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**Thermal Analysis and Control of MIST CubeSat**

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Master Thesis

**Thermal MIST Analysis CubeSat and Control of** *Author:* Shreyas Chandrashekar

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**Abstract**

The thermal analysis and control provides the necessary means to control the temperature of the satellite during the harsh conditions in space. MIST CubeSat presents a challenging task to design such a system with its various payloads and subsystems on board. This thesis report aims to describe the modelling and design of the thermal control system developed for MIST CubeSat in detail.

Each of these payloads and subsystems have different thermal requirements that has to be met in order to maintain thermal equilibrium. Hence in this project, all the units are given equal importance for the analysis to ensure the safety. A detailed thermal model of MIST CubeSat was developed using Systema-Thermica software. With this model, three different thermal cases such as the Hot Operational case, Cold Non-Operational and Operational cases were analysed. Furthermore, an initial dissipation profile for all the units present in the CubeSat was created for the thermal analysis. Based on the temperatures obtained, a thermal control system was designed to maintain the thermal balance between the satellite and the environment. This report also gives details of the assumptions made at certain points of the analysis.

The thermal control system for MIST CubeSat consists of both passive and active means. The passive means includes the use of thermal tapes on some of the payloads and subsys- tems on board. It was observed that the passive means were not enough to maintain the temperatures and hence active systems such as heaters were implemented for certain units. The results indicate that not all the payloads are within the tolerable limits and hence further development of the thermal control system is needed. Lastly the results include the overall design changes made in the model and a conclusion along with a possibility of future work has been discussed.

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**Sammanfattning**

Termisk analys och kontroll förser de nödvändiga metoderna för att kontrollera temper- aturen på satelliten under de extrema omständigheterna i rymden. MIST CubeSat pre- senterar en utmanande uppgift i att designa ett sådant system med dess olika nyttolaster och delsystem ombord. Denna rapport syftar till att beskriva i detaljerad modellering och designen av den termiska kontrollen som har utvecklats för MIST CubeSat.

Var och en av dessa nyttolaster och delsystem har olika termiska krav som måste upp- fyllas för att upprätthålla termisk jämvikt. Därför i detta projekt, alla enheter ges lika stor betydelse för analysen för att kunna garantera dess termiska jämvikt. En detaljerad termisk modell av MIST CubeSat har utvecklats med hjälp av Systema-THERMICA pro- gramvara. Med denna modell, tre olika termiska fall har analyserats; Varmt operativt fall, Kallt icke-operativt samt kallt operativa fall. Experimentens och del systemens dissi- pationsprofil kommer ha betydelse för temperaturen av enheten och en förenklad profil för de olika enheterna har implementerats i denna termiska modell. Baserat på de tempera- turer som erhölls, ett termiskt styrsystem var konstruerad för att bibehålla den termiska jämvikten mellan satelliten och omgivning. Denna rapport presenterar också detaljer om de antaganden som gjorts vid vissa moment i analysen.

Det termiska styrsystem för MIST CubeSat består av både passiva och aktiva metoder. Den passiva metoden inkluderar användning av termisk tejp på en del av nyttolasterna och delsystemen ombord. Det kunde konstateras att den passiva metoden inte var tillräckligt för att bibehålla temperaturerna och därmed aktiva system, såsom värmare användas för vissa enheter. Resultaten tyder på att inte alla nyttolaster ligger inom acceptabla gränser och därmed ytterligare utveckling av den termiska styrsystem behövs göras. Slutligen, resultaten inkluderar de övergripande konstruktionsändringar som gjorts i modellen samt en slutsats om möjlighet till framtida arbete har diskuterats.

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**List of Abbreviations**

**BOL** Beginning Of Life

**CUBES** CUbesat x-ray Background Explorer using Scintillators

**EOL** End Of Life **ESA** European Space Agency

**IR** Infra Red **ISIS** Innovative Solutions In Space

**ICD** Interface Control Document **JUICE** JUpiter ICy moon Explorer

**KTH** Kungliga Tekniska Högskolan

**MIST** MIniature Student saTellite **MOREBAC** Microfluidic Orbital REsuscitation of BACteria

**OBC** On Board Computer

**PCB** Printed Circuit Board **RATEX-J** RAdiation Test EXperiment for Juice

**SEUD** Single Event Upset Detector

**SiC** Silicon Carbide

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**Introduction**

MIST (MIniature Student SaTellite) is a 3U CubeSat being primarily built by the students of KTH Royal Institute of Technology under the supervision of Dr.Sven Grahn. This project started in late 2014 by the initiative of KTH Space Center. It is the first satellite by KTH and is intended to be launched in the year 2017. The CubeSat has eight payloads of different technical and scientific experiments provided by KTH and Swedish Industries. One of the primary aims of this initiative is to provide the students with a sense of real life projects in the area of space technology.

The payloads within the CubeSat are named accordingly as CubeProp, SEUD, MORE- BAC, RATEX-j, CUBES, SIC, LEGS and finally a Camera. Due to the presence of several payloads, there are many challenges encountered while designing the CubeSat and one among them is the thermal analysis. The environmental factors of the satellite during its mission such as the radiation from Sun, Earth and the influence of sun lit and eclipse side along with the internal heat dissipation from the components inside forms an integral part of the design considerations. Besides the subsystems, each of these payloads have different temperature ranges within which they have to be maintained for functioning properly. Once the satellite is placed in orbit, it undergoes extreme fluctuations in tem- peratures that can affect this performance. Hence it is very important for the satellite to have a reliable thermal control subsystem to guarantee the thermal requirements in every possible way.

**1.1 Aim**

The main aim of this thesis is to perform a detailed thermal analysis of the MIST CubeSat through simulations in Systema-Thermica and design a suitable thermal control system based on those simulation results. This thesis work entails the detailed description of the thermal model built and the simulation results for hot and cold cases.

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1. Introduction

**1.2 Boundaries**

The current thesis work offers the possibility of exploring ways to design a thermal control subsystem for MIST CubeSat. However, considering the available resources and the time constraints, the thesis work is carried out under certain boundaries that are defined below.

• The thesis work only intends to present the simulation results of one such design of the thermal control system and possible suggestions for further design.

• The thesis work only presents the simulation results of the topic using Thermica software and thus no experimental work will be accomplished.

• The thesis will include only the implementation results for the model built and there will be no validation of results presented.

**1.3 Report Outline**

This report gives a detailed information about the thermal modelling and control of MIST CubeSat. In Chapter 1, a brief introduction about the topic and aim of this thesis work is described. Chapter 2 gives a detailed description about the MIST satellite along with its components. In Chapter 3, a detailed write up about the thermal mathematical model is explained. Chapter 4 contains the simulation results for the cases analyzed. In Chapter 5, the thermal control aspects for the MIST is discussed. Lastly a conclusion for the analysis and possible recommendations for future work is included along with the appendix and references.

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**The MIST CubeSat**

The objective of a thermal study is often to understand the behaviour and performance of a satellite structure. For efficient analysis of any satellite, a thermal engineer must be aware of the intended mission and its characteristics along with the detailed overview of the entire structure of the CubeSat.

**2.1 MIST Mission Characteristics**

The mission objective of MIST CubeSat is to mainly provide students with hands on experience in satellite design and to demonstrate the scientific experiments in space. MIST is the first mission initiated by KTH with an expected mission life time of one year. One of the reference orbits is defined for the LTDN of 1045 at an altitude between 636.8 - 650.8 Km and an inclination of 97.9430 degrees. Furthermore, it is a sun synchronous orbit where in the ground track repeats every 4 days or 59 revolutions around the Earth [2].

However due to the presence of several payloads and other external factors, the launch will be delayed to early 2018 as of current status.

**2.2 Satellite Overview**

MIST is a 3U CubeSat with the dimensions of 10x10x30 *cm*3. The satellite comprises of both subsystems and the payloads inside the structure. All of these systems will mostly consist of Printed Circuit Boards (PCB) as a base line structure. The various subsystems used in the CubeSat are Batteries, power supply unit, On Board Computer, transceiver, Magnetorquer and finally an antenna system. These subsystems are an essential part of the satellite mainly required for keeping the satellite in orbit.

The several payloads in MIST as mentioned before are CubeProp, SEUD, MOREBAC, RATEX-J, CUBES, SIC, LEGS, and lastly a Camera. A display of the entire satellite without the body mounted solar panels is shown in the Figure 2.1 below. The outer3

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structure consists of two deployable solar panels at the top and body mounted solar panels on all the sides. The detailed study of these systems together is required in order to model them individually and predict their thermal behaviour for such a mission.

**Figure 2.1:** Structure of MIST [30]

**2.3 Subsystems**

The middle stack of the satellite holds the various subsystems required. The entire struc- ture along with these above mentioned subsystems are procured from ISIS (Innovative Solutions In Space) based in The Netherlands. All these components are off the shelf and are readily available from ISIS. The components follow PC104 standards and have specific dimensions in relation with the CubeSat structure built by ISIS.

**2.3.1 Batteries**

Batteries are generally used on board the satellites to make sure it meets the power requirements during the detumbling and eclipse phases of the orbit. They help in storing, regulating and distributing the necessary power required to complete the mission without any hazard. The batteries used for space applications are generally rechargeable ones. MIST intends to use NanoPower BP4 battery pack from GomSpace which is shown in Figure 2.2. There are four lithium ion cells attached to the PCB which are repacked with some insulation material such as kapton and glued with aluminium brackets for mechanical and thermal stability. These batteries also have built in heaters and temperature sensors to regulate the thermal constraints in space [3]. Although batteries can operate over wide temperature ranges, care must be taken during charging and discharging process. With regard to thermal design of the satellite, batteries are known to be the most sensitive and critical component.

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**Figure 2.2:** NanoPower BP4 battery pack [3]

**2.3.2 Electrical Power System Board**

The Electrical Power System (EPS) board used in MIST is Nanopower P31-us from GomSpace which is specially designed for small, low cost satellites with power demands from 1 - 30 W [4]. It acts as a power converter to condition the output power from solar panels to charge the provided lithium-ion batteries.

**Figure 2.3:** NanoPower P31-us [4]

Figure 2.3 shows the EPS board currently used for MIST and is considered to be an important unit that has to be thermally stable.

**2.3.3 On Board Computer (OBC)**

The On Board Computer used for MIST is from ISIS which is intended for space applica- tions. It provides powerful computing functions by running specialized software to control and manage the operations of the satellite [5]. It helps in the communication between the On-board subsystems and ground station. When the ground station is not in reach, OBC takes over the control of all critical operations on board. Figure 2.4 shows the OBC board along with the daughter board used. Having broader temperature ranges, this subsystem is unlikely to be any kind of concern for the thermal analysis.

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**Figure 2.4:** ISIS OBC board [5]

**2.3.4 Magnetorquer (iMTQ’s)**

The attitude and determination control system for MIST comprises of the magnetorquer alone since it is a magnetically controlled satellite. It is solely responsible for keeping the CubeSat dynamically stable. The magnetorquer is again procured from ISIS which is specifically designed for CubeSat applications.

**Figure 2.5:** ISIS Magnetorquer Board [6]

This magnetorquer is equipped with internal 3-axis magnetometer, 3 magnetorquers and a micro-controller as shown in Figure 2.5. The power dissipation is upto 1.2 W and the broader temperature qualifications for this board makes it a thermally stable component compared to batteries [6].

**2.3.5 TRXVU Transceiver**

The ISIS TRXVU is a CubeSat standard compatible transceiver module used my MIST for communication purposes. The module is as shown in Figure 2.6. It performs the function of both transmitter and receiver at appropriate frequencies. This has the highest power dissipation of 4.0 W compared to the other subsystems [7]. However this power is only consumed during transmission and after which it changes to idle mode when inactive.

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**Figure 2.6:** ISIS TRXVU Transceiver Board [7]

The thermal connections between this module and the structure should be properly pro- vided in order to avoid any over heating of the components.

**2.3.6 Antenna System**

The ISIS deployable antenna system used for MIST consists of four memory alloy tape antennas upto 55 cm length which can deploy from all four sides of the structure upon command [8]. The main purpose of this antenna system is to deploy the stowed antennas so that it can be used for RF transmissions.

**Figure 2.7:** ISIS deployable antenna system [8]

This antenna system has a thermal mass of 100 gms and has a broader temperature requirements. Figure 2.7 shows the exact model that will be used for the MIST CubeSat.

**2.3.7 Solar Panels**

The solar panels are on board the satellite for power supply. There are two deployable solar panels at the top of the satellite and the rest of the solar panels are mounted on each7

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side of the CubeSat. Both the deployable and body mounted solar panels are designed in such a way that it is in interface with the CubeSat electrical power system (EPS) and On board Computer (OBC) [9]. Figure 2.8 shows the solar cells and the body mounted solar panels for a dummy structure. The solar cells employed are used generally for space applications and hence they can withstand higher temperatures. The deployable solar panels are hinged at the top of the CubeSat structure and are deployed after detumbling process in space.

**Figure 2.8:** Body Mounted solar panels [9]

**2.4 Scientific Payloads**

The upper and the lower stack of the CubeSat holds the various payloads that are provided by the experimenters. There are eight payloads that will be carried to space for various scientific experiments. A detailed overview of these payloads will be discussed in this section since it plays an important role in the thermal design.

**2.4.1 CubeProp**

CubeProp is the propulsion module from Nanospace company in Uppsala, Sweden. It is half the unit (0.5 U) in size and is as shown in Figure 2.9. The purpose of this experiment is to get a flight heritage for this module so that it can be used specifically for CubeSat applications in the future. The goal will be to use the propulsion system in such a way that precision control of the satellite can be demonstrated and also to test the total impulse capability of the system to be around 40 Ns [10]. The module consists mainly of thrusters, propellant tank, valves, filters and electronic boards. The main concern from the thermal standpoint is the propellant tank where in the fuel used is butane.

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**Figure 2.9:** NanoSpace CubeProp Module [CAD Model] [10][28]

The tank has to be thermally controlled within the required temperatures such that it does not over heat or freeze the fuel during the mission. Hence the CubeProp is an important payload and is one of the critical units in MIST that has to be maintained.

**2.4.2 SEUD**

SEUD stands for Single Event Upset Detector which is developed by KTH. The purpose of the experiment is twofold, one is to test the in house concept of self healing computer system in space to see if it will be able to heal itself by correcting faults during run time. The second purpose is to measure the expected SEU frequency in near Earth orbit.The payload is intended to be a simple FPGA (field-programmable gate array) board and the experiment layout is as shown in Figure 2.10.

**Figure 2.10:** Architecture of SEUD Experiment [11]

This experiment is unlikely to be considered as a critical unit in terms of thermal condi- tions, nevertheless it has to be within the limits. The temperature requirements for this unit is much wider than compared to others and also has a bit higher power dissipation of upto 1.2 W [11].

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**2.4.3 MOREBAC**

MOREBAC stands for Microfluidic Orbital Resuscitation of Bacteria is an experiment that is proposed by the Division of Proteomics and Nanobiotechnology, KTH. The main aim of this payload is to transport freeze dried micro-organisms into orbit, resuscitate them through media addition and finally measure their growth characteristics in orbit after a certain storage period [12]. The experiment is still in its development stage and hence only the sketch of the experiment is available as of now which is as shown in Figure 2.11. This experiment is also one of the most critical unit because of its narrow temperature demands. The bacteria can only sustain within the thermal limits for this experiment to work. Therefore this unit is expected to be the driving factor for thermal design and control.

**Figure 2.11:** Crude sketch of the MOREBAC experiment [12]

**2.4.4 RATEX-J**

RATEX-J stands for RAdiation Test EXperiment for Juice mission proposed by Swedish institute of space physics in Kiruna, Sweden. It is a prototype which consists of three different detectors to be implemented in the JDC (Jovian plasma Dynamics and Com- position) instrument for ESA’s Jupiter Icy Moon Explorer (JUICE) mission. The initial model of the experiment is as shown in Figure 2.12.

**Figure 2.12:** Model of RATEX-J experiment [13]

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The three different particle detectors are Solid State Detector (SSD) , Multi-Channel Plate (MCP) and Ceramic Channel Electron Multiplier (CCEM) [13]. This experiment is exposed continuously towards space for the experiment to be successful and therefore the side which has detectors does not have any body mounted solar panels covering them.

**2.4.5 SIC**

The SiC (Silicon Carbide) experiment is intended to study the silicon carbide material in harsh space conditions for future use in electronics. This application has also been already suggested for a Venus lander mission [14]. The payload consists of a SiC transistor, a Graphene transistor and a Silicon transistor on simple PCB. Through the MIST mission, it is being tested for in orbit low TRL (Technology Readiness Level) technologies.

**Figure 2.13:** Schematic of the Experiment [14]

From the thermal standpoint, this payload is unlikely to be considered as critical because of its broader temperature range. Since this experiment is still in its development phase, only the schematic of the experiment is shown in the Figure 2.13.

**2.4.6 CUBES**

CUBES stands for CUbesat x-ray Background Explorer using Scintillators is an experi- ment proposed by Particle and Astroparticle Physics group at KTH. The main purpose of this experiment is to study the in orbit radiation environment using a detector com- prising a silicon photomultiplier coupled to scintillator material. The studies will focus on possible radio-activation, induced fluorescence and radiation damage for the scintillator11

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materials [15]. This experiment has very narrow temperature range within which it has to be maintained and also the scintillators should be exposed to space all the time. This is also an important payload to be considered for thermal design. The overview of the experiment is shown in Figure 2.14.

**Figure 2.14:** Layout of the Experiment [15]

**2.4.7 LEGS**

The piezo LEGS experiment is proposed by the company Piezomotor AB in Uppsala, Sweden. The aim of this experiment is to test the piezomotor applications in space. It is of interest to observe that the motor works in the vacuum filled radiation environment. Finally the test will be to observe the motors function over time (several months) to check for possible change of performance and the distance the motor can work [16].

**(a)** Driver Board of Peizo Motor

**(b)** Piezo Motor

**Figure 2.15:** LEGS Module [16]

The payload consists of the driver board and the piezo motor as shown in Figure 2.15a and 2.15b . The thermal conditions required are feasible but since the experiment is positioned with CUBES experiment, it is also exposed to space continuously.

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**2.4.8 Camera**

The camera intended to be used in MIST is Raspberry Pi camera as of now. The goal of this experiment is to capture and reconstruct high quality images from MIST. The images will be captured using High Dynamic Range (HDR) techniques, compressed using a new learning based compression method adapting to the input data, and processed using compressive image reconstruction techniques [17]. The final images of the camera will be displayed at Tekniska Museet in Stockholm. The camera module of the MIST is situated at the lower stack and is facing the Earth (Nadir pointing). Thermal management of this payload is also equally important as a whole. Figure 2.16 shows the currently considered Raspberry Pi camera module connected to Raspberry Pi.

**Figure 2.16:** Camera Module [17]

**2.5 CubeSat Structure**

MIST intends to use the ISIS modular structure which is of the CubeSat standards. The ISIS CubeSat STS (STructural Subsystem) is built in such a way that the PCBs can be mounted on to a set of four ribs. These structural ribs interface with side frames. Figure 2.17 shows the intended MIST structure delivered by ISIS.

**Figure 2.17:** ISIS 3U Modular Structure [18]

The rails on the outside are black anodized painted to have absorptivity to emissivity13

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ratio equal to 1 for a better thermal stability [18]. The structure is according to CubeSat standards and hence it must withstand the harsh temperature conditions in space.

**2.5.1 MIST CubeSat Orientation**

The CubeSat’s direction of orientation and the coordinate frames are very important for a thermal engineer as it is to an attitude control engineer. The direction of travel for the CubeSat will determine which face of the satellite is experiencing maximum and minimum solar exposure. Along with the direction of travel, it is also important to know the placements of payloads within the CubeSat which are placed according to the criteria required for the experiment. The orbital frame (U,V,W) is defined as follows :

• U is along the direction of the radius vector (Zenith) from the Earth’s center to the satellite.

• V is perpendicular to U and points in the general direction of orbital motion.

• W is perpendicular to the orbital plane and completes the coordinate system. Figure 2.18 shows the orbital frame of reference stated.

**Figure 2.18:** The Orbital Frame

The particle detector experiments like the RATEX-J and the CUBES need to be placed in the dark side of the satellite where there is minimum exposure to the Sun. Hence these particle detectors are placed in -X direction which point in -W direction of the orbital plane in a Sun synchronous orbit specified earlier. With regard to the Camera, it is always facing the Earth and hence is placed on the -Z face (Nadir pointing) and this is pointing in the -U direction of the orbital plane. Lastly, it is observed that -Y direction is aligned with the +V direction. Figure 2.19 shows the orientation of body and orbital frames in the reference orbit described in section 3.1.

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**Figure 2.19:** Body and Orbital frames in reference orbit

Since the experiments like RATEX-J and CUBES are facing the -X direction and cannot be shadowed by the deployable solar panels, they are made to be deployed from the Y faces and are pointing towards +Z direction of the CubeSat. In addition to this, the experiments have to be exposed to space and hence there is no body mounted solar panel in the -X direction of the lower stack. The orientation of the antennas from the work by Bsc. thesis students of MIST shows that the shorter element of the antenna should be along the ± Y direction and the longer elements should be along the ± X direction [19].15

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**Theory**

Transfer of energy is one of the basic phenomenons that is observed everywhere in the universe. Heat is a form of this energy that can be transferred from one system to another system as a result of temperature difference. There are three modes of heat transfer mechanisms [22] that are usually observed such as

• Conduction

• Convection

• Radiation

Conductive and radiative heat transfer are the main modes of transfer mechanisms within a spacecraft in space. Convection is not generally observed in space because all the components of the spacecraft are in vacuum. Each of these phenomenons are discussed except for convection as to how they affect the spacecraft in those harsh conditions of space.

**3.1 Conduction**

Conduction is defined as the transfer of energy from the more energetic particles of a substance to the adjacent less energetic particles as a result of interactions between the particles. The rate of heat conduction through the medium depends on geometry of the medium, thickness, material of the medium and finally the temperature difference across the medium.

Consider a steady state conduction through a large plane wall of thickness ∆*x* =*L* and the temperature difference across the wall is ∆*T* = *T*2 − *T*1 as shown in the Figure 3.1. The rate of heat conduction through a plane layer is proportional to the temperature difference across the layer and heat transfer area but is inversely proportional to the thickness of the layer.

̇*Q* = *KA*(*T*1 − *T*2)

∆*x* = −*KA*∆*T*∆*x* = −*KAdTdx* (*W*) (3.1)

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**Figure 3.1:** Heat conduction through a large plane wall of thickness ∆*x* and area A.

where *K* is thermal conductivity in *WmK* and *A* is cross-sectional area of the surface in *m*2. Now this is called the Fourier’s law of heat conduction. The relation 3.1 indicates that the rate of heat conduction in a direction is proportional to the temperature gradient in that direction. The negative sign ensures that the heat transfer in the positive x direction is a positive quantity.

**3.1.1 Thermal Contact Conductance**

This is a property where it describes the ability to conduct heat flow between two bodies. Consider two bodies *A*1 and *A*2 in contact where in heat flows from the hotter body to the colder body as shown in Figure 3.2. Now the heat flow observed between the two bodies *A*1 and *A*2 can be obtained from the Equation 3.2 :

**Figure 3.2:** Thermal contact conductance

*Q*  ̇= (*T*1 − *T*3)

∆*XKA*1*AA* 1 + *hcA* 1+ ∆*XKA*2*AA*

2 (*W*) (3.2)17

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where *T*1 and *T*3 are the temperatures at the end of each bodies and ∆*XA*1 ∆*XA*2 are the distances through which the heat has conducted. Also *hc* is the thermal contact conductance and *A* is the contact area.

**3.1.2 Conductive Couplings**

While performing the thermal analysis, the CubeSat is descretized into several number of nodes for each of the parts modelled. These nodes in turn have conductive heat transfer between them that is taken into account. The conductive heat transfer between two surfaces in contact form a coupling. For example, consider two surfaces *A*1 and *A*2 in contact with each other where in the nodes are present at the centre of each surface as shown in the Figure 3.3. The conductive coupling between two nodes can be obtained from the Equation 3.1 as follows :

**Figure 3.3:** Conductive coupling between two nodes

*GA*1*/A*2 = (*KAdx* )*A*1*/A*2 (*W/K*) (3.3)

*GLA*1→*A*2 = 11

*GA*1 + 1*GA*2

(*W/K*) (3.4)

where the in heat. *GA*1*/A*The 2 the Figure is the conductance *GL*3.3. *A*1→*A*The 2 denotes value of node *A*1 or node *A*2 and dx is the distance traversed by conductive coupling between the two nodes as represented of this thermal conductance depends on the material of the surface, contact pressure between the surfaces, size of the area in contact, surface cleanliness and roughness of the material. The various conductive couplings present in the thermal model are fed in manually for Systema-Thermica software to aid in the calculation of temperatures.

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**3.2 Radiation**

Radiation is the energy emitted by matter in the form of electromagnetic waves (or pho- tons) as a result of the changes in the electronic configurations of the atoms or molecules. In case of heat transfers due to this phenomenon, all bodies above absolute zero emit thermal radiation. The radiative heat transfer from a black body surface is given by the Stefan-Boltzmann law as :

̇*Qmax* = *σAT* 4 (*W*) (3.5) where *σ* = 5*.*67 ∗ 10−8 *W/m*2*K*4 is the Stefan Boltzmann constant, *A* is the area of the surface in *m*2 and *T* is the temperature in *K* [20]. However this is an ideal case for a black body. The radiative heat transfer from the real surfaces is less than the radiation emitted by black body and is expressed as :

̇*Qemit* = *εσAT* 4 (*W*) (3.6) where *ε* is the emissivity of the surface. This property is defined as the ratio between energy that the gray body emits to the energy emission it would have if it were a black body. Another important property of the surface is known as absorptivity denoted by *α* which is the fraction of the radiation energy incident on a surface that is absorbed by the surface.

**3.2.1 Radiative view factors**

The radiative heat exchange depends on the orientation of the two surfaces relative to each other. The view factor also known as shape factor is the one which describes this orientation.

**Figure 3.4:** Two differential areas for calculating view factors [31]

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Consider two surfaces having differential areas *dA*1 and *dA*2 as shown in the Figure 3.4. The distance between the two surfaces is *S* and the angles between the surface normals (*n*1 and *n*2) and the line *S* is *θ*1 and *θ*2 respectively. is given by the expression as

The differential view factor *dFdA*1→*dA*2 *dFdA*1→*dA*2 = *cosθπS*1*cosθ*2 2 *dA*2 (3.7)

Th exact solution for the above equation after solving can be finally written as

*FA*1→*A*2 = 1*A*1

∫*A*1

∫*A*2

*cosθ*1*cosθπS*2 2

*dA*2*dA*1 (3.8)

Equation 3.8 accounts for the effects of orientation on radiative heat transfer between two surfaces. It is an independent quantity which is purely geometrical and does not depend on temperature.

**3.2.2 Radiative heat transfer**

The radiative heat transfer between two nodes *A*1 and *A*2 within the spacecraft can be expressed as follows :

*Q* ̇*A*1→*A*2 = *GRA*1→*A*2*σ*(*T A*41 − *T A*42) (*W*) (3.9) where (also known *Q* ̇*A*1→*A*as 2 is the heat flow from node *A*1 to *A*2 Radiative Exchange Factor (REF)) , in *GRW/KA*1→*A*4 2 between is the radiative those coupling two nodes and coupling *TA*1 and is expressed *TA*2 are temperatures as :

in node *A*1 and *A*2 respectively. Now the radiative

*GRA*1→*A*2 = *εA*1*BA*1→*A*2*AA*1 (3.10) where *A*2 and *εAA*1 *A*expression is the emissivity of node *A*1, 1 shown is the area of that node. in Equation 3.11

Now *BA*the 1→*A*Gebhart 2 is the Gebhart factor from node *A*1 to factor can be calculated from the

*BA*1→*A*2 = *FA*1→*A*2 ∗ *εA*2 +

∑*N*((1 − *εAj* ∗ *FA*1*j* ∗ *BjA*2) (3.11) *j*=1where of node *FAA*1→*A*2. The 2 is the radiative radiative couplings view factor along discussed with the in view section factors 3.2.1 and and Gebhart *εA*2 is the factors emissivity are calculated automatically by Systema-Thermica with the use of Monte Carlo Ray Tracing method and is later supplied to the Thermisol solver for temperature calculations.

**3.3 Space Thermal Environment**

The environment for the spacecraft play an important role in the thermal management system. The main sources for the imbalance of the thermal system of the spacecraft are

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due to solar radiation, Earth Albedo and Earth IR. The temperature surrounding the satellite in space is 2.7K and thus serves as the harsh environment [1]. Figure 3.5 shows the main sources of heat in space.

**Figure 3.5:** The Space environment

**3.3.1 Solar radiation**

Sunlight is a major source of heating that takes place on the satellite. The way in which it affects the spacecraft depends on the distance from the Sun. During summer solstice, the Earth is farthest from the Sun and it receives low intensity of solar radiation up to 1322 *W/m*2 but during winter solstice, the Earth is closest to the Sun and hence the intensity is very high up to 1414 *W/m*2 [21]. This is because of the elliptical orbit of the Earth. Heat transferred due to this is given by :

̇*QA*1*,solar* = *αA*1*SsolarAA*1 (*W*) (3.12)

where  ̇*QA*1*,solar* is the heat input from the solar radiation to the node *A*1, *αA*1 is the absorptivity of the node *A*1, *Ssolar* is the solar flux constant in *W/m*2 which is defined as the amount of incoming solar radiation per unit area that would be incident on a plane perpendicular to the rays, at a distance of one astronomical unit (AU) and *AA*1 is the area of the node perpendicular to the Sun.

**3.3.2 Earth Albedo**

Sunlight reflecting off the Earth or any planet for that matter is called Albedo. It is actually the fraction of the incident sunlight that is reflected off the surface of the Earth.

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Usually the reflectivity is greater over continental regions than oceanic regions and gen- erally increases with decreasing local solar elevation angle and increasing cloud coverage. So in the presence of snow and ice coverage, decreasing solar elevation angle, increasing cloud coverage, Albedo also tends to increase with latitude. As the spacecraft moves away from the sub solar point, the albedo flux reaching the spacecraft decreases. The heat transferred due to Albedo radiation is expressed as :

̇*QA*1*,Albedo* = *αA*1*SsolaraAA*1 *REarth*

(*REarth* + *h*)2 (*W*) (3.13)

where *QA*1*,Albedo* is the heat input from the Albedo radiation, a is the dimensionless Albedo constant, *REarth* is the radius of the Earth and h is the altitude of the spacecraft. The average albedo observed is around 30% [1].

**3.3.3 Earth IR**

All the incident light on the Earth’s surface not reflected as Albedo is absorbed by Earth and eventually re-emitted to space. This re-emitted energy is known as Earth IR. The intensity depends on the local temperature of Earth’s surface and also the cloud coverage. At regions of warmer temperatures, the intensity of IR from Earth is higher but at regions of lower temperatures, the intensity is lower. Also it depends on the cloud coverage. In the warmer regions with more cloud coverage, the intensity is again low because of the blocking due to clouds. The heat transferred due to Earth IR is as follows :

̇*QA*1*,Earth*−*IR* = *εA*1*SEarth*−*IRAA*1 *REarth*

(*REarth* + *h*)2 (*W*) (3.14)

where the *εA*1 is the emissivity of the node *A*1, *SEarth*−*IR* is the Earth IR flux in *W/m*2. The average value observed for Earth IR is 236 *W/m*2 [1].

**3.4 Heat Capacity of the material**

Heat Capacity is basically defined as the ratio of the heat added or removed from the object or material to the resulting change in temperature. The relation shows how the thermal capacity for any material is calculated :

*C* = *Q*∆*T* (*J/K*) (3.15)

where *C* is heat capacity, *Q* is the heat loss and ∆*T* is change in temperature. Now for a specific node *A*1 with density *ρA*1 (*kg/m*3), volume *VA*1 (*m*3) and specific heat *csp* (*J/kgK*), the heat capacity can be calculated as shown :

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*CA*1 = *cspρA*1*VA*1 (*J/K*) (3.16) The temperature is dependent on this quantity wherein the temperature change decreases if the heat capacity is higher.

**3.5 Transient Heat Equation**

The thermal analysis for a spacecraft is generally considered to be a transient process since the concept of heat going in is equal to heat leaving the system is not always true. The transient analysis accounts for the heat storage in the spacecraft as well. Hence the thermal energy balance equation [20] can be written as :

*CidTi*

*dt* = *Q* ̇*int,i* + *Q* ̇*ext,i* −

∑*Ni,j GLi,j*(*Ti* − *Tj*) −

∑*Ni,j GRi,jσ*(*T i* 4− *T j* 4) (3.17)

Equation 3.17 refers to generic nodes *i, j* in a N-node discretized spacecraft where in *i, j* = *A*1*,A*2*,A*3*...etc.* and it includes all the heat inputs experienced by a spacecraft. On the left hand side, there is the heat input due to thermal capacity whereas on the right hand side, there is the internal heat dissipation from the various components. The external heat inputs are the radiation factors in the environment and finally the heat transfers due to conductive and radiative couplings.

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**Thermal Modelling of MIST CubeSat**

This chapter deals with the development of thermal model for MIST CubeSat which will later be simulated to study the thermal behaviour of the MIST during its mission. The entire modelling and simulation is performed with the use of Systema Thermica software which is developed by Airbus Defence and Space [24]. In this process, there are two types of models built, one is the Geometrical Model Management (GMM) and second is the Thermal Model Management (TMM). The GMM includes the geometrical build up of the model MIST in Thermica along with the meshing of geometry into nodes. The TMM however includes the mathematical description of capacitances and conductive couplings for each of the nodes along with dissipation profile for each of the components in MIST.

**4.1 Thermal Model**

The thermal model of the satellite contains the detailed description about the geometry of MIST CubeSat, materials and optical properties for each of the components used and the thermal couplings between those components.

**Figure 4.1:** MIST Thermal Model

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4. Thermal Modelling of MIST CubeSat

The thermal model of the complete MIST CubeSat is as shown in Figure 4.1. This model consists of all the subsystems and payloads present within the MIST CubeSat and each of these systems are discussed in detail. Note that the mesh geometries used are mostly square plate mesh for PCBs, mounting boards and other box shaped structures whereas the connection stack is meshed as rectangular surface with some thickness. Other mesh geometries include cylinders and discs shaped structures only. Most of the materials used in all the models are assumed accordingly as the information regarding them was still not available when this work was done. All the parts are modelled in such a way that the surfaces are exactly in touch with each other as defined in the original design.

The PCBs make up most of the CubeSat and hence the thermal properties are very important when considered. A PCB is generally made up of alternating layers of copper and that of FR4 which act as the insulation. For the MIST CubeSat, eight layers of copper with 50 % of it on outer layers and 40 % of it on the inner layers has been considered. Also the total thickness of the PCB is taken as 1.6 *mm* with the calculated average thermal conductivity of 20.5 *W/mK*. Lastly the average density of 2223 *Kg/m*3 and specific heat of 589 *J/KgK* has been calculated with the same principle from thermal conductivity calculator which was developed in the previous work on thermal analysis by Andreas Berggren [23].

**4.1.1 Batteries**

There are four battery cells which are cylindrical in shape modelled on the PCB along with a connection stack as shown in Figure 4.2. The thermal couplings observed for this battery is between the cells and PCB, connection stack and PCB and finally PCB with the structure rods. The coupling between the PCB and battery cells includes the coupling of thermal strap which is the main reason for giving mechanical stability to the system. This thermal strap is not geometrically modelled but mathematically considered in the calculations of couplings. The materials used for the batteries along with the capacitances obtained can be seen in the Table 4.1.

**Figure 4.2:** Thermal Model of GomSpace Batteries

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4. Thermal Modelling of MIST CubeSat

**Table 4.1:** Model details for the batteries.

**Name of the Material Number of Capacitance per**

**parts used nodes node** (*J/K*)

4 Battery cells Aluminum 6082 cyl. nodes = 12 cyl. node = 5

disc nodes = 8 disc node = 1 PCB Copper 9 2

Connection stack Copper 3 5

The optical coating used for battery cells is Kapton 0.5 mil as mentioned in the interface documents. The PCB has FR-4 coating whereas the connection stack is of copper itself. The conductance coupling between the mentioned parts are shown in Table 4.2. The values for the conductances represent for one element under consideration.

**Table 4.2:** Thermal couplings for the batteries.

**Part 1 Part 2 Conductance**

(*W/K*)

Battery cells PCB 2

PCB Connection stack 0.4 PCB Rods 0.1

**4.1.2 Electrical Power System (EPS)**

The NanoPower P31-us from GomSpace is modelled as a flat PCB with connection stack and small boxes representing the parts of the PCB. The thermal couplings observed are between PCB and the connection stack, PCB with the other boxes and PCB with the structure rods as well. These small boxes are nothing but the electrical units/components part of the PCB. Figure 4.3 shows the thermal model of the NanoPower P31-us built in thermica.

Table 4.3 presents the specific materials used along with their capacitances. The optical properties for each of these surfaces are same as the materials used and no special coating is required for this subsystem. The thermal coupling obtained is presented in Table 4.4.

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**Figure 4.3:** Thermal Model of GomSpace power system

**Table 4.3:** Model details for the power system.

**Name of the Material Number of Capacitance per**

**parts used nodes node** (*J/K*)

5 small boxes Aluminum 6082 5 2 PCB Copper 9 2

Connection stack Copper 3 2

**Table 4.4:** Thermal couplings for the power system.

**Part 1 Part 2 Conductance**

(*W/K*)

Small boxes PCB 4 PCB Connection stack 1 PCB Rods 0.1

**4.1.3 On Board Computer (OBC)**

The On Board Computer is from ISIS and it is modelled as two PCBs stacked together as shown in Figure 4.4. The main PCB is coupled to the connection stacks and the cylinder supports that is in turn coupled with the daughter board. Finally the main electronic board of the OBC is supported by the rods running through. Table 4.5 shows the details of the material used for such a system along with the capacitances per node obtained. The optical properties used for this system is the material itself and no coating is applied as such. The conductances between the couplings mentioned are given in Table 4.6.

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4. Thermal Modelling of MIST CubeSat

**Figure 4.4:** Thermal Model of ISIS OBC

**Table 4.5:** Model details for the OBC.

**Name of the Material Number of Capacitance per**

**parts used nodes node** (*J/K*)

Cylinder supports Aluminum 6082 8 0.2

PCB Copper 9 2

Connection stack 1 Copper 3 3

Connection stack 2 Copper 3 1

OBC daughter board Copper 9 1

**Table 4.6:** Thermal couplings for the OBC.

**Part 1 Part 2 Conductance**

(*W/K*)

Cylinder supports PCB 2

PCB Connection stack 1 1 PCB Connection stack 2 1 PCB Rods 0.1 Cylinder supports OBC daughter board 2

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4. Thermal Modelling of MIST CubeSat

**4.1.4 ISIS Magnetorquer Board (iMTQ’s)**

The ISIS magnetorquer board is modelled as a flat PCB with thickness as shown in Figure 4.5. The torque rods are built perpendicular to each other and are attached to the thermal brackets. Here, the thermal brackets supporting the rods are modelled as thick plates with square cross section but the calculations for the couplings include the long slender brackets actually present in the original layout. The other couplings observed is between the PCB with the connection board and the aircore.

The material used is as represented in Table 4.7 along with the capacitances. The optical properties for the PCB is FR-4 and the other parts have no special coating included in this model. The thermal couplings calculated is as shown in Table 4.8.

**Figure 4.5:** Thermal Model of ISIS Magnetorquer board

**Table 4.7:** Model details for the Magnetorquers.

**Name of the Material Number of Capacitance per**

**parts used nodes node** (*J/K*)

Torque rods Aluminum 6082 6 4

PCB Copper 9 2

Torque rod 1 brackets Aluminum 6082 2 0.2

Torque rod 2 brackets Aluminum 6082 2 1

Connection stack Copper 3 2

Air Core Aluminum 6082 12 4

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**Table 4.8:** Thermal couplings for the Magnetorquers.

**Part 1 Part 2 Conductance**

(*W/K*)

Torque rod 1 Torque rod 1 bracket 1

Torque rod 2 Torque rod 2 bracket 1

PCB Connection stack 1 PCB Air core 1 and 3 9 PCB Air core 2 and 4 8 PCB Rods 0.1 PCB Torque rod 1 bracket 0.3

PCB Torque rod 2 bracket 1

**4.1.5 TRXVU Transceiver**

The TRXVU transceiver is also similarly modelled as others where in it consists of a flat plate as a PCB, rectangular surface with thickness as connection stack and the other small boxes that are present on the PCB shown in Figure 4.6. Table 4.9 shows the materials used are copper for all components in this system.

**Figure 4.6:** Thermal Model of ISIS TRXVU- transceiver board

The thermal couplings observed are between PCB and connection stack, boxes 1,2,3 & 4, and lastly the structure rods as presented in the Table 4.10.

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**Table 4.9:** Model details for the TRXVU transceiver.

**Name of the Material Number of Capacitance per**

**parts used nodes node** (*J/K*)

Boxes 1 and 2 Copper 4 4

Boxes 3 and 4 Copper 2 6

PCB Copper 9 2

Connection stack Copper 3 3

**Table 4.10:** Thermal couplings for the TRXVU transceiver.

**Part 1 Part 2 Conductance**

(*W/K*)

PCB Connection stack 1 PCB Boxes 1 and 2 4 PCB Boxes 3 and 4 6 PCB Rods 0.1

**4.1.6 Antenna system**

The antenna system is a simple box like structure representing the antenna board which consists of the deployable antenna pointers shown in Figure 4.7. The antenna pointers are coupled with the board itself and the board in turn is modelled to be coupled with the ribs present just above the system. However, this connection between the ribs and the antenna system is not modelled geometrically but included in the conductive couplings.

Table 4.11 shows the capacitances per node for the parts mentioned. All the parts mod- elled are mostly made of copper and they are not specially coated other than the material itself. Table 4.12 shows the values for the conductive couplings obtained.

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**Figure 4.7:** Thermal Model of ISIS antenna system

**Table 4.11:** Model details for the antenna system.

**Name of the Material Number of Capacitance per**

**parts used nodes node** (*J/K*)

Antenna pointer part 1 Copper 4 0.4

Antenna pointer part 2 Copper 2 0.1

Antenna pointer part 2 Copper 2 0.4

PCB Copper 9 12

**Table 4.12:** Thermal couplings for the antenna system.

**Part 1 Part 2 Conductance**

(*W/K*)

PCB Antenna pointers part 1 0.4

Antenna pointers part 1 Antenna pointers part 2 3

PCB Ribs 0.3

**4.1.7 Solar Panels**

The solar panels are classified as three different parts such as the deployable solar panels, 2U body mounted panels and 1U body mounted panels. All the panels are modelled as long flat plate with the thickness of 2*mm* as shown in Figure 4.8. These panels are

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supported by the side-frames and structure ribs. The material used for the whole model is Aluminum 6082. The optical properties considered are Aluminum 6082 layer along with the solar cells on the positive outside and black anodized layer on the negative inside. The materials used and the capacitances are shown in Table 4.13.

The thermal couplings between the panels and the structure ribs along with the side- frames are tabulated in Table 4.14.

**Figure 4.8:** Thermal Model of ISIS solar panels

**Table 4.13:** Model details for the Solar panels.

**Name of the Material Number of Capacitance per**

**parts used nodes node** (*J/K*)

Deployable solar panels Aluminum 6082 32 8

2U Body mounted panels Aluminum 6082 64 5

1U Body mounted panels Aluminum 6082 24 5

**Table 4.14:** Thermal couplings for the Solar panels.

**Part 1 Part 2 Conductance**

(*W/K*)

Deployable solar panels Structure ribs 0.3

2U and 1U solar panels Sideframes 1

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**4.1.8 CubeProp**

The NanoSpace CubeProp is a propulsion module consisting of thrusters and hence it is positioned at the top of the CubeSat for easier maneuverability. The thermal model consists of a large cylindrical propellant tank in the middle along with the interface and the main electronic boards supported by small cylinder supports. This tank is positioned properly on a mounting board with the help of screw interfaces on four sides. This interface is not modelled geometrically but considered while obtaining the conductive couplings. Figure 4.9 shows the thermal model of the CubeProp.

**Figure 4.9:** Thermal Model of NanoSpace-CubeProp

**Table 4.15:** Model details for the CubeProp.

**Name of the Material Number of Capacitance per**

**parts used nodes node** (*J/K*)

Propulsion tank Aluminum 6082 5 15

PCB Copper 9 2

Mounting board Aluminum 6082 8 8

Interface PCBs Copper 18 1

Cylinder supports Aluminum 6082 8 1

Mounting supports Aluminum 6082 4 6

The optical properties used as a coating for all the parts plays an important role in thermal activity of the system. These properties can be varied by using different tapes

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on the surfaces. The electronic boards such as the PCBs are FR-4, the mounting board and all kinds of supports along with the tank are of Aluminum 6082. But this coating is later changed for some of the parts during the thermal control analysis to maintain the temperature limits. Table 4.15 shows the values for capacitance for each of the parts modelled in thermica. The thermal couplings observed in this model are mainly between the tank and the mounting board, supports with the mounting board and PCB with the structure rods. Table 4.16 shows the conductance values for all the couplings in detail.

**Table 4.16:** Thermal couplings for the CubeProp.

**Part 1 Part 2 Conductance**

(*W/K*)

PCB Cylinder supports 1

Mounting board Cylinder support 1

Mounting board Interface PCBs 2

Mounting board Propulsion tank 0.1

Mounting board Mounting support 1

Interface PCBs Mounting supports 4

Mounting supports Structure ribs 1

PCB Rods 0.1

**4.1.9 SEUD**

The SEUD thermal model consists of the PCB and the connection stack as the main parts. The PCB is modelled as a flat plate of thickness 2*mm* and it is coupled to two separate flat boxes on the top and bottom. The connection stack is coupled with the PCB as shown in Figure 4.10. The optical properties are the same as the material used and no special coating is considered.

Table 4.17 shows the material considered for each part which is observed to be mostly copper. The thermal couplings between the parts are considered and obtained as shown in Table 4.18.

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**Figure 4.10:** Thermal Model of SEUD

**Table 4.17:** Model details for the SEUD.

**Name of the Material Number of Capacitance per**

**parts used nodes node** (*J/K*)

SEU Top part Copper 9 3

PCB Copper 9 2

SEU Bottom part Copper 9 4

Connection stack Copper 3 2

**Table 4.18:** Thermal couplings for the SEUD.

**Part 1 Part 2 Conductance**

(*W/K*)

PCB SEU Top part 5

PCB SEU Bottom part 4

PCB Connection stack 1 PCB Structure rods 0.04

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**4.1.10 MOREBAC**

The MOREBAC is a biological experiment placed below the SEUD payload in the upper stack. The thermal model of this payload is just simple two boxes of different thickness. The detailed model of the payload is not yet available as the experiment is still in its developmental stage. As a result of this, detailed information regarding the materials or optical properties used are still not available. As for the analysis, the assumption made for one of the boxes is considered to be copper where as the other one is Aluminum 6082. This assumption was merely made based on the fact that MOREBAC intends to use PCBs and a tank to store the bacterias. This design is only to get a fair idea about the temperature limits for this experiment. The thermal model of the experiment is shown in Figure 4.11. The capacitances for each of these materials are calculated based on the information assumed and can be seen from Table 4.19. The thermal couplings exist between the two boxes and one of the boxes is coupled with the structure rods for support. The values presented in Table 4.20 shows the conductances.

**Figure 4.11:** Thermal Model of MOREBAC

**Table 4.19:** Model details for the MOREBAC.

**Name of the Material Number of Capacitance per**

**parts used nodes node** (*J/K*)

MOREBAC Part 1 Copper 9 24

MOREBAC Part 2 Aluminum 6082 9 15

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