Thermal Analysis of a 2U CubeSat

By:
Jeremy Lowman

ME 448 Computational Fluid Dynamics

Overview

This report examines the thermal behavior of 2U cubesat which is a miniaturized, U-class satellite while in outer space. The satellite is a compact 10cm x 10cm x 20cm box with aluminum walls that will contain a battery and a variety of electronics and circuit boards. The following analysis uses Star-CCM+ computational fluid dynamic software to place a simplified model of the satellite in steady-state conditions similar to those in the upper atmosphere. When the satellite is deployed, it will be exposed to a vacuum environment, as well as the low temperatures of space. It will also be exposed to radiation from the sun.

The satellite must maintain an internal temperature between $0^{\circ}C$ and $60^{\circ}C$. In order to see if this is possible, the satellite will be modelled in two different steady-state situations: full direct exposure to the sun and no exposure to the sun. While in orbit, the satellite will operate in either an active or a standby mode which will create internal heat sources of either 3W or 7.5W respectively. For the purposes of this analysis, only the active 7.5W mode will be simulated. Radiative heat flux from the earth will also be neglected as I have not yet figured out how to apply this as a boundary condition in addition to radiation to space boundary condition in Star-CCM+.

Physical Model

The geometry used to used in this simulation was created in Solidworks and consists of 3 parts: an outer wall, a single plate representing a printed circuit board and small rectangular box representing a processor. Figure 1 shows a cutaway view of the model with all parts assembled. Figure 2 shows a close up of just the processor and Figure 3 shows the plate representing the circuit board. No model was needed to represent the regions of empty space inside or outside the model to simulate radiative and conductive heat transfer in this simulation. For simplicity, all parts are modeled as aluminum.

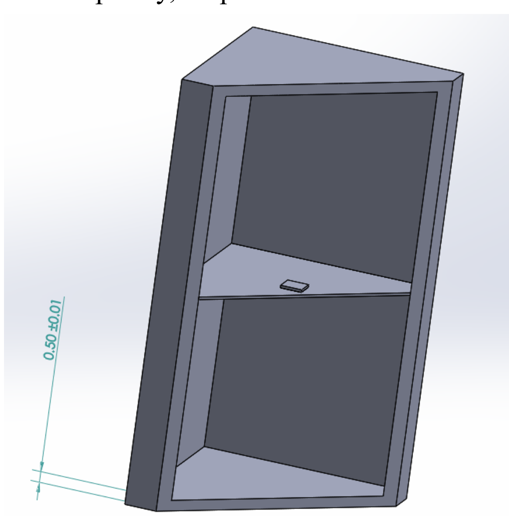

Figure 1: Cutaway view of fully assembled model. All walls are a uniform thickness of 0.5 cm.

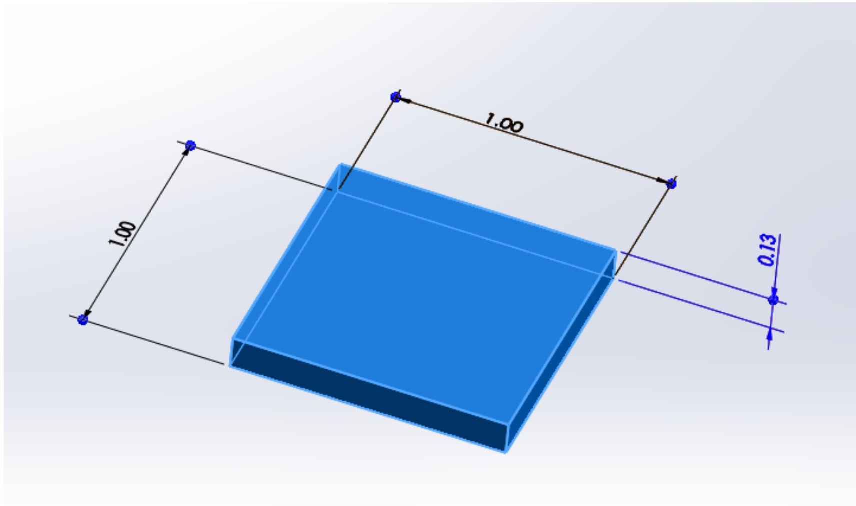

Figure 2: Model of the processor. Dimensions are 1 cm x 1 cm x 0.125 cm.

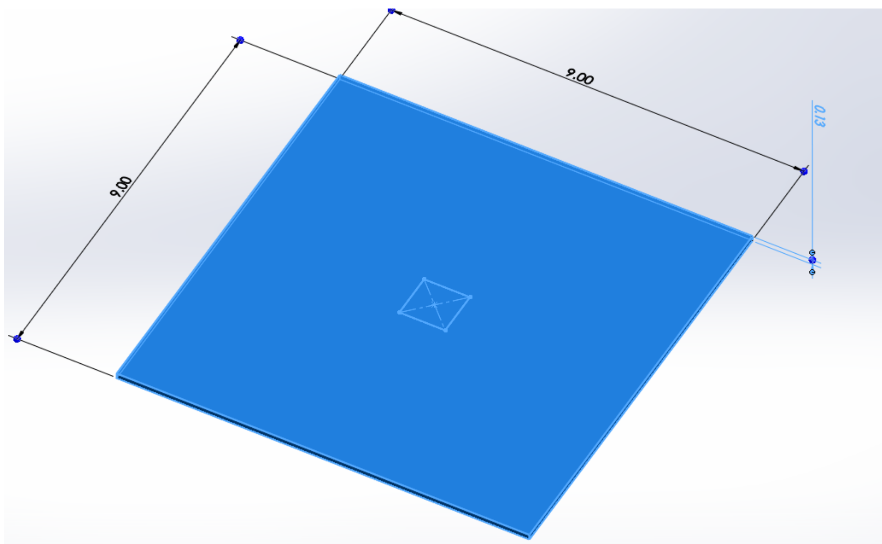

Figure 3: Model of Printed circuit board. Dimensions are 9cm x 9cm x 0.125 cm
The square in the center is a 1 cm x 1 cm inscribed contact point for the processor.

Boundary Conditions

Given that the satellite will be exposed to vacuum conditions, the air density will be too low for any sort of convective heat transfer to occur. Therefore, radiation and conduction will be the dominant forms of heat transfer. The vacuum condition will be modeled by setting each surface's convective heat transfer rate to 0 $\frac{W}{m^2K}$. All surfaces will radiate towards their respective environments. External wall surfaces will radiate towards a deep space ambient temperature of 4 Kelvin while internal surfaces will all radiate towards each other. The processor chip will be designated as a constant 7.5 W energy source. To model full sun exposure, one external 10 cm x 20 cm wall will receive a solar radiative load of 1356 $\frac{W}{m^2}$ also known as the solar constant [1]. In simulations with no sun exposure, the solar load will simply be removed.

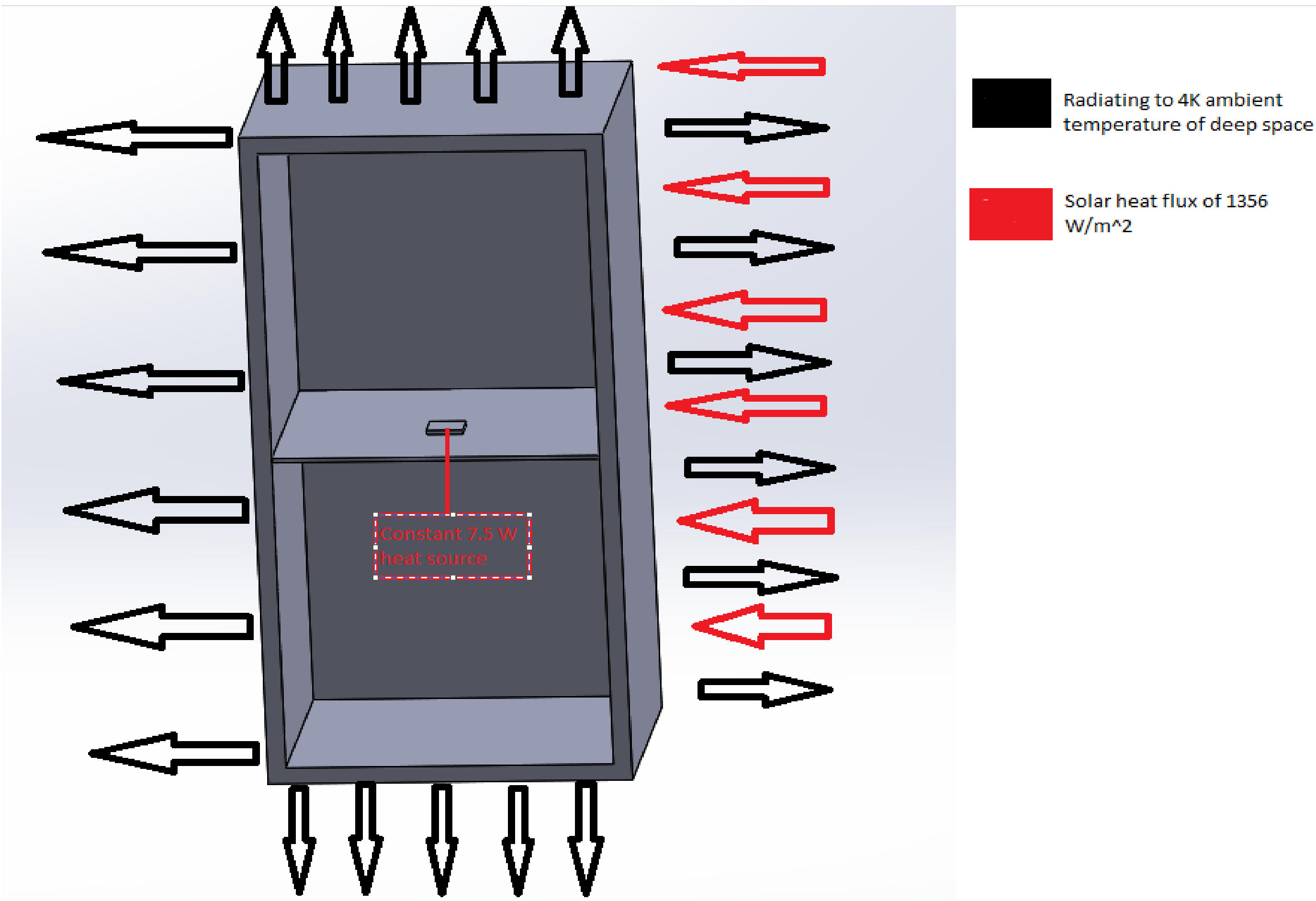

Figure 4: Radiative and heat source boundary conditions. 7.5W heat source conducts through Circuit board and irradiates inner surfaces of satellite. Outer walls radiate to space while one side is subject to a solar heat flux.

CFD Software Features

In order to create the correct environment and boundary conditions to model a satellite in space using Star-CCM+, several specific steps must be followed. As was previously mentioned, convective heat transfer must be set from its default value of 1 $\frac{W}{m^2K}$ to 0. This must be done manually for every surface on the entire model using Star-CCM+. In order for the solar load to work correctly, "solar load" must first be activated in the physics models. Direct solar heat flux must be set from its default value to 1356 $\frac{W}{m^2}$ and diffuse solar heat flux must be set to 0 $\frac{W}{m^2}$. Because the satellite is in the upper atmosphere where there is no cloud coverage, all solar loading will be assumed to be direct. Radiation towards space and between surfaces is enabled by activating "surface to surface radiation" and "grey thermal radiation." The grey thermal radiation ambient temperature is then set to 4 Kelvin. Each individual surface then has its thermal specification set to interact with the environment. One other non-obvious step is necessary for radiative heat transfer in opaque media in Star-CCM+: internal radiation heat transfer must be deactivated. By default, this option is activated which only applies to translucent media such as glass. Correct use of solar loading and radiation to space was verified in a simple model of a single plate exposed to a solar load on one side while simultaneously radiating to space on all sides. Results were corroborated by comparing them to hand calculations. This simulation and report are available upon request. For Star-CCM+ to allow for conduction between separate regions of the model, there must be an interface between the two surfaces in contact. This can be done through a boolean imprint of the two contacting surfaces onto one another and then creating an interface manually or by scribing the contact geometry onto the surface of the Individual part models before assembling them in a CAD program such as Solidworks.

CFD Mesh

Heat transfer problems generally do not require a particularly fine mesh to get an accurate solution. For these simulations, a 4 layer thin mesh was used with a base size of 1 cm. Due to the simplified nature of these simulations, a single mesh was used for the entire model. The result was a reasonably fine mesh that allowed for conservation of energy residuals to reach an order of magnitude of 10^{-7} without requiring a large number of iterations or long computation time. The following figures show the meshing across the different portions of the model.

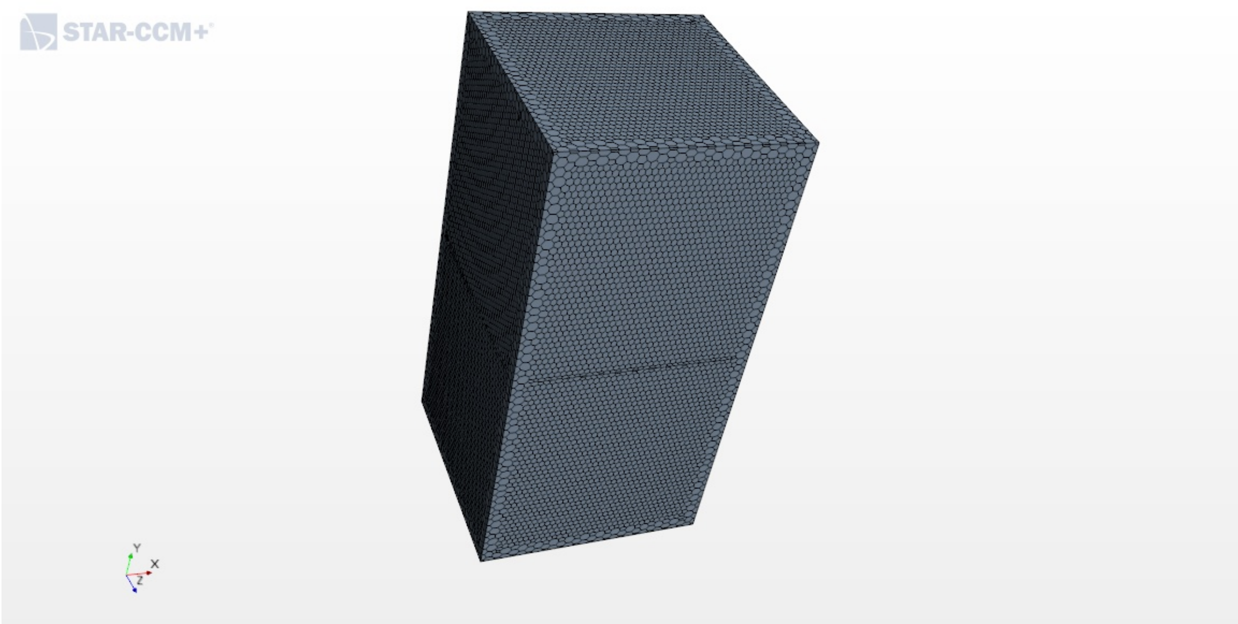

Figure 5: Mesh scene of the outer walls of the model

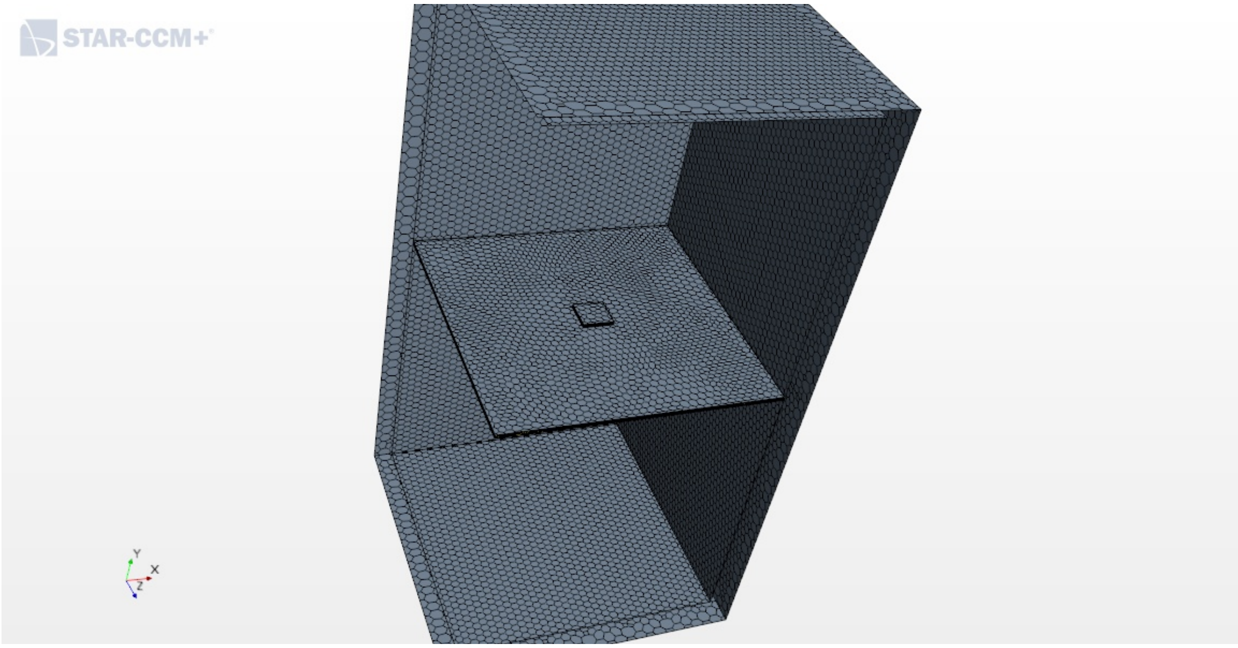

Figure 6: Meshing of the inner components of the satellite.

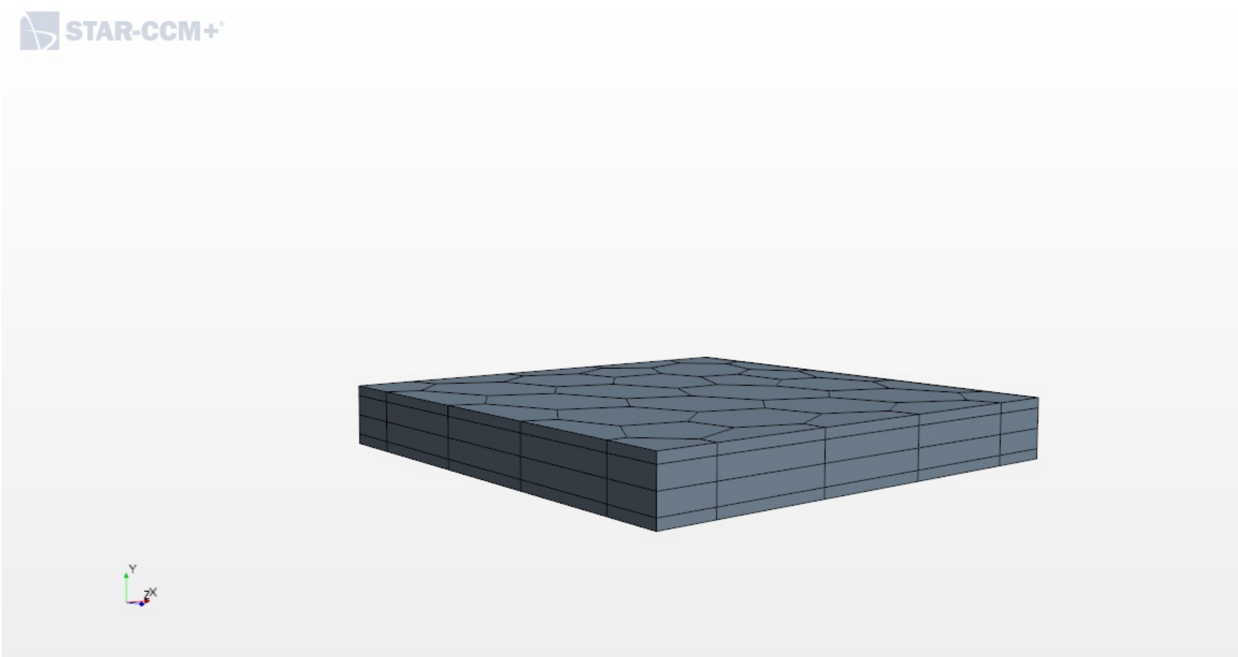

Figure 7: A close up of just the processor chip. The 4 layer thin meshing can be seen on the edges while the face has a polyhedral meshing.

Results and Discussion

-Without Solar Load

With no solar loading and the processor in its active mode producing a constant heat value of 7.5W, the satellite's internal temperatures range from 201.5 K to 211.9 K. These values are significantly lower than the acceptable range of 273.15 K to 333.15 K ($0^{\circ}C$ and $60^{\circ}C$.) However, it is important to note that this is basically a model of the satellite in deep space. There is no interaction with the earth or any other possible heat source. Another factor, discussed in greater detail later, is that the "PCB" surface (plate that the heat source is attached to) is modeled as aluminum here. This allows for far more heat to be conducted away than an actual circuit board would.

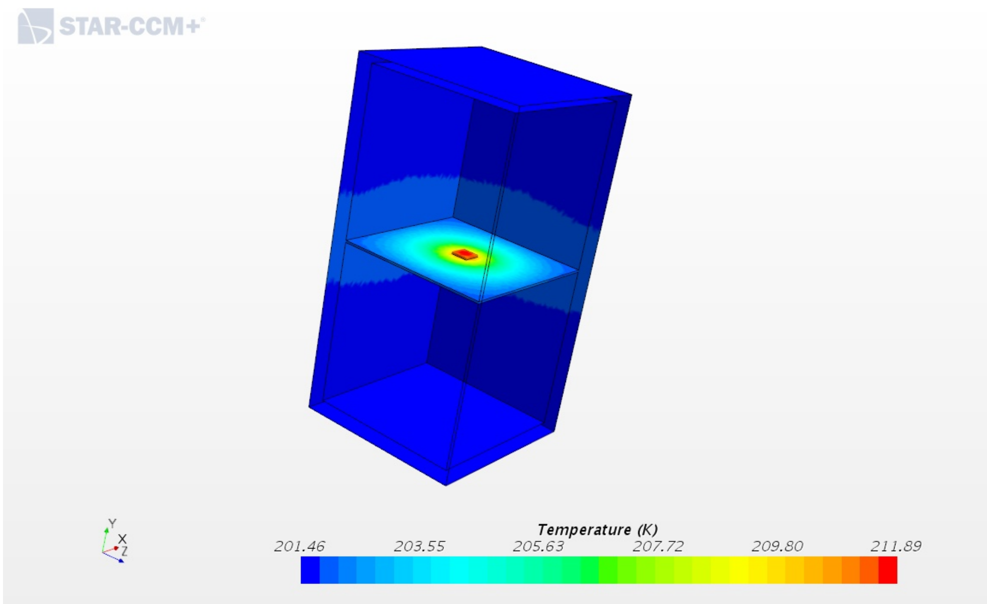

Figure 8: Temperature distribution of satellite in active mode with no sun exposure.

Internal surface irradiation is shown below. This shows heat flux on the internal surfaces due to radiation from the 7.5 W processor. This confirms that the surface-to-surface radiation function of Star-CCM+ is working.

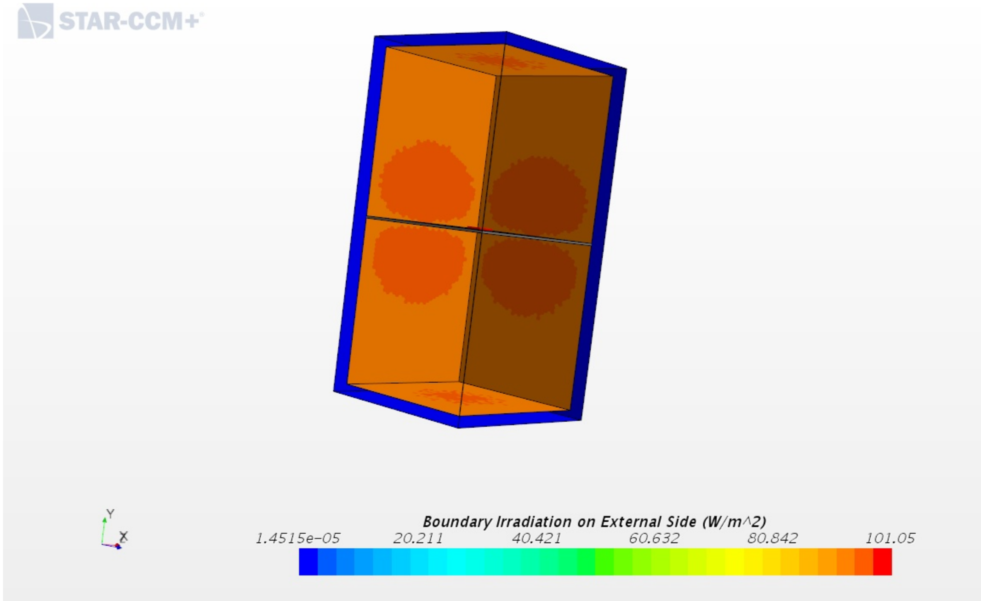

Figure 9: Internal surface irradiation distribution. This shows heat flux on internal surfaces from the processor

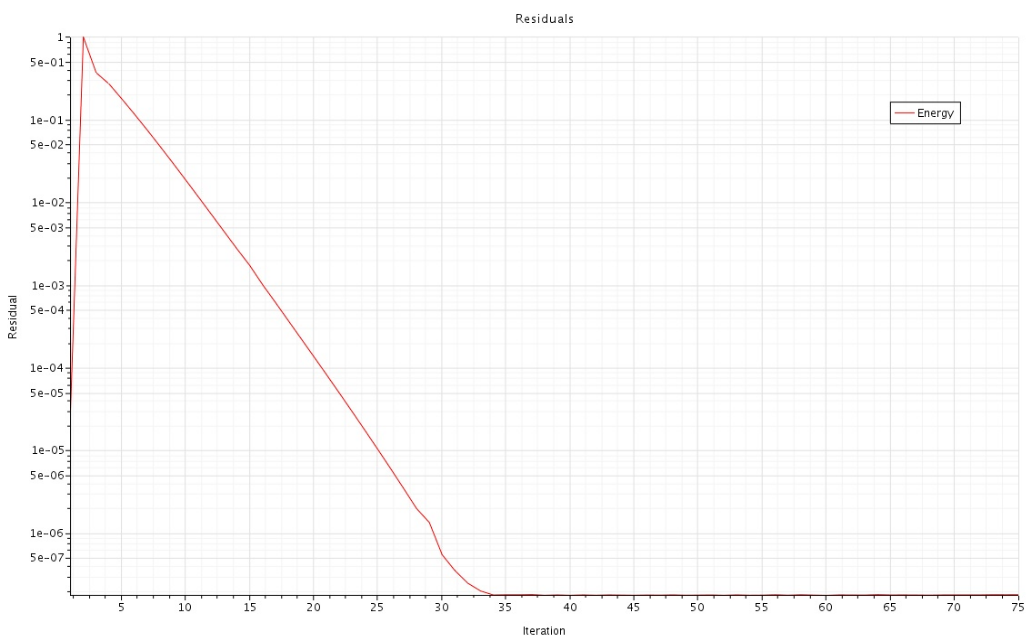

Figure 10: Convergence plot for conservation of energy. Converged to a final solution in approximately 35 iterations with residuals falling to 1.8 E-7.

The convergence plot shows that residuals reduce down to the level of 10^{-7} in just over 30 iterations and converge to a final value of approximately 1.8 E-7 by around 35 iterations. The calculation time for this simulation was relatively quick. Around a minute and a half was spent calculating view factors and setting up the problem. Once the software actually started solving, around 35 seconds passed before the residuals fell to their final value of 1.8E-7. From beginning to end, the simulation took 2 minutes and 44 sec to run 75 iterations.

Table 1: Heat transfer report on satellite model with no Solar Loading

Heat Transfer of Boundary Heat Transfer on Volume Mesh

Part	Value (W)	Errors
chip: chip.chip PCB contact	0.000000e+00	no data
chip: chip.chip PCB contact [PCB/chip]	7.497914e+00	
chip: chip.outer edges	2.054434e-03	
PCB: PCB.PartSurface_cubesat|PCB_cubesat|Walls	0.000000e+00	no data
PCB: PCB.PartSurface_cubesat|PCB_cubesat|Walls [PCB/Walls]	7.447477e+00	
PCB: PCB.PCB bottom	2.620907e-02	
PCB: PCB.PCB chip contact	0.000000e+00	no data
PCB: PCB.PCB chip contact [PCB/chip]	-7.497914e+00	
PCB: PCB.PCB edge 1	0.000000e+00	no data
PCB: PCB.PCB edge 2	0.000000e+00	no data
PCB: PCB.PCB edge 3	0.000000e+00	no data
PCB: PCB.PCB edge 4	0.000000e+00	no data
PCB: PCB.PCB top	2.440980e-02	
Walls: Walls.inner wall 1	-9.556804e-03	
Walls: Walls.inner wall 2	-9.558528e-03	
Walls: Walls.inner wall 3	-9.564864e-03	
Walls: Walls.inner wall 4	-9.558541e-03	
Walls: Walls.inner wall bottom	-7.192479e-03	
Walls: Walls.inner wall top	-7.241906e-03	
Walls: Walls.outter wall 1	1.501215e+00	
Walls: Walls.outter wall 2	1.501205e+00	
Walls: Walls.outter wall 3	1.501200e+00	
Walls: Walls.outter wall 4	1.501208e+00	
Walls: Walls.outter wall bottom	7.475911e-01	
Walls: Walls.outter wall top	7.475807e-01	
Walls: Walls.PartSurface_cubesat|Walls_cubesat|PCB	0.000000e+00	no data
Walls: Walls.PartSurface_cubesat|Walls_cubesat|PCB [PCB/Walls]	-7.447477e+00	
Total:	7.500000e+00	

The heat transfer report (Table 1) shows that all heat transfer is accounted for. The remaining 7.5W represents the constant heat from the processor. This report shows that nearly all of the heat generated by the processor is conducted down through its contact with the “PCB” and then out into the walls which radiate out into space. This makes sense because all parts in this simulation were modeled as aluminum which has a high rate of thermal conductivity.

-With Solar Load

By adding in the Solar load of 1356 $\frac{W}{m^2}$, the temperature range of the model is increased by about 80K resulting in a temperature range of 282.41K to 293.58 K. These values are within the acceptable temperature range of 273.15 K to 333.15 K (0C to 60C.) However, this model also does not include any heat flux from the earth. It may overestimate surface area exposure to space because the close proximity of the earth would limit the satellite's view of deep space.

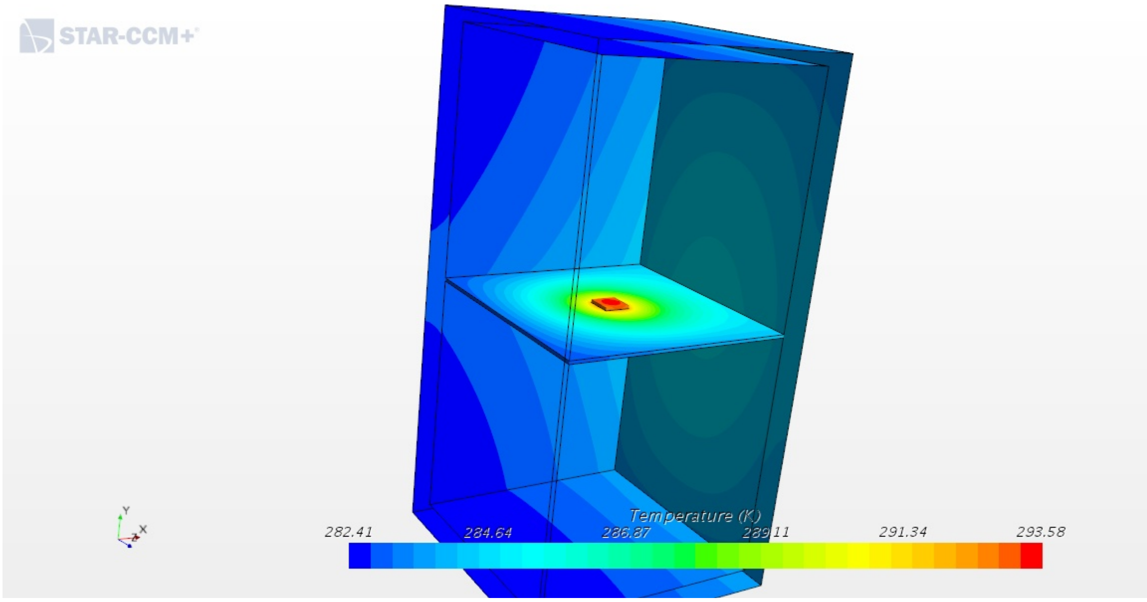

Figure 11: Temperature distribution of satellite in full sun exposure while in active mode with processor chip in the center producing a constant 7.5W.

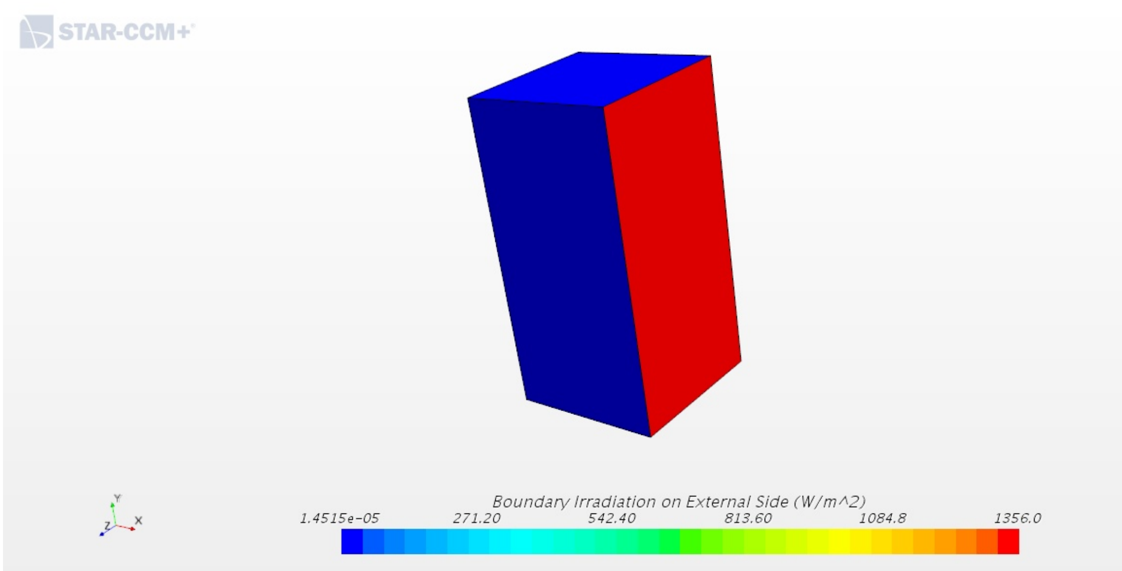

Figure 12: Surface irradiation on external surfaces of satellite. The red surface is being irradiated by 1356 $\frac{W}{m^2}$ from direct exposure to the sun.

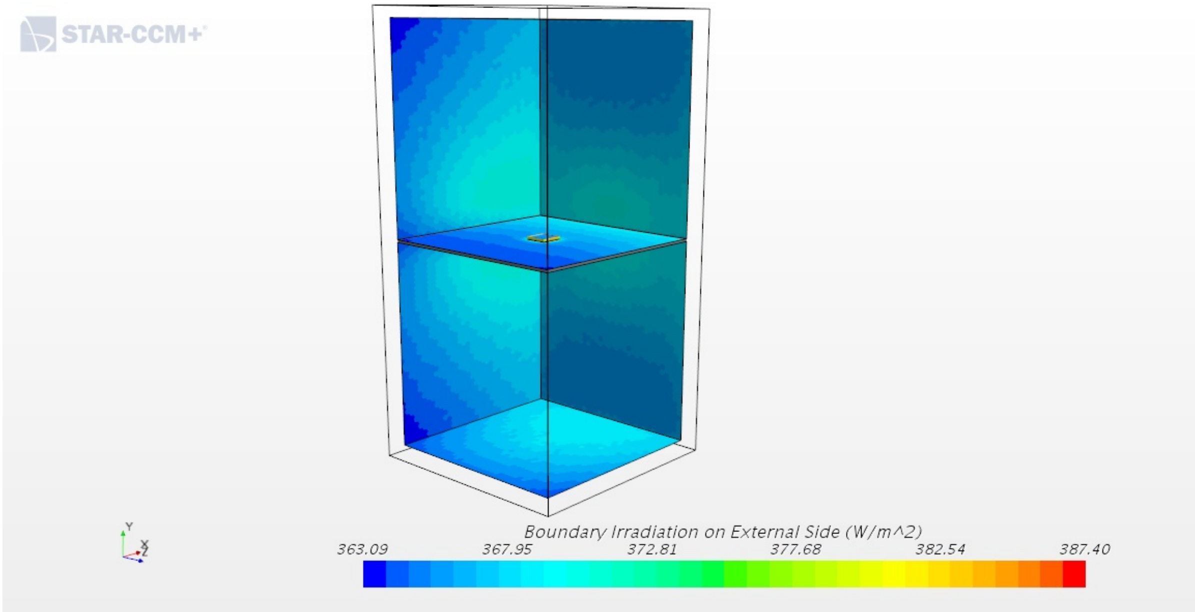

Figure 13: Distribution of surface irradiation on internal surfaces.

The wall on the right side of Figure 13 is exposed to 1356 $\frac{W}{m^2}$ on its external side as shown in Figure 12. Surface irradiation on the inner right wall is dominated by radiation from the processor in the center of the model. This is the reason that surface irradiation is focused near the center of the wall.

The wall on the left side has larger values for surface irradiation due to the higher temperature of the wall next to it. Surface irradiation on this wall is a combination of radiation from the processor at the center and the higher temperature wall to its right and is the reason for the skewed surface irradiation distribution on this wall.

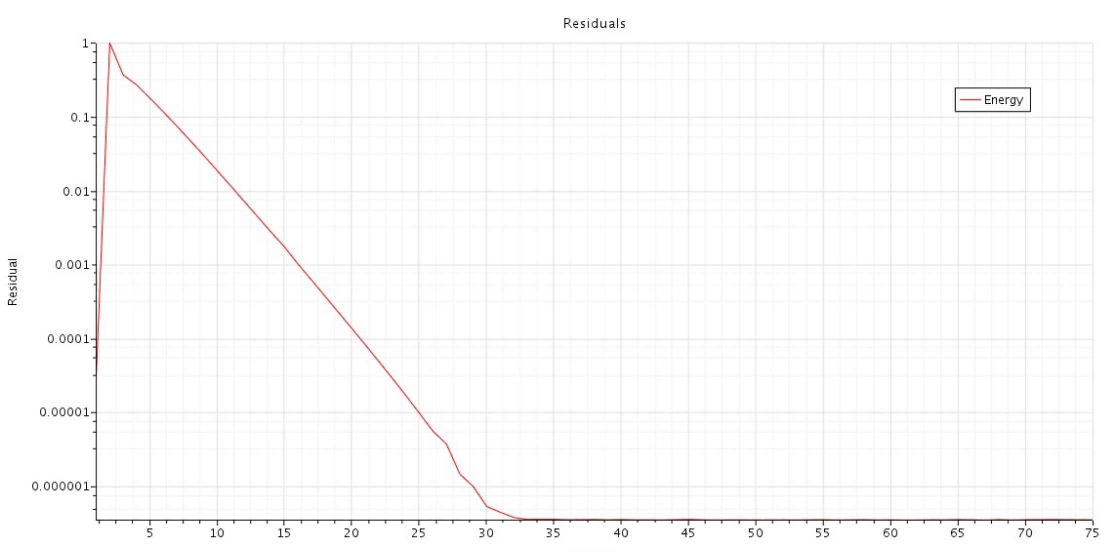

Figure 10: Residuals plot for conservation of energy has converged to a final solution in approximately 35 iterations with residuals falling to 3.5 E-7.

This convergence plot shows that conservation of energy residuals reduced below 10^{-7} just before 30 iterations.and converge to a value of 3.5 E-7 just before 35 iterations. The calculation time for this simulation was also fairly quick. Around a minute and a half was spent calculating view factors and setting up the problem. Once the software actually started solving, around 30 seconds passed before the residuals fell to their final value of 3.5 E-7. From beginning to end the simulation took 2 minutes and 40 sec to run 75 iterations.

Table 2: Boundary Heat transfer report on satellite model with Solar Loading

Heat Transfer of Boundary Heat Transfer on Volume Mesh

Part	Value (W)	Errors
chip: chip.chip PCB contact	0.000000e+00	no data
chip: chip.chip PCB contact [PCB/chip]	7.494565e+00	
chip: chip.outer edges	5.599763e-03	
PCB: PCB.PartSurface_cubesat|PCB_cubesat|Walls	0.000000e+00	no data
PCB: PCB.PartSurface_cubesat|PCB_cubesat|Walls [PCB/Walls]	7.351479e+00	
PCB: PCB.PCB bottom	7.419130e-02	
PCB: PCB.PCB chip contact	0.000000e+00	no data
PCB: PCB.PCB chip contact [PCB/chip]	-7.494565e+00	
PCB: PCB.PCB edge 1	0.000000e+00	no data
PCB: PCB.PCB edge 2	0.000000e+00	no data
PCB: PCB.PCB edge 3	0.000000e+00	no data
PCB: PCB.PCB edge 4	0.000000e+00	no data
PCB: PCB.PCB top	6.929260e-02	
Walls: Walls.inner wall 1	5.021189e-02	
Walls: Walls.inner wall 2	-3.456171e-02	
Walls: Walls.inner wall 3	-7.802812e-02	
Walls: Walls.inner wall 4	-3.457957e-02	
Walls: Walls.inner wall bottom	-2.599078e-02	
Walls: Walls.inner wall top	-2.613463e-02	
Walls: Walls.outter wall 1	-1.576636e+01	
Walls: Walls.outter wall 2	5.835736e+00	
Walls: Walls.outter wall 3	5.782024e+00	
Walls: Walls.outter wall 4	5.835723e+00	
Walls: Walls.outter wall bottom	2.906473e+00	
Walls: Walls.outter wall top	2.906411e+00	
Walls: Walls.PartSurface_cubesat|Walls_cubesat|PCB	0.000000e+00	no data
Walls: Walls.PartSurface_cubesat|Walls_cubesat|PCB [PCB/Walls]	-7.351479e+00	
Total:	7.500002e+00	

The heat transfer report (Table 1) shows that all heat transfer is accounted for. The remaining 7.5W represents the constant heat from the processor. This report shows that nearly all of the heat generated by the processor is conducted down through its contact with the "PCB" and then out into the walls which radiate into space. This makes sense because all parts in this simulation were modeled as aluminum which has a high rate of thermal conductivity. Radiative heat transfer from the outer surfaces of the processor is slightly higher when no solar load is involved due to the higher temperature difference between the outer walls and the processor. Radiative heat transfer increases faster than conductive heat transfer as temperature differences increase due to the exponential nature of the Stephan-Boltzman law of radiative heat transfer.

Conclusion

These simulations have shown the model to reach a steady state temperature range of 201.45 K to 211.89 K without exposure to the sun and 282.41 K and 293.58 K. These temperatures stay below our maximum operating temperatures of 273.15 K to 333.15 K. This is potentially good news. However, these simulations neglect heat flux from the earth and may be overstating the satellites surface area exposure to deep space. Additionally, the heat transfer report shows unrealistically high conduction rates from the heat source to the outer walls through the printed circuit boards. This issue stems from modelling all components as aluminum. Contact resistances between surfaces were also neglected which will further decrease conduction rates when given accurate values. These factors are all likely contributing to an artificially low temperature in the processor.

This report has successfully demonstrated surface to surface radiation between multiple surfaces of differing temperatures and has also employed the Solar Loading physics model. These simulations have demonstrated that Star-CCM+ can successfully model the environment in outer space in both full direct sunlight as well as model the conditions of deep space. Further refinement of material properties and boundary conditions will be able to more accurately represent the environment in the upper atmosphere and better approximate the heat transfer conditions the satellite will experience while orbiting the earth.

References

1. Zirnin, Harold. “Solar Constant” Britanica.com
   https://www.britannica.com/science/solar-constant (accessed 3/15/19)