

S. KUBADE^{1*}, S. KULKARNI¹, P. DHATRAK¹

TRANSIENT THERMAL ANALYSIS OF 1U MODULAR CUBESAT BASED ON PASSIVE THERMAL CONTROL SYSTEM

Cube Satellites are miniaturized satellites used for space research with a mass of not more than 1.33 kg per unit. They are widely used in space applications because of its low cost of manufacturing and flexibility of applications. Since, they use commercial off-the-shelf components, thermal consideration of internal components of 1-unit cube satellites becomes a necessity. In this paper, transient thermal analysis of a 1-unit cube satellite is conducted to analyze its behavior during the first 29 seconds of orbit insertion from the launch vehicle. Transient thermal analysis yielded a temperature range that exceeded the optimum limit. As a result, to reduce heat dissipation, two main types of thermal management systems for satellites: active control and passive control systems are included. To maintain critical components at their operating temperature, a passive thermal control is implemented. Thermal strap and multi-layer insulation are used to analyze internal components of 1-unit cube satellite. Using graphite fiber thermal strap and aerogel multi-layer insulation for internal components, the 1-unit modular cube satellite is found to be more suitable under low earth orbit conditions.

Keywords: CubeSat; Transient thermal analysis; Passive Thermal Control; Thermal strap; MLI

1. Introduction

Cube Satellite (CubeSat) is a cube shaped satellite with a volume of 1000 cm³. Nowadays, access to space is limited and expensive. Minimizing the CubeSat's cost and making space accessible to everyone is the objective to design the CubeSat [1]. CubeSats come in several sizes such as 1unit (1U), 1.5U, 2U, 3U and 6U and the standard electronic components required for a CubeSat are frequent and affordable [2]. The standard mass of a 1U CubeSat is approximately 1.33 kg. Launch, mission lifespan, and re-entry self-destruction are the three primary operating phases regarding the thermal environment of the CubeSat [3]. CubeSats usually depend on Commercial off-the-shelf components (COTS) because of their light weight and low cost. The CubeSat mainly consist of the three main PCBs (printed circuit boards), a transceiver, two memories and a main chip [4]. There will be other components also like camera and batteries [5]. One of the satellite's most key parts, the thermal control system, ensures that the temperature stays within a specified range. Without taking thermal consideration, electronic component overheating, equipment malfunction, or mission failure will occur [2]. The main objective of the CubeSat design is to function in a challeng-

ing thermal vacuum environment in orbit while staying within its permissible temperature range. There are two types of thermal control systems namely active control and passive control [6]. The active thermal control is done by using moving fluids or mechanism, or power. This is achieved through conductive and radiative heat path involving mechanically pumped fluid or heating elements to perform heat transfer. This control is very massive, complex, and expensive [7]. Some examples are heaters, cryocoolers and thermoelectric coolers. The passive thermal control system keeps component temperatures stable without the use of powered equipment. There is no mechanical moving part, fluid, or power consumption. It is simple, low cost, more efficient and can be used in spacecrafts because of their power budget constraints, low mass requirements and less complexity to design. Some examples are thermal straps, Multi-Layer Insulation (single layer in some cases) and coatings [8].

Passive Control system includes – Multi Layer Insulation (MLI), thermal coatings, variable emittance coating, thermal strap and single layer insulation. On space missions, thermal straps are a popular passive heat transfer device that are efficient in transferring heat from the spacecraft's inaccessible areas and radiating it into space. The length and styles of thermal straps can vary

¹ DR. VISHWANATH KARAD MIT WORLD PEACE UNIVERSITY, PUNE, INDIA

* Corresponding author: sunidhikubade2@gmail.com



depending on the CubeSat requirement. They are flexible and effective thermal linkages because they are made of tiny wires of high thermal conductivity metals or foils [9]. Another viable option for thermal management is the use of Multi-Layer Insulation. A multilayer insulation is a substance made up of several insulating layers and is a simple, low-mass thermal management technique which does not consume power and is hence appealing to missions with limited power resources. It is an acceptable thermal management option for nanosatellite systems [10]. Since CubeSats have a low mass requirement, a single layer insulation can be used as a thermal control. Therefore, the aim of the present study is to analyse 1U modular CubeSat with internal components under solar radiation, albedo, earth IR and thermal radiation loading conditions using passive thermal control system.

2. Materials and Methods

In this section the 1U CubeSat and the internal components, material selection, finite element (FE) meshing, loads and boundary condition is discussed.

2.1. CAD Geometry Modelling

This section consists of CAD geometries of all components in the 1U CubeSat. A modular structure for the CubeSat's base frame is chosen as it is light weight, compact, versatile and will allow satellite designers to be more flexible during the design, development, and testing phases [7]. The model is designed based on the 1U standards of CubeSat stated by NASA. The CubeSat has dimensions of $100 \times 100 \times 100 \text{ mm}^3$. The CubeSat design was made by keeping structural stability in mind. The CubeSat panels are made of Aluminum 7075 T6 as it is light weight and has a high tensile strength. Exploded views of the CAD geometries is shown in Fig. 1.

The main PCB will be consisting of the main chip, a transceiver and two memories [4] as shown in Fig. 2(a). The materi-

als of the PCB are described in the materials section. Before mentioning the materials of these components, it is important to understand the functions of these. The main chip receives or transmits signals. It is like an artificial brain controlling operations and mathematical calculations. The transceiver converts electrical signals to light signals and vice versa and the memories are used to store images and information [11]. As displayed in Fig. 2(b), four rods have been used to support the PCBs and each rod consists of a threaded rod and a hollow spacer [4]. The battery is made up of four lithium-ion cells as shown in Fig. 2(c), that have built-in heaters and temperature sensors to regulate the thermal constraints in space. The batteries are mounted on the PCB board in Fig. 2(d). Aluminum 6082 is used in these batteries for mechanical and thermal stability. Batteries are known to be the most sensitive and critical component of the satellite's thermal design and therefore care must be taken during charging and discharging processes. In Fig. 2(e) the Raspberry Pi camera to be used is displayed. The camera is attached on the PCB as illustrated in Fig. 2(f). It is used to capture and reconstruct high-resolution images from the CubeSat. High Dynamic Range (HDR) techniques is used to capture the images [5].

2.2. FEA Meshing

The basic idea of meshing is to make calculations at finite number of points and then interpolate the results for the entire domain-surface or volume. Finite element method reduces the degree of freedom from infinite to finite with the help of discretization or meshing (nodes and elements) [12,13]. For a 1U CubeSat the approximate number of elements required is estimated. To perform the numerical simulation, a quadratic 2D element is used to model the CubeSat frame with average element size of 2 mm whereas the internal components has been modeled with linear quadrilateral element with average size of 1 mm. The mesh properties utilized for the CubeSat components are listed in TABLE 1.

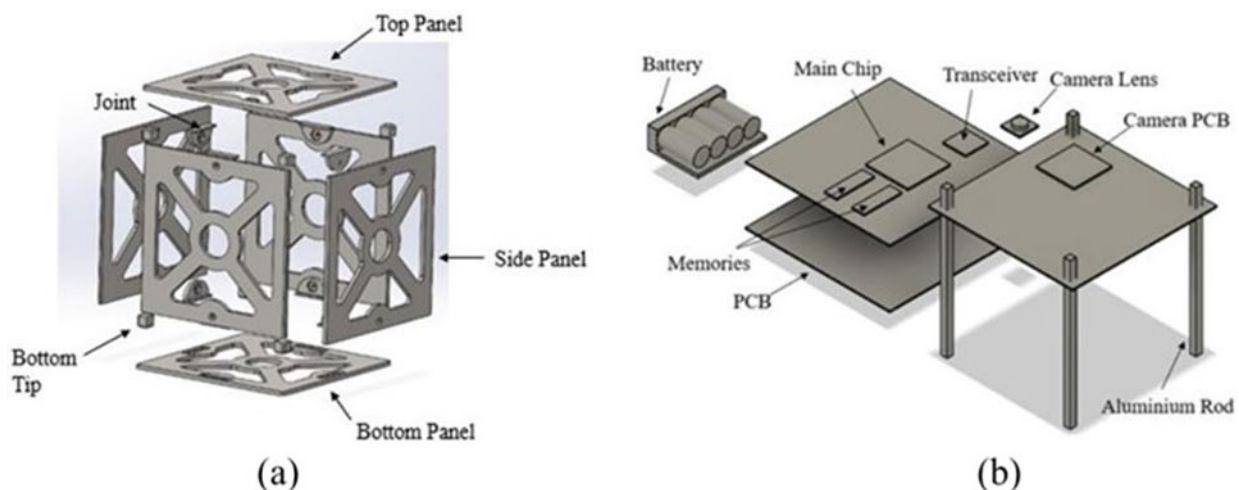


Fig. 1. (a) Exploded CAD model of 1U CubeSat (b) Exploded view of Internal Components of 1U CubeSat

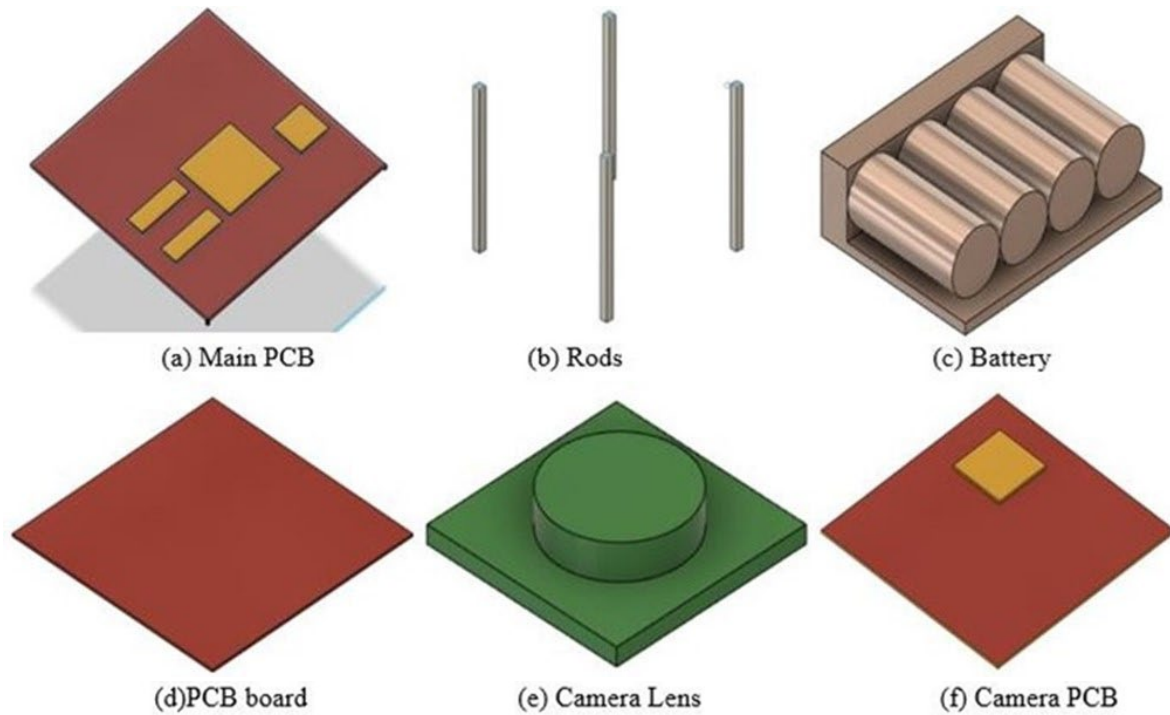


Fig. 2. Internal Components of the 1U CubeSat Model

TABLE 1

Mesh properties of the components of the CubeSat

Sr No.	Components of CubeSat	Element size (mm)	Min. Edge Length (mm)	Avg Surface Area (mm ²)	Number of Elements	Number of Nodes
1	Battery	0.5	2	389.71	76965	273915
2	Camera lens	0.5	1	43.787	2810	14879
3	Main PCB	0.5	1	720.54	88913	167685
4	Rods	1	4	261.33	6144	34820
5	Base frame	2	0.9	142.89	66477	136289
6	Thermal strap	2	95	7760	9604	68208
7	Insulation	2	1.5	1403.4	12480	69909
8	CubeSat	2	0.9	142.89	66477	136289

2.3. Material Properties

Three major PCBs have been modelled for the internal stack. These PCBs are made up of ten layers of Cu-Pure. These layers are stacked inside an FR-4 substrate giving a total thickness of 1.6 mm. All the rods are made up of Aluminum 6082 [4]. There are four lithium-ion cells attached to the PCB which are made up of Aluminum 6082 [5]. In the table below, the various materials for the internal components are listed.

2.4. Thermal Control

The maximum suggested operational temperature for most electrical components is 80°C. Above this value, the component's efficiency begins to decline until it reaches the maximum survival temperature, which is around 120°C. As a result, the goal is to keep all components below the maximum operational temperature and never exceed the survival temperature of 120°C [4]. Operating range of each component is listed in TABLE 3.

TABLE 2

Materials used for the internal components of the CubeSat

Internal components	Material used	Density (kg/m ³)	Conductivity (W/mK)	SpecificHeat (J/kg K)	Emissivity values
Camera PCB	Copper	8933	287.6	195	0.03
Camera lens	Aluminium 6082	2710	180	900	0.09
Battery	Aluminium 6082	2710	180	900	0.09
Main PCB	FR4 substrate	1850	0.35	1300	0.9
Rods	Aluminium 6082	2710	180	900	0.09

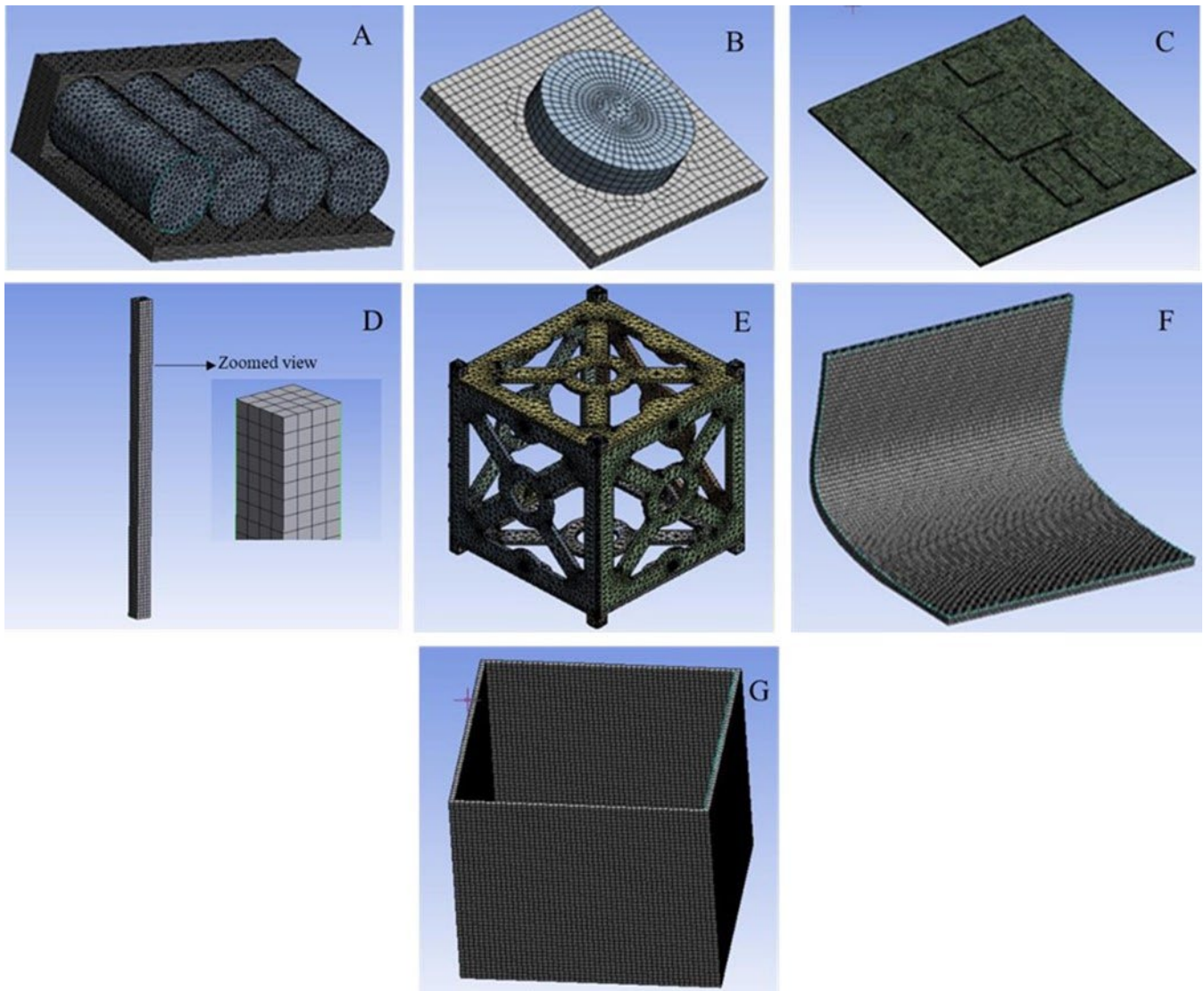


Fig. 3. 2D Meshed Models of (A) Battery (B) Camera lens (C) Main PCB (D) Rods (E) Base frame (F) Thermal strap (G) Insulation

TABLE 3
Operating temperatures of internal components
of the CubeSat [1,3,5]

Components of CubeSat	Minimum Temperature (°C)	Maximum Temperature (°C)
Main PCB-FR4 substrate	-50	110
Main PCB-Copper	0	150
Camera	0	70
Battery	-20	60
Rods	-20	60

Throughout the satellite mission, the thermal control system aims to maintain all components within their permissible temperature ranges. Every component must perform as expected from start to finish throughout its lifetime [14]. There have been plenty of space missions in which spacecraft is exposed to a wide range of thermal environments. There are several instances of these missions. Two spacecrafts involved in the joint ESA-JAXA mission to Mercury are subjected to extraordinarily intense solar radiation. The most challenging thermal condition is ultimately

being experienced by NASA's Parker Solar Probe, which is passing directly through the Sun's atmosphere. Explorations to the limit of our solar system, such as Pluto, which receives less than 0.1% of Earth's solar energy, would be accompanied with additional difficulties [15].

Small-scale satellites utilize passive thermal control systems more frequently due to their affordability, lack of additional power requirements, simplicity of usage, and better thermal performance. Passive thermal control systems include various options such as thermal straps, MLI (or in some cases a single layer insulation) and coatings. In this study thermal strap and Single layer Insulation have been implemented. Due to its reflective and absorbing qualities, multi-layer insulation (MLI) blankets are recommended for space applications since they help the spacecraft in preventing any form of radiation [16]. Thermal straps are passive heat transfer devices that are frequently used on space missions to conduct the heat from inaccessible regions of the spacecraft and radiate into space. MLI, however, generally does not perform well on small satellite platforms because the efficiency of MLI decreases as the size decreases as heat transfer

at the blanket edges increases. Hence, single layer insulation made up of aerogel is used for this paper. Aerogel withstands temperatures up to 593°C (1100°F). The lightweight nature of Aerogel makes it perfect for use with extremely delicate and fragile components. Thermal strap is selected as the CubeSat's insulation because it is available in a variety of shapes and lengths based on the demand [9]. Thermal straps are well suited for small scale satellites. Graphite fibre is chosen as the material for the thermal strap as it is exceptionally stable at temperatures below 2000°C, thereby making it ideal and safe for use in space.

In the present study, thermal strap is used for internal components whereas single layer insulation is used for CubeSat structure as shown in Fig. 4.

2.5. Loads and Boundary Conditions

2.5.1. Initial Conditions

Time Period of 29 seconds varying from 25°C to -20°C is considered for Transient thermal analysis of the 1U CubeSat. This time is considered as it is the approximate time the 1U CubeSat requires for orbit insertion after being launched by the P-POD [17].

2.5.2. Solar Radiation

The amount of solar energy per unit area on a sphere centered at the Sun with a distance d is shown in equation (1)

$$J_s = \frac{P}{4\pi d^2} \quad (1)$$

Where P is the power output of the sun when the object receives the radiation. In this case the satellite is situated 1 AU away from the sun ($1 \text{ AU} = 1.496 \times 10^{11}$). The power output then is equivalent to 3.856×10^{26} Watts [18]. Using equation 1, the mean value of solar radiation is taken to be $1371.08372 \pm 5 \text{ W/m}^2$.

2.5.3. Albedo

The albedo, which is measured in percent of the solar flux and is highly variable, is the quantity of sunlight that is reflected to the spacecraft from the Earth. It is a function of climate state and has a significant impact on the Earth's climate [19]. The planetary albedo is the percentage of incoming solar radiation that Earth scatters back into space. The processes that control its amplitude, distribution, and unpredictability have an impact on Earth's climate and its ability to change since this reflected energy is a crucial part of the planet's energy balance [20]. The albedo radiation is determined by atmospheric properties, a visibility factor, and the planetary albedo, which is the percentage of solar radiation reflected on the space body [18]. The albedo radiation is calculated (480 W/m^2) using equation (2)

$$J_a = J_s * F * a \quad (2)$$

Where J_a is albedo radiation, J_s is Solar radiation, F is visibility factor and a is albedo percentage [21].

2.5.4. Earth Infrared Radiation (IR)

The Earth's surface absorbs and re-emits the light, which is not reflected as albedo, this incident light is known as Earth IR. The planetary far infrared emission is the third radiant heat source for a satellite, particularly those in low earth orbit, or LEO. The earth absorbs some light and re-radiates it as infrared rays. The earth is a 290K heat source that provides far infrared heating. A total value of 239 W/m^2 has been considered [22].

2.5.5. Thermal Radiation

Radiation is the heat transfer that occurs in the form of electromagnetic waves between two or more surfaces through space. Every material emits some heat, and the amount depends on the emissivity of the material. The TABLE 2 mentions the emissivity values of each material used in the 1U CubeSat.

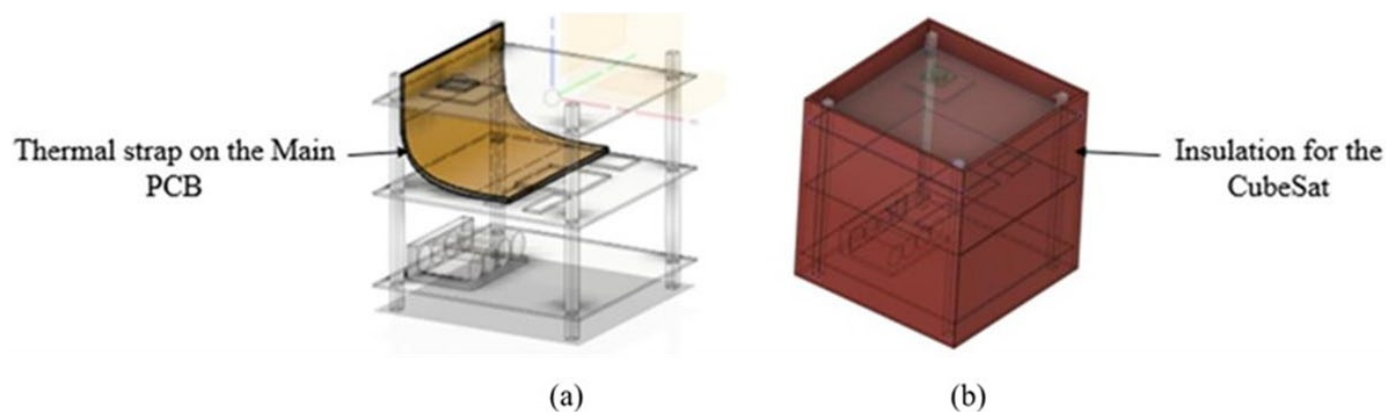


Fig. 4. (a) Thermal strap on internal components (b) Single layer insulation on 1U CubeSat Structure

3. Results and Discussion

André G.C. Guerra et al. [4] conducted a thermal analysis on a 1U CubeSat 90 minutes after its launch. The temperature range obtained was from 45.3°C to 103°C. It was observed that the amplifier heated up the most so a thermal strap was used to radiate the heat. Thermal analysis was also conducted on only the thermal strap whose temperature range was from 46.0°C to 60.8°C. In this study initial 29 seconds post launch is considered for the analysis and a thermal range of 50.20°C to 106.6°C is obtained. It is observed that the PCB panel and its components (memories, transceiver, and main chip) heat up to around 90°C. After using a thermal strap, the temperature range of the PCB components reduces to 47.31°C. Therefore, it is concluded that after the usage of the thermal strap, all the electronic components do not exceed the operational limit. S. Selvadurai et al. [9] have listed viable passive thermal control design methods for nanosatellites and discussed about thermal straps and multi-layer insulation. In this study a detailed transient thermal analysis is performed on the two potential passive thermal control methods.

Gabriel Salazar-Salinas et al. [16] have carried out a study on two types of passive thermal control methods: SLI and coatings. The degradation of the surface paint caused by ultraviolet radiation and atomic oxygen is an important consideration when using thermal paints. Insulation systems have a longer service life than paints and coatings due to the type of material and optical properties. Therefore, in this study, SLI has been used as a passive thermal control. As a result, the overall temperature of the CubeSat reduces by 20.7°C.

Transient thermal analysis is performed for the initial 29 seconds the CubeSat takes for orbit insertion after being launched from the P-POD (Poly-Picosatellite Orbital Deployer). This analysis was conducted on the following models to determine an appropriate operating temperature range for base frame, internal components of the 1U CubeSat, thermal strap, and single layer insulation. Fig. 5(A) displays the transient thermal analysis of the entire CubeSat structure without any internal components. The temperature range attained for the CubeSat frame is from 41.86°C to 44.29°C which is within the acceptable limit. According to the results as shown in Fig. 5(B) the operat-

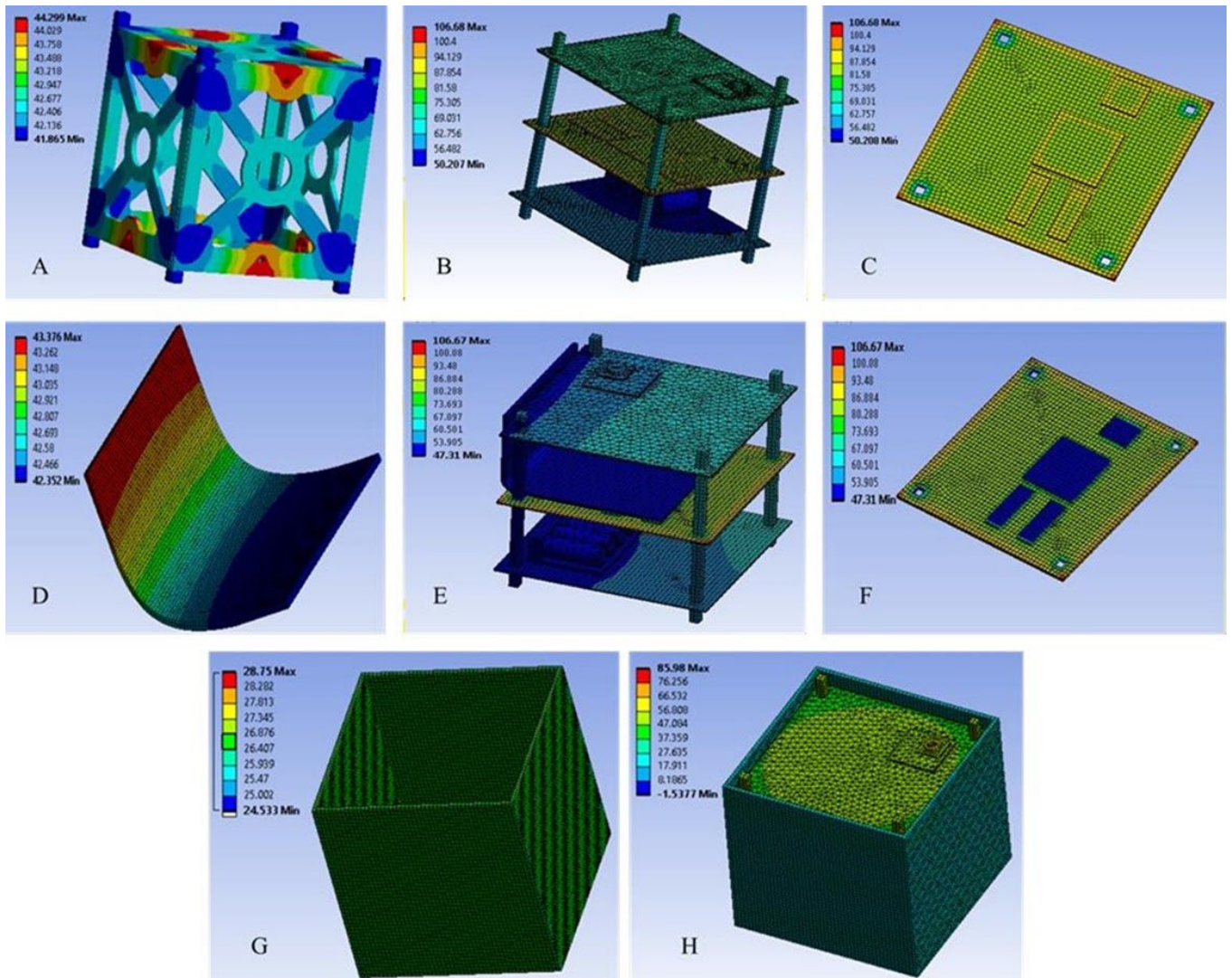


Fig. 5. Transient Thermal Results of (A) Base frame (B) Internal components (C) Main PCB without thermal strap (D) Thermal strap (E) Internal components with thermal strap (F) Main PCB with thermal strap (G) SLI (H) Internal components with SLI

ing temperature of the internal components of the 1U modular CubeSat is from 50.20°C to 106.68°C. The internal components consist of the three PCBs, main chip, transceiver, camera, batteries, and memories out of which the main PCB heats up the most. Therefore, the main PCB is considered for further analysis. The operating temperature of the main PCB components (around 90°C) is depicted in Fig. 5(C). Since the operating temperature of most electronic components does not exceed 80°C [4], hence, a thermal strap made up of graphite fibre is mounted on the main PCB which consists of a main chip, transceiver and memories as shown in Fig. 5(D). The analysis revealed that the temperature range attained under space conditions is 42.35°C to 43.37°C. Fig. 5(E) indicates the thermal strap attached on the electronic components. After applying the thermal strap, the temperature range of the PCB components reduces to 47.31°C as displayed in Fig. 5(F), which is sufficiently below the operational temperature limit. SLI is also analyzed as a passive thermal control method to cover the internal components and the material used for SLI is aerogel. For SLI the range obtained is 24.53°C to 28.75°C denoted in Fig. 5(G). The temperature range obtained after applying SLI on internal components is from -1.53°C to 85.98°C as displayed in Fig. 5(H). Therefore, it is concluded that after applying the graphite fibre thermal strap the main PCB components temperature is significantly reduced by 52.9% (40°C) whereas aerogel based SLI shows a temperature reduction of 19.4% (20.7°C).

Since the overall temperature of the internal components reaches 106.68°C which is close to the survival temperature of most electronic components (120°C). Therefore, passive thermal control system is used so that the 1U modular CubeSat can function properly within the survivable limit. Thermal strap and SLI are two passive thermal control systems analyzed. The main PCB attained a temperature of around 40°C after applying the thermal strap which is within its operational limit. Therefore, the 1U modular CubeSat is found to be safe under low earth orbit conditions.

Fig. 6 shows the relation between temperature and time for the thermal strap and single layer insulation, considering the initial 29 seconds of orbit insertion from the launch vehicle.

Fig. 6(a) depicts a graphical representation of how the thermal strap's temperature varies over time. Similarly, Fig. 6(b) indicates the behavior of SLI over time.

4. Conclusion

Transient thermal analysis was conducted on a 1U Modular CubeSat to examine the various possible solutions for thermal control which would satisfy the requirement for a CubeSat mission in the low earth orbit. The approximate time a CubeSat takes to enter the low earth orbit after being launched from the P-POD (Poly-Picosatellite Orbital Deployer) is considered for transient condition. MLI (Multi-Layer Insulation) and thermal strap are the two viable options used for passive thermal management system. Using graphite fibre thermal strap and aerogel SLI for internal components, the 1U modular CubeSat is found to be appropriate under low earth orbit conditions.

Acknowledgement

The author(s) received no financial support for the research, authorship, and/or publication of this article.

REFERENCES

- [1] S.J. Kang, H.U. Oh, On-orbit thermal design and validation of 1U standardized CubeSat of STEP cube lab, *International Journal of Aerospace Engineering* **2016**, (1-17) (2016). DOI: <https://doi.org/10.1155/2016/4213189>
- [2] J.R. Wertz, W.J. Larson, *Space mission analysis and design*, Microcosm Press and Kluwer Academic Publishers (3rd ed.) (1999).
- [3] N. Athirah, M. Afendi, K. Hafizan, N.A.M. Amin, M.S.A. Majid, Stress and thermal analysis of cubesat structure, *Applied Mechanics and Materials* **554**, (426-430) (2014). DOI: <https://doi.org/10.4028/www.scientific.net/AMM.554.426>

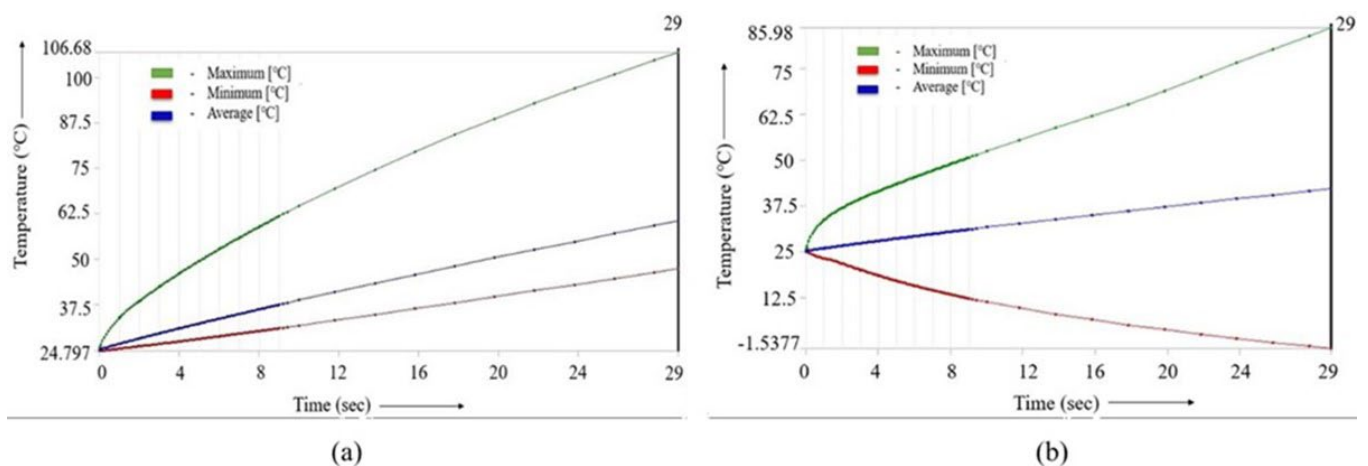


Fig. 6. Temperature vs. Time Graph of (a) Internal components with Thermal Strap (b) Internal components with SLI

- [4] A. Gomes, C. Guerra, Design, Thermal analysis and integration of small satellites with a network of autonomous vehicles, Faculty of Sciences of the University of Porto (2018).
- [5] S. Chandrashekar, T. Karlsson, Thermal Analysis and Control of MIST CubeSat, Master Thesis, KTH Royal Institute of Technology, Sweden (2017).
- [6] J.P. Mason, B. Lamprecht, T.N. Woods, C. Downs, CubeSat on-orbit temperature comparison to thermal-balance-tuned-model predictions, *Journal of Thermophysics and Heat Transfer* **32**, 1, (237-255) (2018).
DOI: <https://doi.org/10.2514/1.T5169>
- [7] H.H. Nguyen, P.S. Nguyen, Communication Subsystems for Satellite Design, *Satellite Systems – Design, Modeling, Simulation and Analysis*, IntechOpen (2021).
DOI: <https://doi.org/10.5772/intechopen.73789>
- [8] <https://www.nasa.gov/smallsat-institute/sst-soa-2020>
- [9] S. Selvadurai, A. Chandran, D. Valentini, B. Lamprecht, Passive Thermal Control Design Methods, Analysis, Comparison, and Evaluation for Micro and Nanosatellites Carrying Infrared Imager, *Applied Sciences* **12**, 6, (2022).
DOI: <https://doi.org/10.3390/app12062858>
- [10] A. Rossi, Thermal Management Methods of Nanosatellites, *International Journal of Engineering and Technical Research* **2**, 10, (82-85) (2014).
- [11] S. Waydo, D. Henry, M. Campbell, CubeSat Design for LEO-Based Earth Science Missions, *IEEE Aerospace Conference Proceedings 1* (1-11) (2002).
DOI: <https://doi.org/10.1109/AERO.2002.1036863>
- [12] N.S. Gokhale, S.S. Deshpande, S.V. Bedekar, A.N. Thite, Meshing, in: *Practical Finite Element Analysis (1st ed.)*, Finite to Infinite, (2018).
- [13] C.E. Lopez, G.S. Jacobson, J.N. Peters, N.A. Bograd, P.J. Kroyak, Worcester Polytechnic Institute, Design and Analysis for CubeSat Missions, (2018).
- [14] M. Bulut, A. Kahrman, N. Sozbir, Design and Analysis for Thermal Control System of Nanosatellite, *Proceedings of the ASME 2010 International Mechanical Engineering Congress & Exposition IMECE2010 (1-4)* (2010).
DOI: <https://doi.org/10.1115/IMECE2010-39716>
- [15] S. Tachikawa, H. Nagano, A. Ohnishi, Y. Nagasaka, Advanced Passive Thermal Control Materials and Devices for Spacecraft: A Review, *International Journal of Thermophysics* **43**, 6, (2022).
DOI: <https://doi.org/10.1007/s10765-022-03010-3>
- [16] G.S. Salinas, E.B. Ramírez, E.A. Gauna, Thermal Analysis of a 3U-Cubesat, a Case Study of Pakal Satellite, *Proceedings of the 8th International Conference on Fluid Flow, Heat and Mass Transfer (FFHMT'21)* (137-144) (2021).
DOI: <https://doi.org/10.11159/ffhmt21.137>
- [17] R. Seetharaman, A. Singh, R.S. Sumit, J. Krishnaprasad, S. Nazim, G. Watts, Modal, Static Structural and Transient Thermal Analysis Of A Standard 1u Cubesat, *Birla Institute of Technology and Science Pilani* (2019).
DOI: <https://doi.org/10.13140/RG.2.2.34054.52805>
- [18] J. Carlos, C. Ortega, N. Saraí, M. Sisniega, U.A. Mendoza, R.O. Rivas, Analysis of the temperature of a 1U CubeSat due to radiation in space, *The 2017 World Congress on Advances in Structural Engineering and Mechanics (ASEM17)* (1-10) (2017).
- [19] A. Donohoe, D.S. Battisti, Atmospheric and surface contributions to planetary albedo, *Journal of Climate* **24**, 16, (4402-4418) (2011).
DOI: <https://doi.org/10.1175/2011JCLI3946.1>
- [20] G.L. Stephens, D. O'Brien, P.J. Webster, P. Pilewski, S. Kato, J.L. Li, The albedo of earth, *Reviews of Geophysics* **53**, 1, (141-163) (2015).
DOI: <https://doi.org/10.1002/2014RG000449>
- [21] <https://spaceplace.nasa.gov/what-powers-a-spacecraft/en/>
- [22] S. Corpino, M. Caldera, F. Nichele, M. Masoero, N. Viola, Thermal design and analysis of a nanosatellite in low earth orbit, *Acta Astronautica* **115**, (247-261) (2015).
DOI: <https://doi.org/10.1016/j.actaastro.2015.05.012>