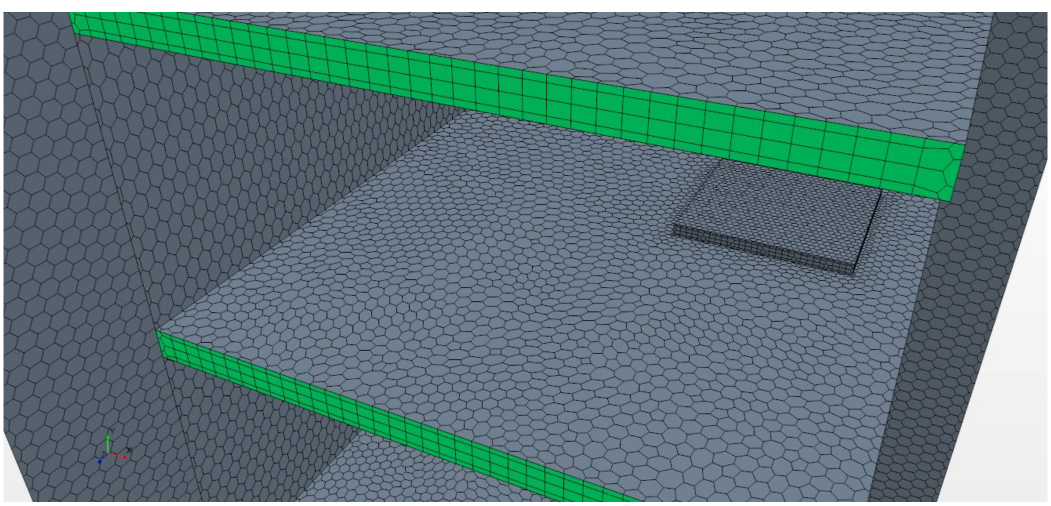

Figure 4 - A close look at the mesh of the components inside of the CubeSat. It should be noted that the heater's mesh is finer than the PCBs or the wall's. This is due to the size of

the heat source, and the importance of accurately capturing the conductive and radiative modes of heat transfer.

5. Results and Discussion

After running the simulation, it took approximately 70 iterations for the model to reach a point of convergence. In real time, it took approximately 20 minutes on my PC at home to run this simulation. The temperature correction model is used as a sanity check to ensure that as residuals decrease, there is a reduction in the change of temperature per iteration of the model. Due to E-13 convergence, this is a confirmation that error in the model does not play a large role in accuracy of the calculations. Thus, any inaccuracies will be due to simplifications made in the model. Figure 5 outlines plot with the residuals and temperature correction.

It is now important to analyze if what's going *in* is also going *out*. The boundaries analyzed are the interfaces between the Heaters/PCBs, and PCBs/Aluminum wall. The plot depicts a an average of E-6 difference in heat flux, which denotes at steady state there is minimal heat flux at this interface. Figure 7 is the report from STAR-CCM+ that confirms the regions used.

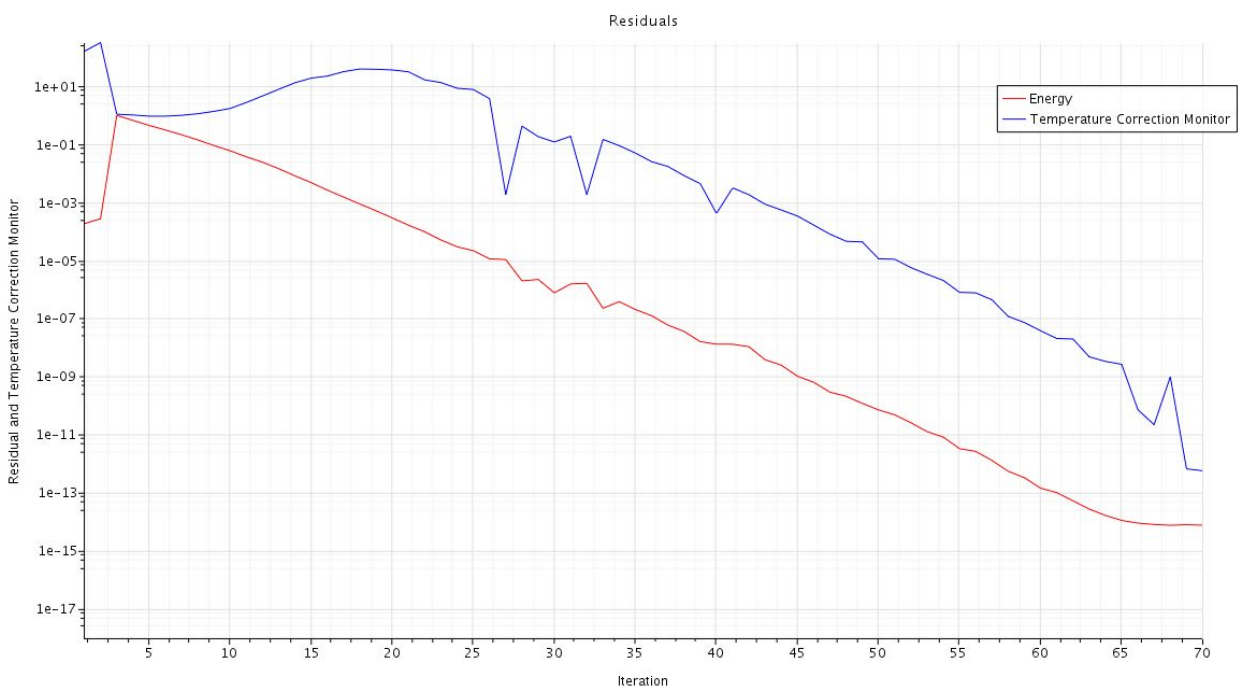

Figure 5 - Plot of the residuals and temperature correction of the model. Convergence at E-13 signifies very minimal error in the model. Double precision, at E-16, would be preferable.

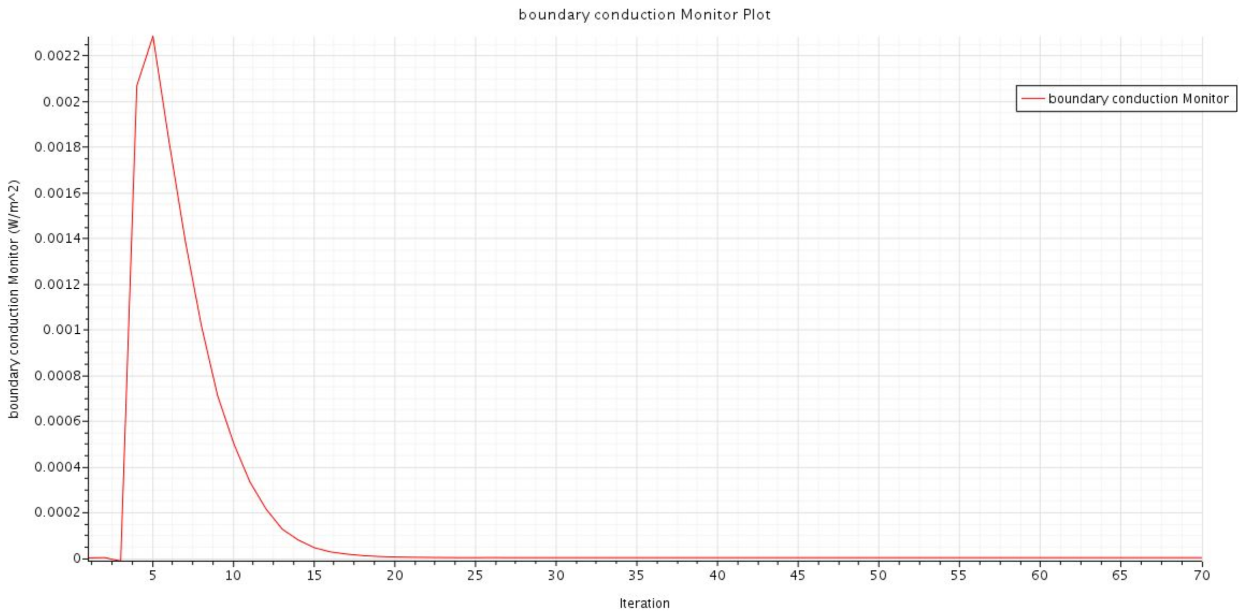

Figure 6 - Plot of the conductive boundary convergence between the Heater/PCBs, and the PCBs/Aluminum wall. This plot sums the heat fluxes from the selected sources at each iteration and takes an average for the final report.

Part	Value (W/m^2)
1w heaters: heater.PartSurface_Assembly 1|heater_Assembly 1|pcb [heater/pcb]	5.530089e+02
3w heater: heater 3w.PartSurface_Assembly 1|heater 3w_Assembly 1|pcb [heater 3w/pcb]	8.281781e+03
al end caps: al prism end caps.PartSurface_Assembly 1|al prism end caps_Assembly 1|al hollow prism [al hollow prism/al prism end caps]	-1.789471e+02
al hollow prism: al hollow prism.PartSurface_Assembly 1|al hollow prism_Assembly 1|al prism end caps [al hollow prism/al prism end caps]	1.789471e+02
al hollow prism: al hollow prism.PartSurface_Assembly 1|al hollow prism_Assembly 1|pcb [al hollow prism/pcb]	-1.411000e+03
pcbs: pcb.PartSurface_Assembly 1|pcb_Assembly 1|al hollow prism [al hollow prism/pcb]	1.411000e+03
pcbs: pcb.PartSurface_Assembly 1|pcb_Assembly 1|heater [heater/pcb]	-5.530089e+02
pcbs: pcb.PartSurface_Assembly 1|pcb_Assembly 1|heater 3w [heater 3w/pcb]	-8.281781e+03
Total:	-4.487083e-06

Figure 7 - Report from the boundary conduction monitor plot. It represents the individual interfaces being analyzed for heatflux. Note: Although it says “3w heater” in the report, 7.5 W was applied for this model.

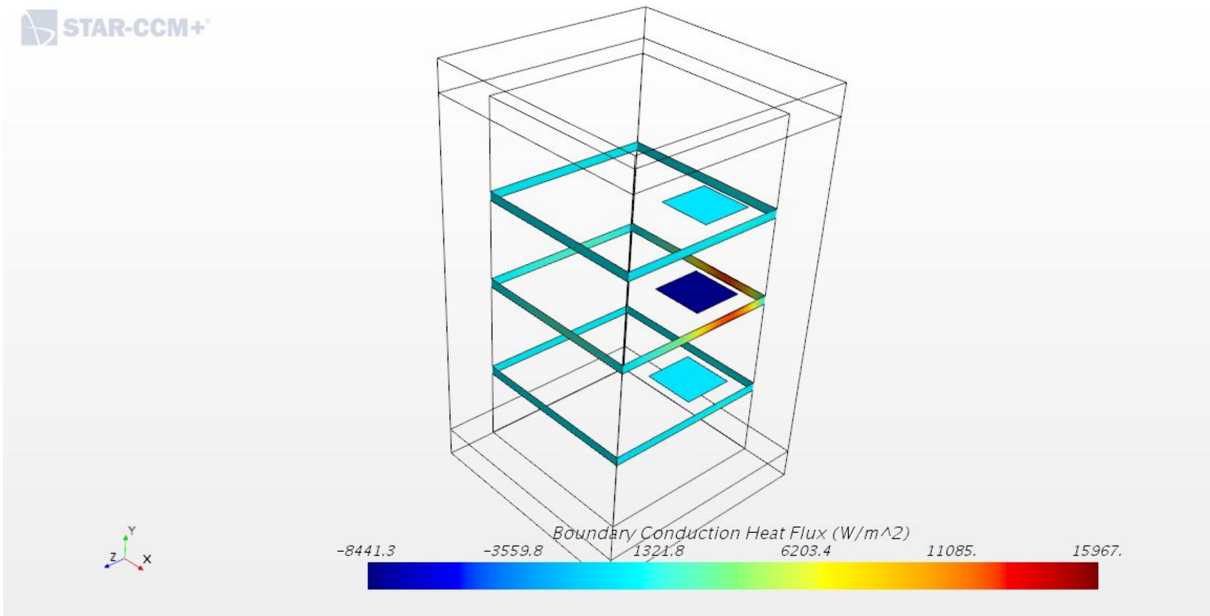

Figure 8 - A boundary conduction heat flux scene from STAR-CCM+. The interfaces shown are the direct contact between individual interfaces between parts, including Heater/PCB, PCB/Aluminum Wall. Heat flux at the 7.5 W heater displays -8,441.3 W/m^2, while the 1 W heaters display 511.2 W/m^2.

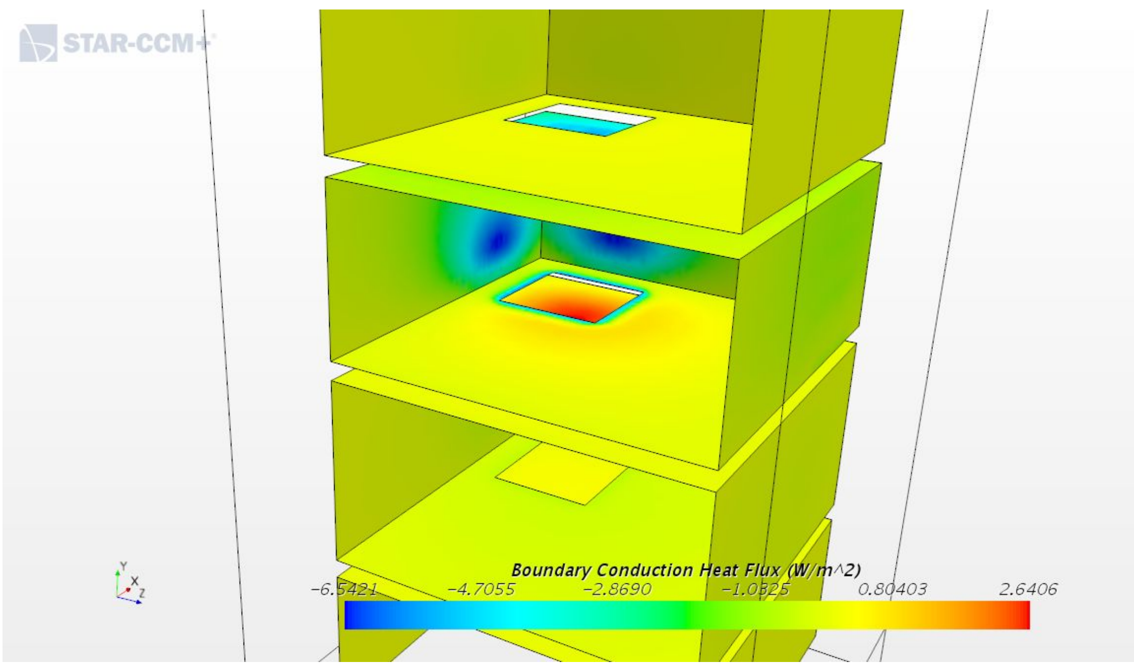

Figure 9 - The conductive heat flux throughout the main PCB bodies and the aluminum frame. The center block is primarily interesting due to the blue areas on the wall. This displays that radiation from 7.5 W heater had created a high temperature gradient in those two areas, that in steady state those areas begin to cool and lose heat to the local aluminum frame via conduction.

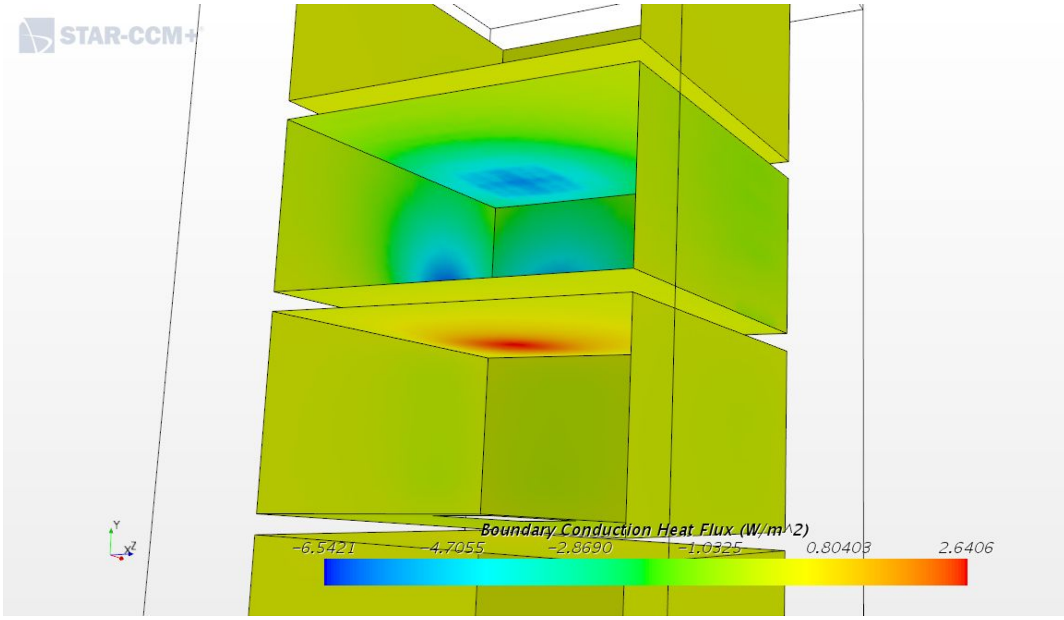

Figure 10 - Another view of the image from figure 9, except viewing towards the +y direction. Similarly to the side walls, the wall normal to the 7.5 W heater had undergone radiative heating, and is now cooling to the surrounding aluminum frame via conduction. The red area denotes that a small amount of conductive heating had penetrated the board, but only at the scale of 2.64 W/m^2.

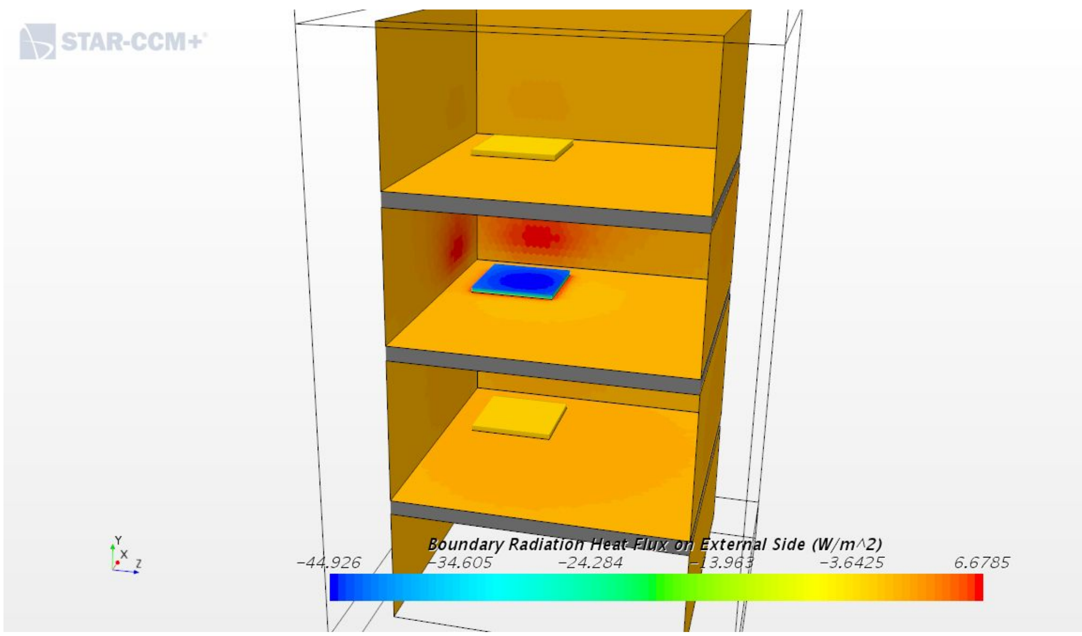

Figure 11 - A scalar scene from STAR-CCM+ of the radiative heat flux from the heaters. The 7.5 W heater displays a moderate amount of lost heat via conduction at 45 W/m^2. That radiation is transferred to the nearby walls, in the same locations depicted in figure 9 and figure 10.

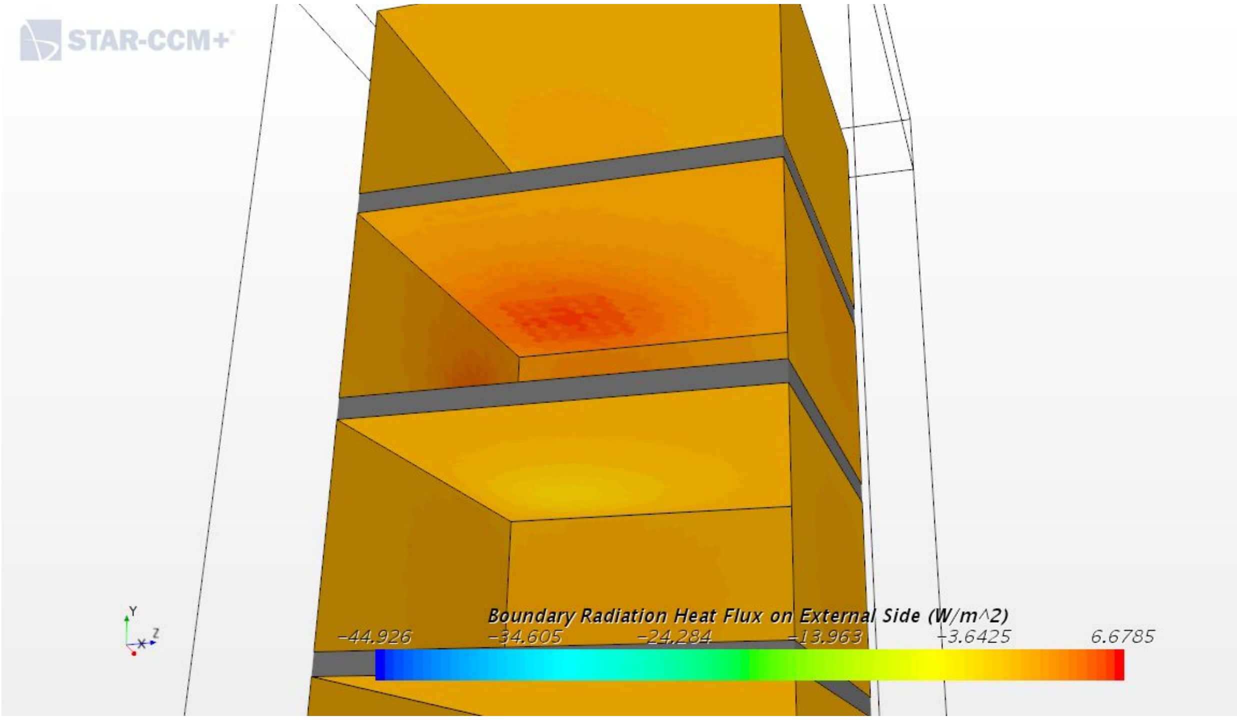

Figure 12 - Another view of figure 11, except viewing towards the +y direction. This clearly displays the radiative heat flux imposed on the surrounding walls, from both the 1 W heater (3rd from the top) and the 7.5 W heater. The yellow patch on the 3rd ceiling displays a negative heat flux, which is caused by the conduction that made it through from the 7.5 W heater slightly radiative away while still interacting with the 1 W heater's radiation.

The temperature in the model is sensible: Due to all 6 sides of the aluminum frame radiating to 4 K, the satellite will reach cold temperatures if radiation from the earth and sun are ignored. The temperature gradients across the aluminum frame are acceptable, with the largest difference being from 184 K to 188 K. Thus, thermal stresses caused by conduction is not a concern. Figure 13 and figure 14 are graphic representations of the steady state temperatures of the satellite.

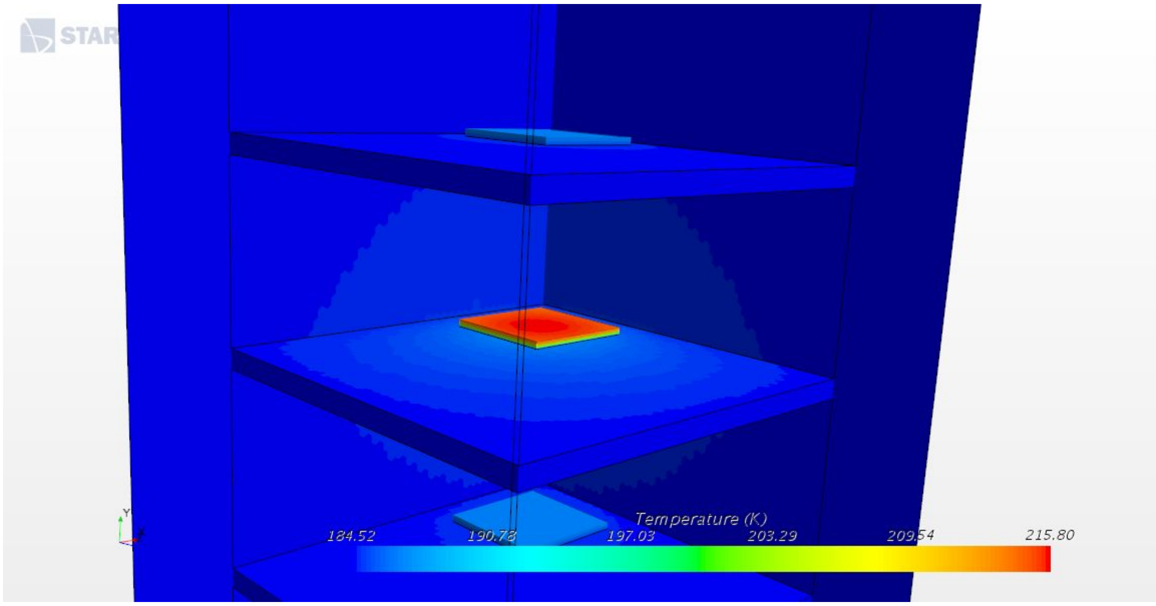

Figure 13 - A temperature scene from STAR-CCM+ detailing the temperature spread of the inner satellite in steady state, with the heaters near the aluminum wall.

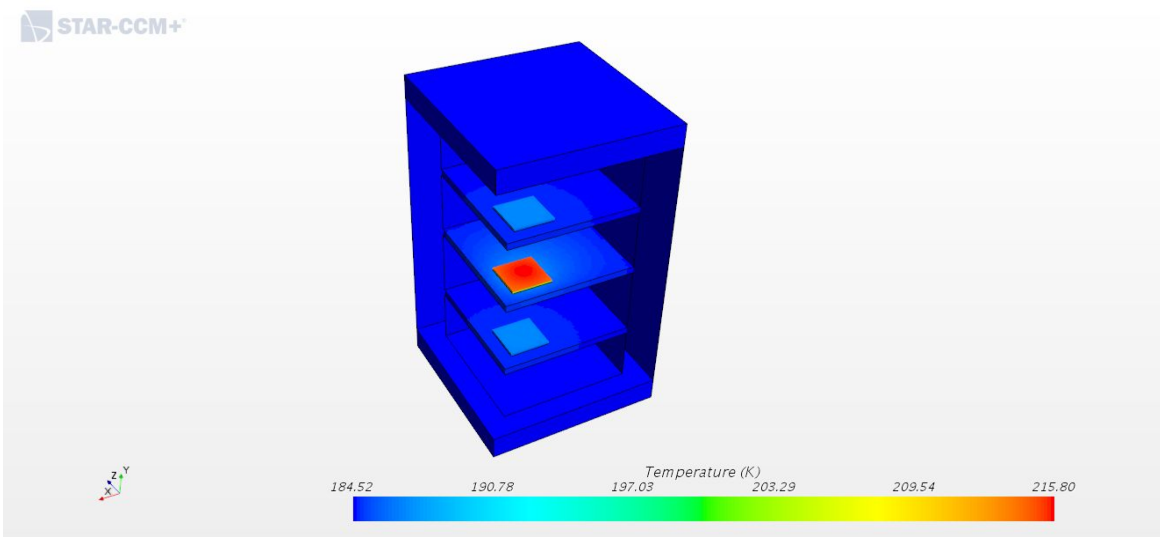

Figure 14 - A temperature scene from STAR-CCM+ detailing the temperature spread of the inner satellite in steady state, with the heaters away from the aluminum wall.

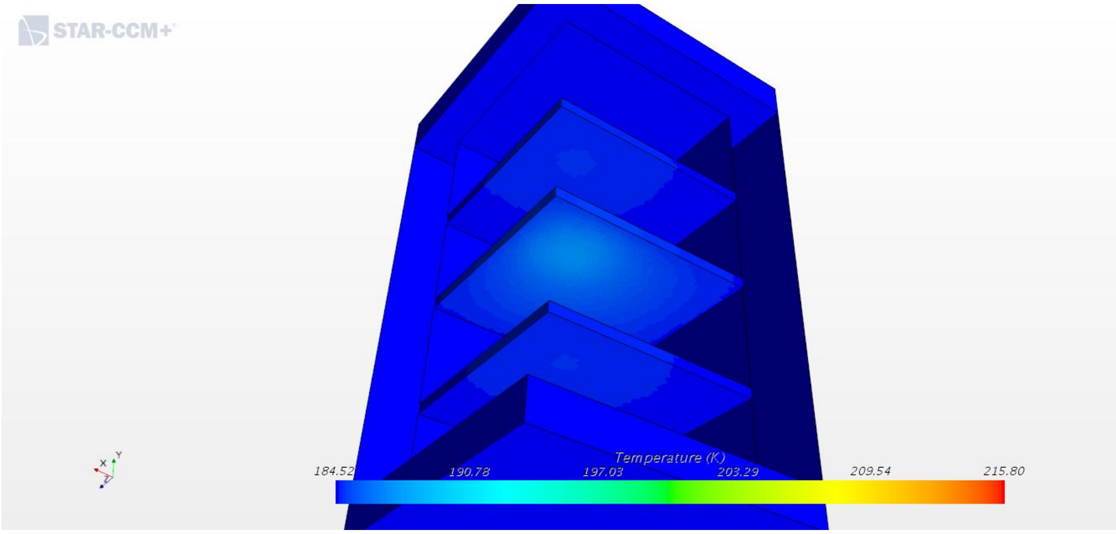

Figure 15 - A temperature scene from STAR-CCM+, viewing the CubeSat at +y. The interesting thing to note is the temperature spot below the middle PCB. The hottest spot in that temperature field is approximately 192 K.

6. Conclusion

Heat transfer analysis of a nanosatellite is tricky, particularly because of radiation. Radiation includes 4th order terms, which is a great way to generate a lot of error in a model. This report was able to examine and analyze the internal conductive and radiative modes of heat transfer of OreSat. It was found that there is a non-negligible amount of heat flux at the PCBs/Aluminum Wall interface, and that there is meaningful spread of heat throughout the PCBs, especially from the 7.5 W heater. Knowing the primary locations of radiative concentrations is beneficial due to knowing what areas are *possibly* in jeopardy of being too hot, and eventually, leads to knowing what sides of the satellite need to rotate out of sunlight to cool off to a manageable temperature. The temperature values align with that *Chandrashekar* [2] found with their analysis of a 3U CubeSat in their cold case scenario, with their CubeSat in the shadow of the earth. Theirs included radiation from earth, however.

If additional time was permitted for this analysis, solar and earth loads would be included. These are major sources that, in actuality, will play a large factor of how the internal heat transfer of OreSat will behave. However, getting these right can be tricky and they add an additional layer of complexity and error checking for the model as a whole. Additionally, including more complex geometry of the circuit boards and the aluminum frame would greatly improve model error. Due to each PCB having dozens of components and holes, the conduction would drastically change as it is highly geometry dependent.

7. References

[1] - Azar, K; Graebner J. E. (1996). "Experimental Determination of Thermal Conductivity of Printed Wiring Boards". Proceedings of the Twelfth IEEE SEMI-THERM Symposium: 169–182. doi:10.1109/STHERM.1996.545107.

[2] - Chandrashekar, Shreyas. “Thermal Analysis and Control of MIST CubeSat.” *KTH Royal Institute of Technology*, 8 Feb. 2017, doi:10.1117/12.2320750.5836569058001.