Preliminary Thermal Design of Micro-satellites Deployed from Japan Experimental Module Small Satellite Orbital Deployer

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Introduction

Thermal design guarantees a spacecraft’s survivability and functionality under extreme thermal environment conditions during its mission. However, for micro- and nano-satellites this is a big challenge because of low heat capacities resulting to a drastic fluctuation in temperature of the whole structure and some of its onboard components while on-orbit. In addition, many of these satellites are only equipped with body-mounted solar cells implying that electric power to control the temperature of all critical components actively may be insufficient. Thus, due to such limitations, passive thermal control is the most feasible approach to satisfy the thermal requirements of 0-40°C for internal components, and -20 to 60°C for external components.

Passive thermal control may be achieved through variation of absorptivity and emissivity of structures and components, manipulation of thermal conductance values between structures and/or components by using material inserts, and application of multilayer insulation (MLI) to certain parts of the satellite.

In this paper, a thermal design for micro-satellites deployed from the International Space Station through Japan Aerospace Agency’s (JAXA) JEM Small Satellite Orbital Deployer (J-SSOD) was done by implementing a design concept, based on the proposed procedure by Totani et. al [1]. However, unlike conventional 50-kg cubic micro-satellites deployed in space through piggyback, the satellite is rectangular and follows an ISS-like orbit with an orbit beta angle varying per day as shown in Figure 1.

![Figure 1. Beta angle history of International Space Station from January to July 2015](image)

The primary goal is to list down all combinations of optical properties for outer panel surfaces, emissivity of the inner surface of the outer panel, and emissivity of inner panel surfaces satisfying set thermal design requirements despite the satellite being subjected to extreme thermal environments in space.

Satellite Structure and Internal Layout

Three internal configurations for a micro-satellite with dimensions of 55 cm x 35 cm x 55 cm were considered. These are 1 Internal Panel, 2 Internal Panels: T-type, and 3 Internal Panels. Node IDs given to each panel are shown in Figure 2. Node 1 was allocated to the +Z Panel which is nadir-pointing.

![Figure 2. Schematic of three most common internal configurations for micro-satellites: (a) 1 Internal Panel; (b) 2 Internal Panels: T-type; (c) 3 Internal Panels along with the corresponding node ID for each panel.](image)

As all panels were assumed to be made of 5052 aluminum alloy with a specific heat of 879 J/kg·K. The outer structure and inner structure was assumed to have a total mass of 15 kg and 35 kg, respectively. Each panel has a thickness of 10 mm except for Node 9 in the 3 Internal Panel case where the thickness was set to 20 mm.

Analysis Method

A simplified design lead to a simplified analysis with small number of nodes, and reduction in development costs and time. By utilizing a simplified design and applying simple thermal design concepts, nodal analyses were carried out. The temperature of each node was calculated for 32 orbits using a tool created in MATLAB. These temperatures were then cross-checked with the defined temperature limit. A list of possible combinations of optical properties that satisfies this design requirement are outputted in .txt file which may be used in determining the possible coating and surface
finishes applied to the spacecraft. The main advantage of such method is faster calculation time even with varying parameters. A flowchart of the analyses carried out in MATLAB is shown in Figure 3. Multi-nodal analysis using Thermal Desktop, one of the popular commercially-available software, was then performed to verify the results.

Space Environment Heat Flux

The net heat rate from the environment is expressed as

\[ Q_{\text{ext}} = G_s \alpha_O A_p + G_s \alpha_O A_f + q_{\text{IR}} + q_{\text{IR}} \epsilon_{\text{Fsc}} - \sigma T_0^4 A_s \]  

(1)

The first term on the right-hand side of the equation above describes the direct solar radiation absorbed by the satellite. Meanwhile, the second and the third term indicates the energy absorbed by the satellite due to albedo and infrared radiation emitted from the Earth’s surface, respectively. Lastly, the fourth term denotes the energy released by the satellite to space.

The environmental heat fluxes applied to Eq. (1) are summarized in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Worst case conditions used in analyses [2,3]</th>
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</thead>
<tbody>
<tr>
<td><strong>Worst Cold</strong></td>
</tr>
<tr>
<td>Direct Solar, W/m²</td>
</tr>
<tr>
<td>Earth IR, W/m²</td>
</tr>
<tr>
<td>Albedo</td>
</tr>
<tr>
<td>Inclination, deg</td>
</tr>
<tr>
<td>Right Ascension of Ascending Node, deg</td>
</tr>
<tr>
<td>Argument of Perigee, deg</td>
</tr>
<tr>
<td>Beta angle, deg</td>
</tr>
<tr>
<td>Initial Temperature, °C</td>
</tr>
<tr>
<td>Internal Heat Dissipation, W</td>
</tr>
</tbody>
</table>

Heat Transfer between Structures

The heat transfer between the inner and outer structures consists of thermal conduction and radiation. Radiative and conductive heat transfer rates [4] are expressed by the general equations below.

\[ Q_{\text{rad}} = \sum \sigma (T_i^4 - T_j^4) \]

(2)

\[ Q_{\text{cond}} = \sum k_{ij} A_{ij} (T_i - T_j) \]

(3)

In the simplified analyses, component shapes were not considered. The internal configuration factor from panel to panel were calculated using form factors between identical, parallel and directly opposite plates, and plates with a common edge [5]. On the other hand, for Thermal Desktop, radiation view factors are numerically calculated.
The absorptivity ($\alpha_O$) and emissivity ($\varepsilon_O$) of the outer panel surfaces were calculated as:

$$\alpha_O = (1 - \rho_{sc}) \alpha_R + \rho_{sc} \alpha_{sc} \tag{4}$$

$$\varepsilon_O = (1 - \rho_{sc}) \varepsilon_R + \rho_{sc} \varepsilon_{sc} \tag{5}$$

where $\rho_{sc}$ is the filling factor.

Values calculated were then applied to all external surfaces of outer panels except $+Z$ panel. It was assumed that no solar cells were mounted on the $+Z$ or the nadir-pointing panel. Thus, the $\rho_{sc}$ of $+Z$ panel was 0. In effect, $\alpha_O = \alpha_R$ and $\varepsilon_O = \varepsilon_R$. Moreover, $\varepsilon_{O,I}$ was assigned to the inner surface of all outer panels. Whereas, $\varepsilon_I$ was employed to the inner panel. $\Delta\alpha_R$ and $\Delta\varepsilon_R$ were set to 0.01 in the calculations. Meanwhile, an interval of 0.1 were set for both $\varepsilon_{O,I}$ and $\varepsilon_I$.

1 Internal Panel

Figure 6 displays all the combinations that satisfied the design temperature range for a 1 Internal Panel configuration with an internal heat dissipation of 15W during worst cold and 25W during worst hot.

To check the results yielded from the MATLAB program, three points from Figure 6 were selected. Transient temperature history of all three points during worst cold and worst hot cases are summarized in Figure 7. As anticipated, Combination 2 was within the design limits. Whereas, Combinations 1 and 3 didn’t satisfy the upper and lower limit, respectively.

Comparison between three configurations

Figure 8. Comparison of results between three internal configurations.

All three results were combined in Figure 8 to display the difference in combinations visually. From the figure, more combinations were observed for the 1 Internal Panel Configuration.

Figure 9. Internal node temperatures on selected point from Figure 8 for each configuration.

In addition, by choosing one point from Figure 8 and calculating the internal temperatures for each configuration, a decrease in the temperatures as observed in Figure 9. Intensified heat exchange between the panels both conductively and radiatively greatly contribute to this decrease. For conductive heat transfer, more internal panels lead to more connections between the internal and external structure. Whereas for radiative heat transfer, as the number of internal panel increases, total net heat transfer between inner and outer structure
increases. This hypothesis can be proven by calculating and comparing $Z$ value derived from Eq. (2), which includes the net heat transfer leaving the surface and heat exchange between inner and outer structure, for each configuration’s internal panels.

$$Z = \sum_{i=1}^{n} \frac{1}{A_i} \left( \frac{1}{\varepsilon_i} + \frac{1}{\varepsilon_j \eta_i} \right)$$

(6)

The $Z$ values for each configuration is summarized in Table 2. As expected, higher $Z$ values are acquired as the number of internal panel increases implying a higher effective $Q_{IO}$.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$Z$ Values</th>
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<tbody>
<tr>
<td>1 Internal Panel</td>
<td>6.533x10^{-3}</td>
</tr>
<tr>
<td>2 Internal Panels: T-type</td>
<td>8.032x10^{-3}</td>
</tr>
<tr>
<td>3 Internal Panels</td>
<td>1.094x10^{-2}</td>
</tr>
</tbody>
</table>

Comparison with a cubic-shaped satellite

Finally, a list of combinations for a cubic-shaped micro-satellite with a 1 Internal Panel configuration was also generated.

Figure 10. Optical property combinations for a cubic-shaped satellite with 1 Internal Panel configuration when internal heat dissipation of 15 W and 25 W was set for cold and hot case, respectively.

Comparison between Figure 6 and Figure 10 shows that a cubic-shaped satellite has a larger range of values for both absorptivity and emissivity compared to a satellite with dimensions of 35 cm x 55 cm x 55 cm. Thus, a micro-satellite deployed from J-SSOD is more difficult to design thermally as compared to a 50-cm cubic-shaped micro-satellite. Also, it may be concluded that shape plays a vital factor in the design.

Conclusion

Passive thermal control for satellites, deployed from the International Space Station through Japan Aerospace Agency’s (JAXA) JEM Small Satellite Orbital Deployer, by determining all possible combinations of optical properties was carried out. Three most common internal configurations were considered. The possible combinations were listed down through a tool created using MATLAB.

Input parameters necessary were orbital elements for the two worst conditions, satellite dimensions and internal configuration, and material properties. As observed in the results, each configuration had a unique set of combinations. The difference in the number of combinations was mainly influenced by both radiation and conduction heat transfer. It was found out that there are more combinations for a 1 Internal Panel configuration as compared to other internal configurations. In addition, a wider range of absorptivity and emissivity values were noticed for a cubic-shaped micro-satellite as opposed to a micro-satellite with dimensions of 35 cm x 55 cm x 55 cm. This clearly tells us that shape and/or dimensions of a satellite is significant in thermal design. Finally, the results were verified and validated using the commercial software Thermal Desktop.

References


