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THERMAL ORBITAL SPACECRAFT ANALYSIS OF AN ADDITIVELY MANUFACTURED DEPLOYABLE RADIATOR OSCILLATING HEAT PIPES (AMDROHP) CUBESAT

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ABSTRACT

As small spacecraft technologies develop, thermal management devices need to meet the growing demands of high-powered electronics. Currently being developed to meet this demand in CubeSats is the Additively Manufactured Deployable Radiator Oscillating Heat Pipes (AMDROHP). AMDROHP seeks to implement the high thermal conductivity and two-phase technology of Oscillating Heat Pipes into a unique deployable radiator design for a 3U CubeSat, taking advantage of additive manufacturing capabilities. While much consideration has been put into designing the AMDROHP on its own as a heat exchanger, there is also the need for it to be evaluated thermally at a system-level with the rest of the CubeSat while in orbit. In this study, thermal orbital spacecraft simulations, through the Thermal Desktop software, were performed to analyze how AMDROHP thermally integrates and interacts with the rest of the CubeSat and evaluate the survivability of temperature-sensitive components on the spacecraft. The simulations in this study included an 11th-orbit beta angle sweep for a tumbling orientation of the spacecraft in Low Earth Orbit (LEO). These simulations were performed with two AMDROHP devices in the CubeSat bus, each under a direct 25W heat input and performing with a thermal conductance of 6 W/K, which corresponds to the projected performance of the AMDROHP device while in operation. In this paper, the Thermal Desktop model of the AMDROHP CubeSat includes all major physical components, connections, heat loads, and thermal and optical materials. Then, steps are taken to improve the computational speed of the model. Furthermore, the means of addressing the modeling of the complex two-phase behavior of the OHP is outlined. Then, a number of test cases considering various operating conditions were simulated. From these simulations, orbital temperatures of sensitive components, primarily electronics, were collected and analyzed to find the minimum and maximum operating temperatures across all potential orbits. These temperatures were then evaluated to determine the component's survivability in a worst-case scenario in orbit. From the results, it was found that, with the projected conductance of AMDROHP, all components operate under safe temperature conditions for any beta angle while in Low Earth Orbit. The evaporator is consistently the hottest component of the spacecraft and electronics boards all maintain survivable temperatures and are not at risk of over or underheating, even at worst case temperatures for all orbits tested. Based on the results and analysis of this conceptual study, it is suggested that AMDROHP will perform as an effective management device for small satellites.

1. INTRODUCTION

To be able to fully explore the mysteries of space, scientists need the most advanced technology to perform research from spacecraft. As technology advances, the amount of power needed to enable these tools to be used also increases, which comes at the cost of increasing heat generation by temperature sensitive electronics devices. In small spacecraft, where volume is scarce and components are tightly packed together, this is an even more serious concern. This means that to meet the demands of high-powered electronics in small spacecraft, there needs to be cooling systems that can effectively transfer heat away from the high-powered electronics. Currently in development as a method for highly conductive heat transfer for high-powered electronics in CubeSats (Miniature Cube Satellites), is the Additively Manufactured Deployable Radiator Oscillating Heat Pipes (AMDROHP). AMDROHP is an implementation of the high thermal conductivity, two-phase technology of Oscillating Heat Pipes in a device with deployable capabilities, additively manufactured as a single piece device to fit in a 3U (3, 10 cm x 10 cm Units) CubeSat. An image of AMDROHP can be seen in FIGURE 1, consisting of an evaporator panel where the heat load is applied to the device, a condenser panel where from which the heat is radiated from the device into space, and the spring joint hinge mechanism which serves as part of the fluid path for the two-phase device.

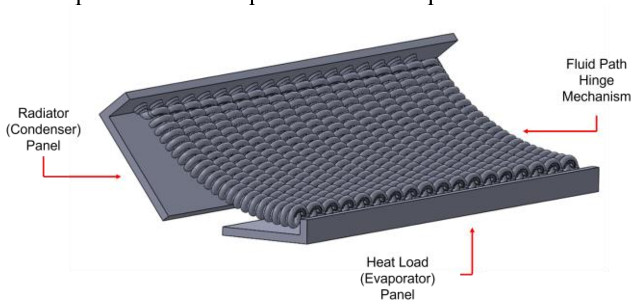

FIGURE 1: AMDROHP WITH LABELED COMPONENTS

The goal for the AMDROHP CubeSat mission is to serve as a demonstration of the AMDROHP technology. To be successful in its mission, two AMDROHPs need to be able to operate at a system level in a 3U CubeSat in Low Earth Orbit (LEO) with none of the spacecraft components over or underheating. Each AMDROHP will undergo a heat load of 25W on board the 3U CubeSat and need to be able to maintain suitable temperatures of -20°C to 60°C for all thermally relevant components in the CubeSat. The goal of this paper is to prepare for this mission by performing thermal simulations to predict this performance.

In evaluating a spacecraft cooling device in the context of a spacecraft in LEO, there needs to be a way to computer simulate this process. The most common software used for this application in the aerospace industry is Thermal Desktop (TD) by C&R Technologies. There exist ample examples in literature of similar spacecraft and/or payloads being simulated thermally in orbit using Thermal Desktop.

Salazar-Salinas et al. performed a thermal orbital analysis using Thermal Desktop of the 3U CubeSat known as the “Pakal Satellite” [1]. Similar to the goal of this project, the focus of this analysis was to find the environmental effects on the temperature of components of the spacecraft. In this paper, allowable operating temperatures of all components were compared to the operating temperature range from simulations. From their results, it was found that the only component seeing difficulties in meeting temperature requirements was the On-Board Computer which in certain instances met the lower bound of the allowable temperature range. The recommendation solution that was proposed was using MLI (Multi-Layer Insulation) coatings and paints on certain faces of the CubeSat.
In another analysis of space orbital effects on the temperatures of a CubeSat, Matsushita et al. performed simulations, using Thermal Desktop, on the "EQUULEUS" 6U CubeSat [2]. The process followed in this paper was to begin with a single node simulation and then move to a full-model, multi-node simulation. The goals of this study were again to compare the maximum and minimum temperatures found through thermal desktop for temperature sensitive components to their allowable temperature range. While almost all components met the temperature requirements within a “10°C margin”, there were a number of components that reached or exceeded the temperature range set. The single component that exceeded even the set margin was the “Delphinus” lunar impact detection camera. Solutions suggested to these results were to make better use of waste heat in the spacecraft and to put more consideration into the surface properties of the CubeSat panels. Further, vacuum chamber testing was performed as a way to validate these TD simulation results.

Isaacs et al. performed Thermal Desktop simulations of a lightweight CubeSat frame made from an additively manufactured PCM (Phase Change Material) [3]. These custom panels are made for the purpose of storing temperature and energy as a method for thermal stability in spacecraft. A thermal simulation of a single panel was performed to show the melting and freezing process of the PCM contained in a metal case across orbit. Then, a full CubeSat frame will all six panels was simulated and analyzed. From these results, it was found that a 9.5 W heat input for the mass of the panels, put the PCM in a state of continuous melting and solidifying that allowed for very consistent temperature across orbit.

Yendler et al. explored different possible designs of heat pipe deployable radiators for CubeSats including a “rigid panel” and “rollout” deployable radiator and performed preliminary Thermal Desktop analysis of this “Thermal Management System (TMS)” [4]. It was decided that the “rollout” design was preferable due to the lack of thermally constraining hinges and less volume required to store it in the CubeSat when stowed. Further, through TD simulations, it was found that through using integrated heat pipes (IHPs), temperatures across orbit could be reduced 10 to 15°C.

A critical part of the AMDROHP design is Oscillating Heat Pipes (OHPs), which are two-phase thermal devices that enable high rate of heat transfer [5]. While research is currently being performed to better understand the operating principles of these complex two-phase heat exchangers, modeling the operating process of OHPs is difficult. Daimaru et al. introduced a “one dimensional slug flow model” to describe and simulate the phenomena that occur inside the OHP [6]. While this model uses very thorough analysis and achieves accurate results, it is difficult to use in complex applications such as AMDROHP and its application in space. It is of interest to explore how other researchers have approached the problem of the modeling of complex physical phenomena with or in conjunction with Thermal Desktop.

Walker et al. approached the problem of modeling of the thermo-electrochemical process of Lithium-Ion Batteries (LIBs) for the International Space Station (ISS) in Thermal Desktop [7]. Experimental test data of the battery undergoing similar conditions to the ISS was taken and used to model the heat being generated by the battery as a function of the depth of discharge, open circuit potential, working voltage, and convection. This experimentally derived function was then used to define the heat being generated by the battery based on the conditions that the battery was under. Through this method, this studied used external experimental data to develop a function that Thermal Desktop could utilized in its calculations of a simulated model of an LIB. For the AMDROHP study if in the future, enough experimental thermal test data was taken, this is a possible route for implementation into the thermal model at a later date from this study.

Barnes et al. created a Thermal Desktop system-level model of the "Exploration Portable Life Support System (xPLSS)" which support the life functions of a human outside of a spacecraft [8]. In this model, a thermal control loop (TCL) is used to help remove waste heat from the crewmember and electronics. The process of the TCL involved phase-change of a working fluid, which was modeled using Thermal Fesktop. The phase-change modeling works like a binary control where if the working fluid cools to below its specified dew point temperature, meaning there is liquid present, the properties of the fluid node in the model are changed to that of the working fluid as a liquid. This method is interesting for distinguishing liquid and vapor, however for a complex process of the OHP, where there exist many vapor bubbles and liquid slugs, modeling this phenomenon in such would be a very in-depth process beyond the scope of this study.

The AMDROHP design being modeled in this study involves complex, optimized geometries, specifically hollow helical springs. For finite element modeling tools, including Thermal Desktop, simpler geometries are preferred as they result in simpler meshes and less nodes, making calculations less computationally expensive. Different approaches for modeling spacecraft component geometry with both satisfactory resolution and simulation time are explored.

Fabanich took the method of using an external meshing software, SpaceClaim, to mesh geometrically complex parts of an Advanced Stirling Radioisotope Generator and import that mesh into thermal desktop [9]. Through use of this external software, unnecessary features of the model were able to be excluded from the mesh including holes and fillets. Also, this tool was used for repairing meshes in which geometries led to small mesh elements or gaps in the mesh. After a mesh was created with this software, the mesh was then imported and used in a Thermal Desktop model. While some defeaturing and repairing of a mesh will help to improve a custom mesh of a part for TD, the result of a custom mesh is typically a higher-node count in a model. This is the typical trade-off between resolution and computational cost in finite element analysis. As a note, Thermal Desktop also has internal meshing capabilities through TD Mesher, though the user controls for it is limited.

Two other existing works show a common approach when using Thermal Desktop, which is to model all components, including complex geometries, using only primitive shapes, mainly 2D rectangles and cylinders. Young et al. reviewed different CubeSat models created in Thermal Desktop, showing images of these models [10]. In these images, it can be seen how whole spacecrafts can be stitched together with only a few different kinds of 2D shapes, to create satisfactory geometric representations for thermal simulations. Another example is with Amundsen et al.'s model of the Stratospheric Aerosol and Gas Experiment III (SAGE III) instrument aboard the ISS [11]. This representative thermal model is able to create an impressively detailed capture of the instrument using only simple shapes, which allows for significantly reduced node count from full-feature geometry. The benefit of the primitive-only approach is that, in instances of when all that is needed is an average temperature or only a few temperatures in critical locations of a component, the simulation time can be significantly reduced without sacrifice. Modeling a part with such a high resolution that much of the nodal data is not needed, results in the model time not being optimized. Thus, representing a complex shape by primitives, is more computationally efficient. Further, through modeling with primitive shapes over custom-meshing parts, there is more freedom in choosing how fine the mesh can be.

This paper is organized to review the model development and results of the simulations ran. The sections of this paper include review the general model specifications including the components modeled, an overview of how geometric complexities of components were addressed to improve simulation time, a view of the process of the construction and development of the thermal model to its complete form, a description of how the complex two-phase behavior of OHPs was modeled, an overview of the specifications of the orbits simulated, and a look at the process of assigning radiation tasks to certain components to account for internal and external radiation in the model while also improving simulation time.

2. MODEL AND CASE STUDY DEVELOPMENT

2.1 General Model Specifications

The spacecraft thermal orbital simulation model used for this study was created using Thermal Desktop. This AMDROHP CubeSat model includes all thermally relevant components of the spacecraft. These components include the two AMDROHP devices each made up of an evaporator, condenser, and 18 spring deployable joints; AMDROHP hinge mechanism including the four hinges, brackets, and hinge supports. On the spacecraft side, the CubeSat frame including two top hats, side panel frames, solar panel brackets, four CubeSat panels, and two heat shields, and the electronics components including seven batteries, a battery bracket, twelve solar panels, a motherboard, Pibb board, UHF board, and 3 magnetorquers. Images of the model of components can be seen in FIGURE 2, FIGURE 3, and Figure 4. AMDROHP was modeled with 2D primitive shapes. The evaporator and condenser panels were modeled using 2D rectangles with a set thickness and the helical spring hinges were modeled using multiple angled, 2D hollow cylinders with a set wall thickness. Other components throughout the CubeSat were likewise made through 2D rectangles and cylinders. The applied heat loads in this model include 25 W directly to each evaporator, 2.76 W across all batteries, 4.2 W from the motherboard, 1 W from the Pibb Board, 1 W from the UHF Board, and 0.00176 W to each magnetorquer. Through these simulations, orbital conditions were simulated, and worst case high and low temperature were taken for all temperature sensitive components and compared to their allowable operating temperature range.

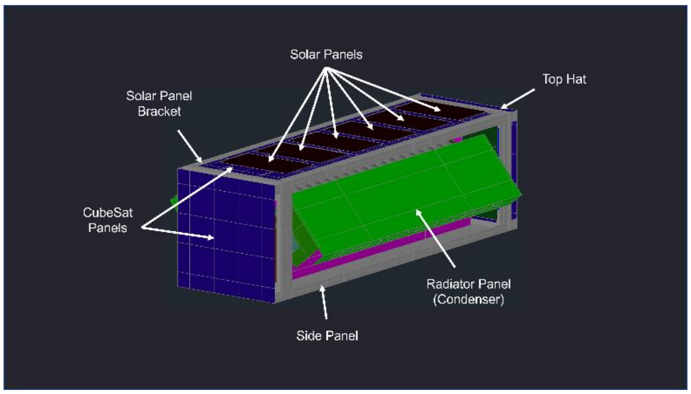

FIGURE 2: THERMAL MODEL – EXTERNALLY VISBLE COMPONENTS

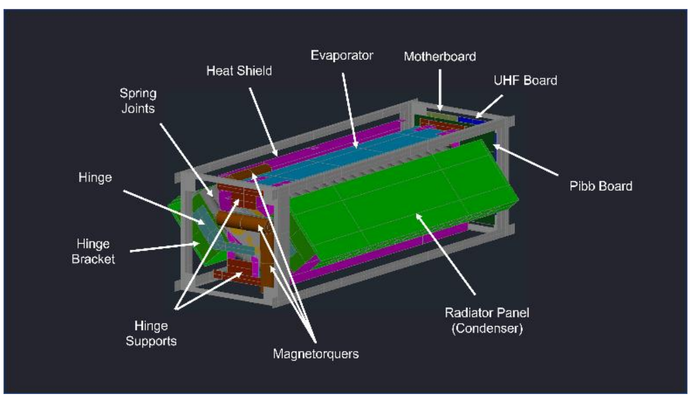

FIGURE 3: THERMAL MODEL – INTERNAL COMPONENTS

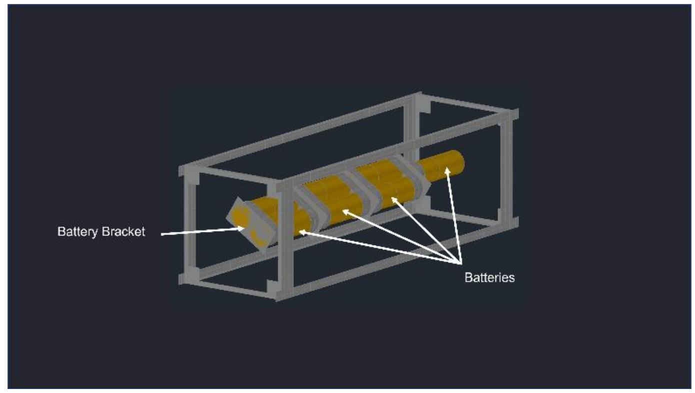

FIGURE 4: *THERMAL MODEL – BATTERY COMPONENTS*

The model created for this study considers conduction and radiation as the modes of heat transfer that can occur. Conduction occurs between the components of the model. Radiation occurs between components as well as from components in the CubeSat to bodies outside of space (e.g., the sun, earth, and open space). In this way, heat can be modeled to move from component to component and be rejected from the CubeSats.

2.2 Balancing Geometric Resolution and Computational Speed

As mentioned earlier, there is always a tradeoff between geometric resolution and computational speed. Using primitive shapes results in more uniform meshes. When there is a lack of complex geometric features, locations where a finer mesh is needed can be reduced. A finer mesh will give a higher geometric resolution but also creates more nodes to calculate for. In the case of Thermal Desktop, this trade-off happens when deciding how to represent components through the shapes they are made up of. In the case of most components, a simple representative primitive shape, usually a 2D rectangle or cylinder with some thickness value, is sufficient for capturing the mass and necessary locations of interest to monitor temperatures. Other times, however, certain components require a higher geometric resolution to capture the temperature at specific geometric features. In an instance such as this, the best method to use is to mesh a true CAD or a true defeatured CAD and import the mesh into Thermal Desktop. Looking at components like the AMDROHP springs, the hinges, battery brackets, and the top hats, while there is a high geometric complexity, accounting for the complexity in the model doesn't improve the model results noticeably when compared to using primitive shapes. For this reason, these components and others were modeled using primitive shapes as opposed to the main alternative of custom meshing the geometrically exact CAD model.

While the spring joints are critical to performance of the AMDROHP, the exact helical geometry is not so critical in capturing their thermal behavior. For this reason, these components were instead modeled as multiple merged, angled cylinders. Further, for components like the hinges, battery brackets, and top hats, these components themselves are not subject to temperature limits and only serve as a medium for which heat passes between thermally important components. For these reasons, function and computational speed were weighed more heavily than having a visually accurate representation of these more geometrically complex components. Thus, because primitive shapes were used for these components, the total node count of the model was able to be minimized, and as such, the time to run the model was significantly more favorable over the alternative route.

2.3 Constructing and Developing the Thermal Model

The process of building the model was to start with a simple representation of the CubeSat and slowly add complexity. The first model iteration started as just a simple rectangular box with a net heat output and single material. Steady state simulations were run first, then transient, checking the results to make sure the temperatures are within expectation before going to the next iteration of the model. Steady state simulations were run first to get an initial look at the temperatures of the components to make sure they make general sense, before having to deal with large amounts of temperature-dependent data. The transient data could give a more detailed look at the results after the steady state results gave some confidence in the model performance.

The second model iteration was to add the AMDROHP payloads to the simple CubeSat bus and monitor the temperatures of the condenser/radiator panels in correspondence with the orientations and beta angles. The data analyzed for this step was the 11th orbit transient data. A specific check done with the results was to track the temperatures of the radiator panels respective to their view factors, along the entire orbit. When the radiator plates are facing the sun or Earth, they will experience an increase in temperature. When the plates are facing open space, or if the spacecraft is in eclipse (behind the Earth from the sun's perspective), the plates will experience a decrease in temperature.

The third model iteration was to add the rest of the CubeSat components as basic representations. The purpose of this iteration is to place all the components in the model and account for all heat loads and thermal connections throughout the model. Once this step was complete, simulations were conducted to track the flow of heat to confirm that all the heat loads are being accounted for and that all the thermal connections are working. For this model, #4-40 bolt "conductors" were the most common thermal paths from component to component.

The fourth and final model iteration was to improve the geometric complexity of the components of the model, while still using primitive shapes, to better capture the geometric features of components. This included better detailing of the CubeSat frame, adding more cylinders to the springs to get a rounder curve, and adding the feet and mounting brackets to the heat shields. Further, the thermal conductors and contactors were adjusted to be at the most geometrically accurate locations in the model. As complexity was added, a balance was reached between reaching a sufficient geometric representation with keeping a low node count. On this iteration, again the same checks are performed on the results of the model simulations and once confirmed to be working, the model was completed and the full set of simulations of interest were run.

2.4 Accounting for OHP Operation and Conductance in the Thermal Model

One of the difficulties in modeling an OHP in Thermal Desktop is accounting for its two-phase operation that allows it to achieve high conductivity. While there exists a descriptive model of OHP slug flow in literature, to be able to adapt such a model in thermal desktop and implement it for this application would be beyond the scope of this study which is to thermally evaluate the AMDROHP CubeSat [32]. For this reason, in this study the highly conductive two-phase phenomena inside the OHP was modeled as simple conduction with custom, high-conductivity materials.

$$G = \frac{\dot{Q}}{\Delta T} \tag{1}$$

Seen in (1) is how conductance (G) is the ratio between the heat input ($\dot{Q}$) and the temperature difference between the evaporator and condenser (ΔT). Knowing that there will be a 25 W heat input into each AMDROHP and operating with the assumption that the AMDROHP will perform with a 6 W/°C conductance, an expected temperature difference from the evaporator to the condenser was calculated, using this formula, to be about 4.2 K. This projected temperature difference is what guides how the custom values of the materials of the AMDROHP will be determined.

Three different custom materials were made for the AMDROHP, including for the evaporator, springs, and condenser. These materials were started with base properties of Aluminum 6061, which is the material AMDROHP will be printed out of. In OHP operation, the evaporator and condenser are generally isothermal and so, the conductivity values of those two materials are set to a large (infinitely high) value such that heat flow is unimpeded in those sections. This leaves the spring material conductivity to be the value that is adjusted to reach the desired temperature difference across the OHP. To achieve this, steady state orbital simulations were run in an iterative process adjusting the value of the spring conductance until a general temperature difference of 4.2 K across the OHP was achieved. Through this process, the OHP operation can be approximated, without having to model the two-phase operation in Thermal Desktop.

2.5 Constructing Orbital Case Sets

The orbit this CubeSat is expected to fly in and is being simulated for is Low Earth Orbit at 400 km. For the current standing of the AMDROHP project, the beta angle for which the payload in the CubeSat will potentially fly has yet to be determined. For this reason, a beta angle sweep is performed where a set of simulations for beta angles 0°, 15°, 30°, 45°, 60°, 75°, and 90° is simulated and the worst-case temperatures are considered across all beta angles. For the orientation of the CubeSat, orientation control is not being designed as a feature of the AMDROHP CubeSat, so the orientation of the CubeSat is modeled to be tumbling. To model this tumbling orientation in a way that represents "random" tumbling, a custom orientation was created in Thermal Desktop. The CubeSat was modeled to make 5, 7, and 9 rotations per orbit in the X, Y, and Z directions, respectively. For each beta angle, the simulations run were 11th orbit transient simulations. Images of the tumbling orbits of each beta angle can be seen in Figure 5.

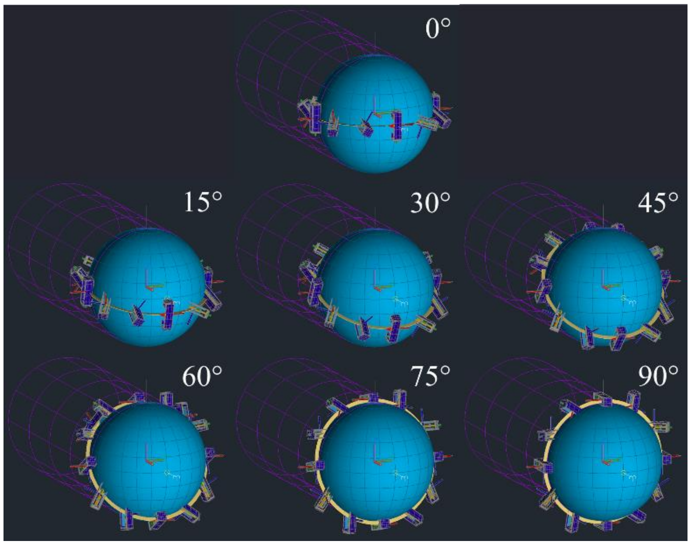

FIGURE 5: TUMBLING ORBIT FOR BETA ANGLE RANGE

With the components given an initial temperature of room temperature, each of the model components take time to heat up until they eventually reach a "pseudo steady state" repeating pattern across each orbit. The 11th orbit data is taken, as 10 orbits is more than sufficient time for the CubeSat temperatures to reach the point of every subsequent orbit behaving at the same repeating pattern. A visual of this occurrence can be seen in Figure 6**Error! Reference source not found.**. In this figure, a n ode of one of the AMDROHP evaporators is tracked across 11 orbits, in the Beta 0° orbit. By the 11th orbit, the temperature over orbit follows a repeating pattern, unchanging from orbit to orbit. For this study, first a simulation for 10 orbits was run, then, the end conditions of those results were used to initialize a simulation for one more orbit, the 11th orbit.

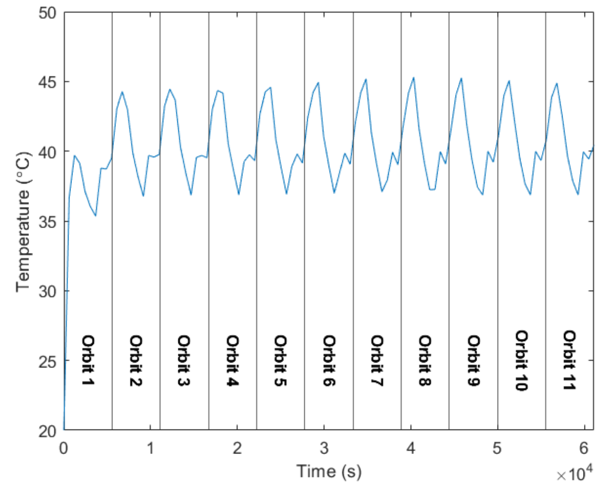

FIGURE 6: TEMPERATURE DEVELOPMENT ACROSS 11 ORBITS

2.6 Assigning Radiation Tasks

All components of the AMDROHP CubeSat were assigned a radiation task to calculate how heat radiated from themselves to and from other components. Components exposed to external radiation from the Sun, Earth, and open outer space were assigned a radiation task to calculate radiation exchanges with external sources. For this second radiation task, only components with exposure to these external sources were included to perform these calculations. By doing this, computational expense can be saved by not having to calculate the radiation from these external bodies to components deep inside the CubeSat bus that are not significantly affected by radiation with sources outside of the CubeSat bus.

3. RESULTS AND DISCUSSION

After running simulations for the range of potential beta angles, the hottest and coldest temperatures for every temperature sensitive component are found and plotted against their allowable operating temperature range. All components are subjected to a -20°C to 60°C allowable temperature range. The results of the minimum and maximum temperatures of each temperature-sensitive component for the simulations run can be seen in Figure 7.

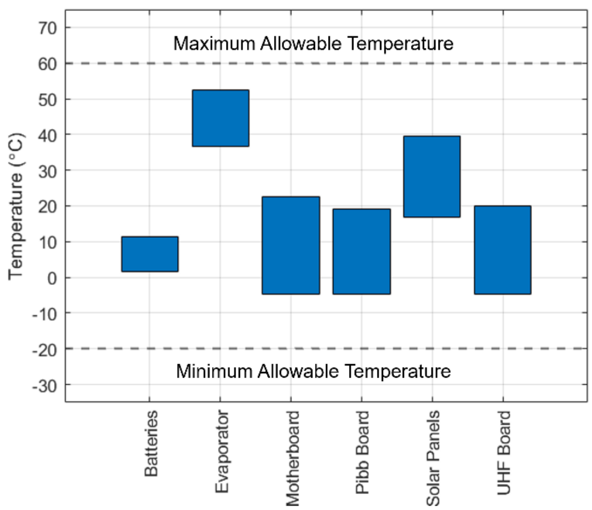

FIGURE 7: COMPONENT TEMPERATURE EVALUATION

Among all temperature-sensitive components in the CubeSat, the evaporator is consistently the highest temperature. The temperature range that the evaporator sustains is 36.6°C to 52.3°C. This is to be expected because the evaporator is directly undergoing the largest heat load of all of the components. The batteries operate under the temperature range of 1.7°C to 11.5°C which is below room temperature across all orbits. This is due to the low thermal load and being thermally shielded by the heat shields. The solar panels are the second hottest components to the evaporator at a temperature range of 16.9°C to 39.7°C. This is due to the fact that they are located on the exterior of the CubeSat and have direct exposure to external radiation. Furthermore, the evaporators are bolted to the opposite side of the same CubeSat panels as the solar panels. This can be referred back to in Figure 2**Error! Reference source not found.** and F igure 3. This allows for a direct conduction path between the two components. For these reasons, the solar panels at hotter than the other, non-evaporator components. The electronics boards including the motherboard, Pibb board, and UHF board all maintain below-room average temperature ranges, -3.3°C to 19.4°C, -4.7°C to 14.5°C, and -1.9°C to 18.1°C, respectively. These components are bolted to the CubeSat frame with the main thermal path from the evaporators being conduction through the frame. In addition, the electronics components are protected by heat shields and evaporators are not facing the same direction, thus radiation within the spacecraft is not significant. Based on these results, all components are at no risk of reaching an inoperable temperature, in any beta angle.

It is important to note that the temperatures of the CubeSat are dependent on the conductance that AMDROHP is operating at. If AMDROHP were to operate at a lower conductance, the temperatures at which components are at in the CubeSat would be different that shown here. As AMDROHP, as a thermal device continues to be developed and new performance projections are made, the model will update to accommodate these changes and results will be reanalyzed.

4. CONCLUSION

In this study, the AMDROHP being developed to address high heat generated from electronics in small satellites, was simulated evaluated thermally in orbit, at a system level in a 3U CubeSat. The model utilized 2D primitive representative geometric shapes, instead of complex 3D imported meshes, to meet favorable computational speeds. A conduction model with custom materials for the AMDROHP device was developed to emulate and meet the expected thermal performance of the two-phase operation of AMDROHP. Finally, the minimum and maximum temperatures, across a sweep of beta angles in a tumbling orientation, for each temperature sensitive component was compared to their allowable temperature ranges. Based on the results of this study, the CubeSat’s temperature-sensitive components will maintain favorable thermal conditions and are not at risk of over or underheating at any point during orbit.

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