Analysis of Thermal Systems of In-Atmosphere CubeSat Structures

Ryan James Morse

Follow this and additional works at: https://louis.uah.edu/honors-capstones

Recommended Citation
https://louis.uah.edu/honors-capstones/151

This Thesis is brought to you for free and open access by the Honors College at LOUIS. It has been accepted for inclusion in Honors Capstone Projects and Theses by an authorized administrator of LOUIS.
Analysis of Thermal Systems of
In-Atmosphere CubeSat Structures

By
Ryan James Morse
An Honors Capstone
Submitted in partial fulfillment of the requirements
For the Honors Diploma
To
The Honors College
of
The University of Alabama in Huntsville
4/28/15
Honors Capstone Directors:
Professor Matthew Turner
Principal Research Engineer
Dr. Phillip A. Farrington
Professor of Industrial and Systems Engineering and Engineering Management

Ryan Morse 4/30/15
Student  Date

4/30/15

4/30/15

4/30/15

4/29/15

4/30/15
# Table of Contents

Abstract ......................................................................................................................... 2  

Introduction .................................................................................................................. 3  

Chapter One .................................................................................................................. 4  

Chapter Two ............................................................................................................... 11  

Conclusion ................................................................................................................. 20  

Bibliography ............................................................................................................... 22  

Appendix ..................................................................................................................... 23
Abstract

This design project explored the thermal properties and thermal integrity of a CubeSat structure launched in a weather balloon for MAE 492 Mission Design and Development. Major hardware components held a minimal operating temperature of approximately -10°C. This requirement had to be maintained while the Cubesat moves through zones with ambient temperatures of approximately -60°C. The hardware elements had to be insulated and heated to keep within operating temperatures.

The effectiveness of insulators and the placement of heaters were used as objectives in the development of a Matlab Program. This program evaluated and visualized heat losses in the system through Finite Element Analysis and Finite Volume Modeling. Matlab was chosen to allow production of a hands-on model, as opposed to using a premade Finite Element Analysis tool.

The result of the project was an output of three-dimensional meshes of the internal temperatures, which could be iterated to show the effect of differing heater placement. This output mesh developed optimized placements for internal temperatures. Future CubeSat missions through the Integrated Product Team may use this Matlab code for thermal design analysis.
Introduction

A CubeSat Structure is defined by the California Polytechnic State University in their CubeSat Design Specification (Mehrparvar 2014) that was made available to the MAE 492 Integrated Product Teams (IPT) by Professors Turner and Farrington. These professors tasked the IPTs with two assignments that made heavy use of the CubeSat Structure. The first assignment, developed by the Space and Missile Defense Command (SMDC), was to integrate a Nexus 5 smartphone into a CubeSat, demonstrating the phone’s camera as a potential telescope. The second assignment was developed by the College of Charleston, who tasked the IPT with utilizing air sensors in lowly populated regions to build a baseline reading of multiple gases in the atmosphere.

To satisfy all components of this mission, the IPT designed and created a CubeSat structures that would be tested by being flown on a weather balloon in the low-atmosphere. While there were many available potential topics for an Honor’s thesis, the most pressing matter for this class was the internal temperature of the structure during the mission. The external air temperature of the weather balloon flight had been expected to reach temperatures of -60 °C, while the sensors and other electronics of the mission had minimal operating temperatures in the range of 0 °C to -10 °C.

To develop the internal thermal integrity of the IPT project, an in-depth investigation into heat losses was required. It was found that the best method for approaching such a task was through Finite Volume Modeling (FVM), an engineering tool that uses boundary layer effects to develop models (Peiro and Sherwin 2005). To allow the author to understand the process of an FVM and thermal systems better, a Matlab program was developed, independent of existing Finite Analysis tools.
Chapter One

Payload Development

The first developed layout of the structure, shown in Figure 1, has the CubeSat separated into two sides. This 10x10x30cm³ box is divided into a larger heated side and a smaller non-heated side. The larger side contains the Nexus 5 smartphone, an Arduino Uno, and a rechargeable hand warmer. The smaller side contained the gas sensors that would be used for the College of Charleston mission. The choice of separating the two sides was made to minimalize heat losses that the airflow around the sensors would cause.

![Figure 1: Initial CubeSat Structure](image)

The CubeSat structure was modified over time. It was found that the internal design of the structure was in need of major changes. The two-side strategy did not consider the effect of the low temperatures on the surface of the printed circuit boards (PCBs) of the sensors. The new design made use of a gas hood, shown in Figure 2, which would provide the airflow directly to the gas sensor faces while keeping the printed circuit boards inside the safe air pocket.
The fully implemented CubeSat Structure is shown in Figure 3. The structure is exposed to show the easily assembled locking wall pieces and the locations of internal hardware. The heater is connected to the bottom side of the Arduino in this model, against the wall. The left side of the CubeSat contained the gas hood and the four sensors. These two sections interlocked to make the full structure. The only connection to outside air were through the main structural walls and the gas hood.
Design Testing

There were multiple stages of testing in the development of the CubeSat structure. Shown below in Figure 4 is the process of testing accomplished by the IPT. Each test is defined by the structure used, the test environment, and the thermal insulation that was tested. Initial testing allowed the IPT to gain an understanding of the thermal challenges this mission posed.

Figure 4: Testing Stages

The first test used a small structure to investigate the properties of the Polylactic Acid (PLA) plastic used by the 3D printer supplied to the IPT. The structure was wrapped in three layers of Pella Smartflash Insulation Tape. This test doused the structure with liquid nitrogen, reaching an external temperature of -80°C. Both the internal and external air temperatures were
recorded over time, as shown in Figure 5. The internal temperature fell to -37.5°C in 3 minutes and 22 seconds while the external temperature moved from the room temperature of 25.5°C to -80°C. It only took 1 minute and 24 seconds to break the restriction of -10°C. This was unacceptable, as the weather balloon flight was expected to last from an hour and a half to two hours. This test was used in the IPT’s early presentation to show progress in developing proper thermal care for the final mission.

Figure 5: Nitrogen Testing

The second phase of testing used the fully developed CubeSat structure. This test was to continue the investigation of the PLA plastic and the thermal tape, now with the inclusion of a rechargeable heater. This test was part of a true weather balloon launch that measured the
temperature inside the large and small sections separately as well as the outside air temperature as the project traveled, shown in Figure 6. As expected from the results of the nitrogen testing, the thermal tape was found to be insufficient as an insulator. The internal temperature of the heated side reached a minimal temperature of -40°C at 1.53 hours into the flight. The outside air temperature gathered from this test was used in the design of the thermal Matlab program.

![Figure 6: Test Flight Temperatures](image)

Two freezer tests were also performed to inspect evaluate the application of new insulation. These tests used the base CubeSat structure with two different amounts of Aerogel insulation as well as the thermal tape used in previous tests. The CubeSat was placed inside a freezer of -84°C while the inside temperatures were recorded on the two sections of the structure. One of the two sides contained the same heater used in the previous test while the other was empty, save for the recording thermocouple. The results of these tests are shown in Figures 7A and 7B. By comparing the results, the benefits of two layers of aerogel was quite noticeable. The single layer test had a minimal temperature on the heated side of -51°C in 1 hour while the two-
layer test had a minimal heated temperature of -22°C in the same time. The questionably low temperature in the unheated section in the two-layer test was caused by unsealed gaps in the structure that allowed minute airflow.

In the two-layer case, it took 28 minutes to break the -10°C boundary point, as opposed to the 1 minute 24 seconds of the nitrogen test. By extrapolating this knowledge to the weather balloon flight test, which had the same insulation as the nitrogen test, the team concluded that two layers of aerogel would be sufficient insulation for the next weather balloon flight.

To measure the temperature of the rechargeable heater, a final test was performed. A SEEK thermal camera was placed in various views of the heater while it ran through its full cycle. Two examples from these videos are shown below in Figure 8. Lines have been added to emphasize wall locations. The image on the left shows a view of half of the CubeSat with the heater and the image on the right shows the heater in the exposed CubeSat where all doors were open. The temperature had been expected to rise in the closed case, as the thermal energy would be contained around the heater. Instead, both cases resulted in an average surface temperature of
30°C. This testing showed that the surface temperature was regulated by the electronics of the heater, which allowed later modeling of the heater as approximating 30°C during its lifecycle.

Figure 8: Thermal Pictures
Chapter Two

Development of the Model

The creation of a volumetric model of the CubeSat structure was imperative to understanding the internal temperatures over the flight path. An initial study was developed by writing a Matlab program that would use the full volume of each layer of the CubeSat, separated as shown in Figure 9. Matlab was chosen because it allowed for a hands-on approach to developing the engineering model. Existing Finite Element and Finite Volume tools, such as Patran, were not employed, as the analysis would be completed without student input. As the description from MacNeal-Schwendler Corporation (MSC) for Patran states (MSC 2015), “Meshes are easily created on surfaces and solids alike using fully automated meshing routines.” The automated meshing of Patran does not allow for much versatility in student development.

Figure 9: Insulation Layering
Additionally, modeling the CubeSat Structure in Patran would require a block of elements to represent the internal air temperature, which would pose many difficulties. As Moore, Donovan, and Powers (1998, 5) stated in their article about the creation of headlights through Patran, “The lamp 3D air volume mesh poses the most difficult meshing problem due to the number of entities inside the enclosed air volume.”

To account for the layering of the walls with PLA plastic, thermal tape, and aerogel, the total heat transfer was found utilizing equation 1 below. The temperature difference between the internal and external air is divided by the thermal resistance of the wall structure.

\[
q = \frac{(T_{in} - T_{out})}{\left( \sum_{i=1}^{n} \frac{s_i}{k_i A_i} \right)}
\]  

(1)

Where \( T_{in} \) is the temperature of the internal air and wall, \( T_{out} \) is the outside air temperature, \( n \) is the number of constituents, \( s \) is the thickness in meters, \( k \) is the thermal conductivity in watts per meter kelvin, and \( A \) is the surface area of the first constituent in square meters. The resultant heat loss is in watts, where one watt is equivalent to one joule of energy per second.

To make use of this heat loss, the change in the internal temperature was developed using the equation 2 below.

\[
\Delta T = \frac{q_t}{mc_p}
\]  

(2)

Where the heat loss occurs in time steps of one second, \( m \) is the unit mass of the volume in kilograms, and \( c_p \) is the specific heat of the volume in joules per kilogram kelvin. The thermal tape conductivity and the specific heat were unknown as the item had been discontinued and the information was no longer available. The thermal conductivity was approximated to be the same as a similar flashing tape (Hanno Sealing and Insulating Systems 2010). The expected heat loss
was then found from the temperatures nitrogen and flight-testing, which was applied to Equation 2 to find the specific heat of the thermal tape.

The first Matlab program developed for this project, included in Appendix A, was used as an initial element analysis of the structure volume. This analysis used each surface as the total volume of each layer. This was a preliminary estimate, as this program does not show the direct effects of the local heat sources and sinks. This basic program was useful to find if the inside of the structure would be, on average, in the correct range of temperatures for the mission hardware. The output of this program is shown below in Figure 10, where the external temperature is the recorded data from the test flight. The most noticeable result shown in the graph is the high temperatures sustained at the levels of the aerogel in comparison to the thermal tape and the wall structure. It should be noted that the graph only shows the first 50 seconds of flight, though the program does include the temperatures for the full duration.

Figure 10: Full-Volume Thermal Model (first 50 seconds of flight)
The next program created was written to further develop the in-depth Finite Volume Model of the CubeSat structure. The full code can be found in Appendix B. The modeling of internal volumes is improved by the number of sides of the volume, but this complicates the stacking of volumes inside the structure (Peiro and Sherwin 2005). To consider these issues best, 1x1x10 cm³ rectangular prisms were used, shown in Figure 11. The heat losses of each volume element were found as the summation of heat flux through each surface. The thermal capacitance of the volume was determined by the element location as tape and wall, aerogel, or standard air (Cao, et al. 2003).

![Finite Volume](image)

**Figure 11: Finite Volume**

The program was written to give allowance to any size of the CubeSat Structure, though the current setup is built on the size of the 3-unit CubeSat, which was 10x10x30 cm³. The elements outside of the boundary walls of the CubeSat structure and inside the gas hood were regulated to the outside air temperature from the initial balloon flight test. The element that represented the heater was regulated to the temperature prescribed by the Seek Thermal video tests. The resulting temperatures were applied to a 3D mesh plot that could be shown at any time.
step. Shown below in Figure 12 shows the resultant mesh of the CubeSat structure at 500 seconds into the flight with the heater placement from the final CubeSat structure.

Figure 12: Thermal Mesh of Default Case

This mesh shows the temperature of each elemental volume in the CubeSat, including the wall structure. The wall of the CubeSat is shown between the black lines. The color bar helps to show the temperature of each node of the mesh. The high peak in the back corner of the structure is the thermal impact of the heater influencing the volume elements surrounding it. The low sink on the left is the thermal impact of the gas hood. The mesh output has many similarities to the original volume analysis, such as the high difference in temperatures that could be sustained across the aerogel boundary. It can be seen that the majority of the internal space was within the -10°C requirement. The mesh also shows the regions of the internal structure that were below the requirement. These regions were along the wall edges as well as the space around the gas hood. The wall that was adjacent to the heater was able to keep within the boundary requirement.
Further Development and Design Changes

The final program was altered to view the potential effects of shifting heater placement. Iterations of heater placement allowed for the measurement of internal average temperature as well as the standard deviation at a specified time. In the 3-unit CubeSat structure, the elements shown in Table 1 were found as significant in average temperature and standard deviation. The symmetric status of the structure lead to two equivalent locations in each category. The nomenclature for location is the distance in centimeters from the origin located at the outside front-left corner of the CubeSat on the vertical mid-plane. For comparison, the original location of the heater was located as 9 cm deep by 25 cm across.

![Figure 13: Origin Location](image)

<table>
<thead>
<tr>
<th>Highest Average Temperature -15.67°C</th>
<th>Lowest Average Temperature -16.71°C</th>
<th>Highest Standard Deviation 15.72°C</th>
<th>Lowest Standard Deviation 14.17°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (cm)</td>
<td>Lateral Distance (cm)</td>
<td>Depth (cm)</td>
<td>Lateral Distance (cm)</td>
</tr>
<tr>
<td>------------</td>
<td>------------------------</td>
<td>------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>10</td>
<td>2</td>
</tr>
</tbody>
</table>
The table shows that the average temperature would be best affected by moving the heater to a central location, 6cm deep by 20cm across, with a slight offset caused by the gas hood. The thermal mesh of the location of highest average internal temperature is shown below in Figure 14. The thermal impact of the heater slightly raises the temperature of the core region of the CubeSat, though the average is hampered by the regions of low temperature that exist around the gas hood and the far reaches of the structure. The higher standard deviation relates how the temperature at these far edges of the structure are much lower than the average. The bulk of sensors and electronics exist within the zone that is effected positively by this adjustment. Since the sensors were the primary concern in the mission, this change would have been beneficial.

Figure 14: Thermal Mesh of Optimized Heater Placement
The location of the heater that caused the lowest average temperature and standard deviation, found in Table 1, was meshed in Figure 15. This helped to validate the modelling of heater placement, as it was expected to place the heater where it would have the least thermal impact on the average temperature. This location would be where the heater is surrounded by heat sinks such as the walls and the gas hood. This orientation placed the heater in the corner closest to the gas hood. The heater has very little impact on the internal temperature of the structure, instead raising the temperature of the closest wall section, which matched expectations. The lower standard deviation was most likely caused by the low impact the heater had on the majority of the internal temperature. Without the impact of a centrally placed heater, there is very little deviation in the internal temperature. There is no circumstance that would lead to the use of this setup; save for a small sensor that requires drastic heating that is found in the corner of the structure.

Figure 15: Thermal Mesh of Worst Case Scenario
Future Implementation

The final program would be useful in future IPT missions that use CubeSat structures in regions where the ambient temperature is known or can be found through testing. The program allows for simple adjustments such as the size of the CubeSat structure. By changing the values in the variables shown in Figure 16, the size of the total structure can be altered. Other adjustments include the thickness and thermal resistances of the insulators, the external air temperature, and the surface temperature of the heater.

```
%% Size of CubeSat
10cm*10cm*30cm
% allow for outside air temp X+2*Y+2
Edge_Right = 32;
Edge_Bot = 12;
```

Figure 16: Code size Variables
Conclusion

It was challenging to assemble all of the needed data to analyze this project. Testing was slow, as the IPT was unable to dedicate time and effort to one small portion of the total project. A significant amount of time was spent outside of the class developing proper tests and finding the availability of these testing facilities. The tests performed were significant in the development of this project as it provided the outside air temperature used in the final program as well as many data sets for comparing trends.

The final program development used known values of thermal conductivities and specific heats found through various resources in developing the thermal capabilities of the CubeSat structure. One material, the thermal tape, required approximations of the thermal conductivity and the specific heat, which were made through analysis of the CubeSat tests. The resultant program has many allowances for altering specifications such as the size of the CubeSat and the thermal coefficients of the insulators. The program can be altered easily if a new insulation is implemented. With this in mind future IPT classes may find this program useful, even in the case where the structure is no longer in CubeSat form.

In the future, the code developed for this project could be modified to show more directly the alterations in thermal flow caused by hardware layout. The final steps of CubeSat design did not allow for much time in studying or recording wiring placement. There had been hopes of including alternate heating techniques, such as small heating pipes, but time constraints have led to the simplified form presented.

Some challenges of this project included developing the working baseline of heat losses, evaluating correct approximations for the thermal conductivity and specific heat of thermal tape, and the extensive technical writing skills required for this paper. There are limited courses
designed for Aerospace students that develop heat functions and technical writing skills. The base knowledge provided by MAE 488 Analysis of Engineering Systems was combined with independent study to develop the thermal methods used in this project. Though many Aerospace engineering classes require written documentation, this is usually in the form of structured lab reports. There was difficulty in preparing this document as provided by the Honors program. If it were not for the compliance of the IPT in additional testing and the assistance of the University of Alabama in Huntsville professors, this paper could not have been seen through to completion.

When the scope of the project was first considered, it was underwhelming, existing as little more than a finite element analysis to be completed through some existing engineering tool. As the project continued, the scope shifted and an engineering ambition took over. From an engineering perspective, there are many portions of this project that could have been improved, such as documentation and personal time management. Writing a Matlab program from scratch may have been overambitious, as some considerations had to be curbed for time constraints, but the final project was the additional work and research that the Honors Capstone was designed to be.
Analysis of Thermal Systems

Bibliography


%% Thermal Graph 3D Bar
% this is the be used to create a graphic understanding of the thermal
% movements on the inside of a CubeSat Structure.
clear, clc, close all

num = xlsread('OUTSIDEHEAT.xlsx', 'Temp data', 'Q2:Q1091');
length(num);

%% General Required Information
Area = 0.111164;
t_tape = 0.00356; %m
t_wall = 0.004; %m
t_aero = 0.035/2; %m
k_tape = 0.0412;
k_wall = 0.13;
k_aero = 0.023;
R_tape = t_tape / (k_tape * Area);
R_wall = t_wall / (k_wall * Area);
R_aero = t_aero / (k_aero * Area);
R = R_tape + R_wall + 2*R_aero;

Temp(1) = 14.5; % initial value
T_tape(1) = 14.5;
T_wall(1) = 14.5;
T_aero(1) = 14.5;
Loss(1) = (Temp(1)-num(1))/R;
for i = 2:length(num)

    % heat Loss
    Loss(i) = (Temp(i-1)-num(i-1))/R;
    Temp(i) = Temp(i-1) - Loss(i)/223;
    T_aero2(i) = Temp(i) - Loss(i)*R_aero;
    T_aerol(i) = T_aero2(i) - Loss(i)*R_aero;
    T_wall(i) = T_aerol(i) - Loss(i)*R_wall;
    T_tape(i) = T_wall(i) - Loss(i)*R_tape;
    j(i) = i;
end

if i<50
Data(:,i-1) = [Temp(i);T_aero2(i);T_aerol(i);T_wall(i);T_tape(i);num(i)];
Analysis of Thermal Systems

end

end

axis([0.5, 48.5, 0, 5, 0, 2000])
width = 1;
a = bar3(Data,width);
colorbar
b = get(a,'Zdata');
for k = 1:length(Data)
    zdata = get(a(k),'ZData');
    set(a(k),'CData',zdata);
    set(a(k),'FaceColor','interp');
end

Appendix B: Full Mesh Thermal Program

%% 3d Plot
clear, clc, close all
num = xlsread('OUTSIDEHEAT.xlsx','Temp data','Q2:Q1091');
length(num);
frames=0;

%% Size of CubeSat
% 10cm*10cm*30cm
% Prevalent 12*32
Edge_Right = 32;
Edge_Bot = 12;

%% General Required Information
Area = 0.0001; % m^2
Volume = Area*0.1;
Density
d_wall = 1210000; %g/m^3
d_air = 1225; %kg/m^3
d_tape = 1000000; %Currently unknown
Analysis of Thermal Systems

\[ d_{\text{aero}} = 350000; \]
\[ t_{\text{tape}} = 0.00356; \text{\% m} \]
\[ t_{\text{wall}} = 0.004; \text{\% m} \]
\[ t_{\text{aero}} = 0.035; \text{\% m} \]
\[ t_{\text{air}} = 0.010; \text{\% m} \]
\[ k_{\text{tape}} = 0.0412; \text{\% W/m*K} \]
\[ k_{\text{wall}} = 0.13; \]
\[ k_{\text{aero}} = 0.023; \]
\[ k_{\text{air}} = 0.02; \]

\[ R_{\text{tape}} = \frac{t_{\text{tape}}}{(k_{\text{tape}} \times \text{Area})}; \text{\% K/W} \]
\[ R_{\text{wall}} = \frac{t_{\text{wall}}}{(k_{\text{wall}} \times \text{Area})}; \]
\[ R_{\text{aero}} = \frac{t_{\text{aero}}}{(k_{\text{aero}} \times \text{Area})}; \]
\[ R_{\text{air}} = \frac{t_{\text{air}}}{(k_{\text{air}} \times \text{Area})}; \]
\[ R_{\text{setter}} = [1, R_{\text{tape}} + R_{\text{wall}}, R_{\text{aero}}, R_{\text{air}}]; \]

\% Resistances
\for I = 1:4;
\for X=I:Edge_Bot-(I-1);
\for Y=I:Edge_Right-(I-1);
\[ R_{\text{set}}(X,Y) = R_{\text{setter}(I)}; \]
\end
\end
\end

\% Setting up thermal capacitance
\% \( C = m \times cp \)
\[ cp_{\text{tape}} = 0.37; \text{\% really Not sure of this value} \]
\[ cp_{\text{wall}} = 0.55; \text{\% J/g*K} \]
\[ cp_{\text{aero}} = 0.841; \text{\% J/g*K} \]
\[ cp_{\text{air}} = 1.0035; \text{\% J/gram*K} \]

\[ C_{\text{tape}} = \text{Volume} \times d_{\text{air}} \times cp_{\text{tape}}; \text{\% J/K} \]
\[ C_{\text{wall}} = \text{Volume} \times d_{\text{air}} \times cp_{\text{wall}}; \]
\[ C_{\text{aero}} = \text{Volume} \times d_{\text{air}} \times cp_{\text{aero}}; \]
\[ C_{\text{air}} = \text{Volume} \times d_{\text{air}} \times cp_{\text{air}}; \]
\[ C_{\text{setter}} = [1, C_{\text{tape}} + C_{\text{wall}}, C_{\text{aero}}, C_{\text{air}}]; \]

\% capacitance
\for J = 1:4;
\for X=J:Edge_Bot-(J-1);
\for Y=J:Edge_Right-(J-1);
\[ C_{\text{set}}(X,Y) = C_{\text{setter}(J)}; \]
\end
\end
\end

% Resistances
\for I = 1:4;
\for X=I:Edge_Bot-(I-1);
\for Y=I:Edge_Right-(I-1);
\[ R_{\text{set}}(X,Y) = R_{\text{setter}(I)}; \]
\end
\end
\end

% Setting up thermal capacitance
\% \( C = m \times cp \)
\[ cp_{\text{tape}} = 0.37; \text{\% really Not sure of this value} \]
\[ cp_{\text{wall}} = 0.55; \text{\% J/g*K} \]
\[ cp_{\text{aero}} = 0.841; \text{\% J/g*K} \]
\[ cp_{\text{air}} = 1.0035; \text{\% J/gram*K} \]

\[ C_{\text{tape}} = \text{Volume} \times d_{\text{air}} \times cp_{\text{tape}}; \text{\% J/K} \]
\[ C_{\text{wall}} = \text{Volume} \times d_{\text{air}} \times cp_{\text{wall}}; \]
\[ C_{\text{aero}} = \text{Volume} \times d_{\text{air}} \times cp_{\text{aero}}; \]
\[ C_{\text{air}} = \text{Volume} \times d_{\text{air}} \times cp_{\text{air}}; \]
\[ C_{\text{setter}} = [1, C_{\text{tape}} + C_{\text{wall}}, C_{\text{aero}}, C_{\text{air}}]; \]

\% capacitance
\for J = 1:4;
\for X=J:Edge_Bot-(J-1);
\for Y=J:Edge_Right-(J-1);
\[ C_{\text{set}}(X,Y) = C_{\text{setter}(J)}; \]
\end
\end
\end
end
Temp(2:Edge_Bot,2:Edge_Right) = 14.5;
Temp(Pos(),Pos()) = Heater;
Temp(6:7,6) = num(1);

Temp(1:Edge_Bot,1) = num(1);
Temp(1,1:Edge_Right) = num(1);
Temp(Edge_Bot,1:Edge_Right) = num(1);
Temp(1:Edge_Bot,Edge_Right) = num(1);

% set resistance

% Iterate through each temperature. Equivalent to time step of one second.
for iter = 1:length(num)
    Tempstor(1:Edge_Bot,1:iter) = num(iter);
    Tempstor(1,1:Edge_Right,iter) = num(iter);
    Tempstor(Edge_Bot,1:Edge_Right,iter) = num(iter);
    Tempstor(1:Edge_Bot,Edge_Right,iter) = num(iter);
end

% Iterate through the rows and columns
for x = 1:2; Edge_Bot = 1;
    for y = 2:2; Edge_Right = 1;
        if iter == 1
            Top = (Temp(x-1,y,iter) - Temp(x,y,iter)) / R_set(x,y); % K / (K/W)
            Right = (Temp(x,y+1,iter) - Temp(x,y,iter)) / R_set(x,y);
            Bottom = (Temp(x+1,y,iter) - Temp(x,y,iter)) / R_set(x,y);
            Left = (Temp(x,y-1,iter) - Temp(x,y,iter)) / R_set(x,y);
        else
            Top = (Temp(x-1,y,iter-1) - Temp(x,y,iter-1)) / R_set(x,y); % K / (K/W)
            Right = (Temp(x,y+1,iter-1) - Temp(x,y,iter-1)) / R_set(x,y);
            Bottom = (Temp(x+1,y,iter-1) - Temp(x,y,iter-1)) / R_set(x,y);
            Left = (Temp(x,y-1,iter-1) - Temp(x,y,iter-1)) / R_set(x,y);
        end
end

delt = (Left + Top + Right + Bottom) / C_set(x,y); % W / J(1/second)/K = K
m(x,y,iter) = delt;

if iter == 1
    Tempstor(x,y,iter) = Temp(x,y,iter) * delt;
else
    Tempstor(x,y,iter) = Temp(x,y,iter-1) * delt;
end

if Tempstor(x,y,iter) < num(iter)
    Tempstor(x,y,iter) = num(iter);
end
end
end

Temp(:,iter) = Tempstor(:,iter);
Temp(Pos(1),Pos(2),iter) = Heater;
Temp(6:7,8,iter) = num(iter);
end
end

Optimize(:,iterationsx,iterationsy) = Temp(:,520); % Set timer to 120 for regular output

opt_av(:,iterationsx,iterationsy) = mean2(Optimize(:,2:11,iterationsx,iterationsy));%sum(Optimize(2:11,2:31,iterationsx,iterationsy))/300;

opt_std(:,iterationsx,iterationsy) = std2(Optimize(2:11,2:31,iterationsx,iterationsy));

% Ending of heater position iteration
end
end

end