Thermal Analysis of Rocket-Mounted Enclosures -Simulation of Unsteady Heat Transfer in Vacuum Environment-

Naoya Tonooka　　Keiichi Fujino

The demands toward space business have been increasing, and the market size is growing year by year worldwide. Space business covers a wide range of areas. For example, it includes satellites that are put into orbit for transmitting information from the sky, rockets that shoot the satellites into space, services that use satellite communication, and ground facilities that support them. Since the environment surrounding satellites and rockets is significantly different from that of the ground, different design methods are required during development. This article introduces the method used for thermal analysis during the development of communication equipment enclosures installed on rockets.

Fundamentals of Thermal Analysis and Heat Transfer

Thermal analysis is a desktop method for calculating a product's temperature distribution and thermal stress due to heat transfer. In thermal analysis, the environment in which the product is placed can be chosen freely, and it is possible to calculate the temperature of places that cannot be measured in real life. It is often carried out during the product development process because it allows design verification before manufacturing, and therefore shortens development time and reduces manufacturing costs.

General thermal analysis uses the finite element method to divide the domain to be analyzed into smaller subdomains. Then, the temperature for each element or contact point is calculated using physical equations related to the three basic forms of heat transfer, which are "thermal conduction," "convection heat transfer," and "radiation heat transfer." They are classified as follows.

1) Thermal conduction: The phenomenon in which heat is transferred from a hot part to a cold part inside an object.

2) Convection heat transfer: The phenomenon in which heat is transferred by flow between a solid surface and a fluid flowing around it. Natural convection is when the flow occurs in a fluid due to the influence of gravity, and forced convection is when a flow occurs in a fluid due to the application of external energy.

3) Radiation heat transfer: The phenomenon in which heat is transferred from a hot object to a cold object directly through space in the form of electromagnetic waves. Therefore, heat transfer occurs even in a vacuum. The phenomenon is also called radiant heat transmission.

When considering the temperature rise of equipment in outer space, the air around and inside the equipment is nonexistent or extremely thin, and transfer of heat through convection heat transfer is considered to be negligible. Therefore, in thermal analysis for outer space, it is only necessary to consider thermal conduction and radiation heat transfer.

Rocket-Specific Conditions

Rockets have the following characteristics based on their intended use.

(1) Lifespan is very short.

After launch, the rocket's role is finished when it reaches outer space and separates the satellite or other payload it is carrying. The duration varies depending on the overall weight and engine performance, but it is around 20 to 50 minutes. Afterwards, the rocket falls back to earth in a controlled trajectory and drops into the sea. When applying this situation to thermal analysis, the method of implementation must be changed from a normal condition. A normal thermal analysis determines the temperature distribution in a steady state (a state in which heat generation and cooling are balanced, and temperature becomes constant) to determine quality. However, with actual materials, it takes time for the temperature to rise after heat is applied, and it is realistic to think that the equipment inside a rocket will stop before the temperature reaches a steady state. For this reason, it is necessary to conduct an unsteady thermal analysis, which determines the temperature according to the elapsed time, rather than a steady thermal analysis that is not affected by changes over time.

(2) Heat dissipation from rocket itself is mainly radiation; from internal equipment it is mainly conduction.

As mentioned previously, convection heat transfer does not occur in outer space, and since there is nothing in contact with the rocket body on the outside, radiation is the means of heat dissipation. On the contrary, the inside of the rocket is temperature controlled to protect the payload and the equipment that controls the rocket[1], and at temperatures around -10 to 65°C, the environment is not as harsh as outside the rocket. The internal equipment is basically fixed to the rocket structure, and heat conduction from the fixed contacts is the main means of heat dissipation. When applying this situation to thermal analysis, the implementation method must again be changed from a normal condition. In normal thermal analysis, calculations are performed under a condition where the generated heat is ultimately transferred to a fluid body and flows outside to dissipate heat. However, when dissipating heat by conduction, a solid object is required to which heat is transferred, and an analysis model that thermally approximates the actual rocket structure must be created. This analysis model is called "heat mass." Heat mass contacts the internal equipment only within the range where heat conduction occurs, and has the same physical properties as the rocket structure. The volume of the heat mass is determined by calculating the amount of heat the heat mass will absorb from the equipment being analyzed, taking into account other equipment installed near the analyzed equipment inside the actual rocket. **Figure 1** shows an image of the heat mass, and **Figure 2** shows the heat flow.

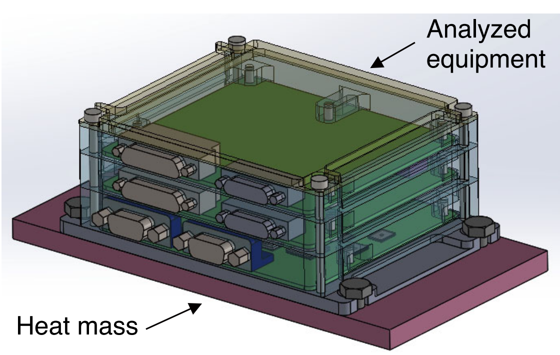

Figure 1. Heat Mass Image

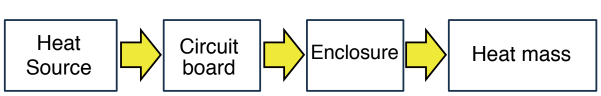

Figure 2. Heat Flow

(3) Environment changes to vacuum during operation.

The equipment inside the rocket begins operating before the launch, and the temperature starts to rise once the operation starts. At this stage, the equipment is still on the ground, so there is air around and inside the equipment. Heat inside the equipment is transferred by thermal conduction and convection. After the rocket is launched, the air pressure decreases as the altitude increases, and the air around the equipment gradually becomes thinner. In order to reduce the risk of malfunctions, rocket equipment has an internal air pressure adjustment structure to prevent damage from sudden changes in air pressure while maintaining airtightness to the extent that electrically conductive contaminants (mainly fibrous foreign matter) do not enter the equipment. Therefore, as the air around the equipment becomes thinner, the air inside also becomes thinner, creating a vacuum state. When applying this situation to thermal analysis, it is difficult to accurately calculate the condition under which the surrounding air decreases over time. For this reason, analysis is performed under the most severe condition of being placed in a vacuum from the beginning. As long as the temperature does not reach a level that would cause damage, it can be assumed that there will be no problem since the temperature in the air will be decreasing.

Unsteady Thermal Analysis

Example of an actual analysis will now be introduced. Thermal analysis was performed on the measurement communication equipment used as part of an avionics system. **Figure 3** shows the exterior of the equipment, and **Table 1** shows the specifications that are related to the thermal analysis.

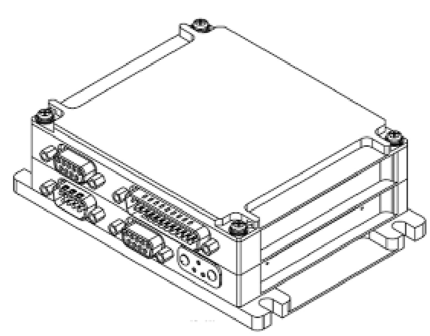

Figure 3. Exterior of Measurement Communication Equipment

*1) SolidWorks is a registered trademark of Dassault Systemes Solidworks.

Table 1. Specifications of Measurement Communication Equipment (excerpt)

Outer dimensions (mm)	110×90×42
Weight (g)	400
Enclosure material	Aluminum (A5052)
Installed circuit boards	2
Power consumption (W)	9.1

SOLIDWORKS®*1) Simulation 2017 was used for the analysis. Although the physical properties of the materials were basically specified from the standard library of the analysis software, thermal conductivity of the circuit board was calculated from an independently modeled board. The circuit board is mainly made of glass and epoxy resin, which have low thermal conductivity, and copper, which has high thermal conductivity. Copper is arranged in layers as a pattern, so when observed as a whole board, it has an anisotropic thermal conductivity, which means heat transfers easily in the planar direction but does not transfer well in the thickness direction. However, there are many through holes in the board connecting the copper in the thickness direction, and thermal conductivity in the thickness direction is locally high at those sections. Therefore, the thermal conductivity was averaged taking into account the thickness of each board layer, the ratio of glass / epoxy resin / copper, and the number of through holes per unit area. Then, a simplified model was created in which the planar direction and thickness direction each has a uniform thermal conductivity.

Values of other parameters used in the analysis are shown in **Table 2**.

Table 2. Other Used Parameters

Parameter	Used Value
Analysis type	Unsteady analysis
Total analysis time (s)	500
Time step (s)	10
Initial temperature (°C)	40
Minimum mesh gap (mm)	1

With regard to the temperature condition of the heat mass, the analysis was performed assuming two different situations.

(1) Initial heat mass temperature 40°C, variable temperature

This situation assumes that only the equipment being analyzed is operating and none of the other surrounding equipment is operating. The rise in the heat mass temperature will only be from absorbing the heat of the analyzed equipment. This is the most lax condition as it does not take into account the influence of the surrounding equipment, but it provides basic data for understanding the temperature rise during independent operation. **Figure 4** shows the temperature analysis result and **Figure 5** shows the temperature distribution change for LANPHY, device which exhibited the highest temperature rise in the analysis.

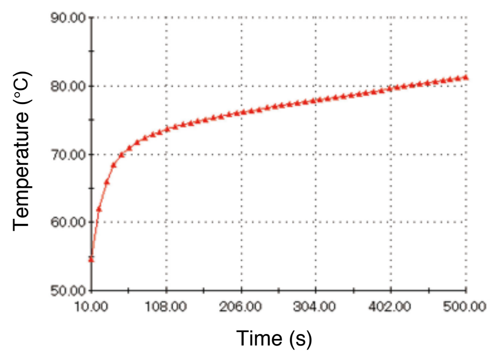

Figure 4. LANPHY Temperature Analysis Result (variable heat mass temperature)

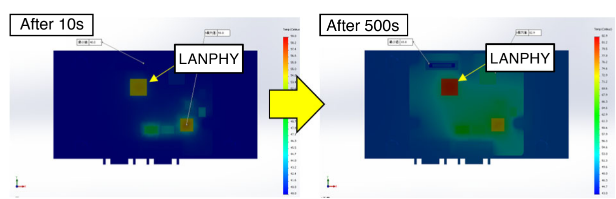

Figure 5. Temperature Distribution Change (variable heat mass temperature)

(2) Initial heat mass temperature 40°C, specified rising temperature

In this situation, the rise in the heat mass temperature is changed over time to simulate the rising temperature of the rocket structure due to the influence of the surrounding equipment. The collected data will be for a more severe environment than (1). The heat mass temperature settings are shown in **Figure 6**. The heat mass temperature is changed unaffected by the heat absorbed from the analyzed equipment.

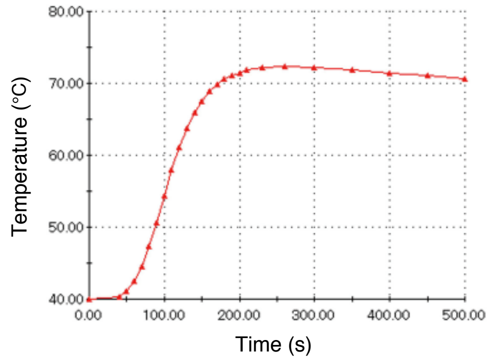

Figure 6. Heat Mass Temperature Settings

Similar to (1), the temperature analysis result and the temperature distribution change for LANPHY are shown in **Figure 7** and **Figure 8**, respectively.

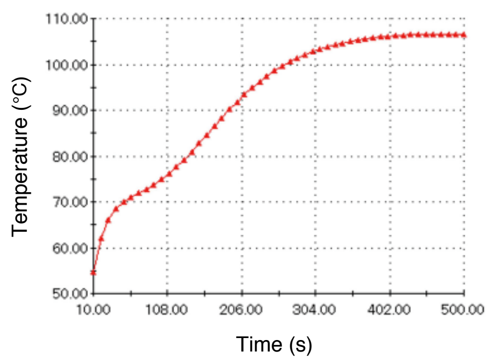

Figure 7. LANPHY Temperature Analysis Result (specified heat mass temperature)

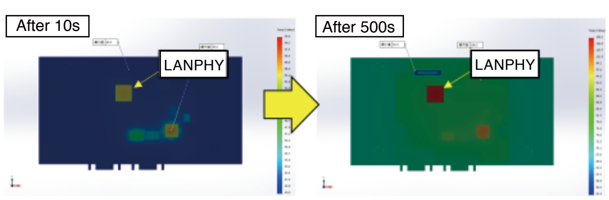

Figure 8. Temperature Distribution Change (specified heat mass temperature)

From (1) and (2), it was confirmed that LANPHY did not exceed the maximum allowable temperature, and it was determined that no additional heat countermeasures were necessary. Other devices were similarly confirmed and found that there were no problems with the entire equipment.

Comparison with Actual Measurements

A prototype was used to measure the temperature rise for verification of the analysis result. To create a vacuum environment, the prototype was placed in a desiccator and the air pressure inside the desiccator was lowered with a vacuum pump. **Figure 9** shows a photo of the setup for the measurements.

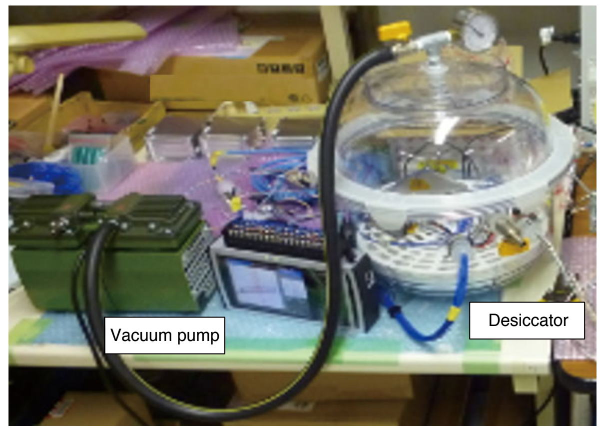

Figure 9. Setup for Temperature Rise Measurements

The test was performed at a low vacuum state of about 5kPa. For reference, atmospheric pressure was 101.325kPa. A thermocouple was used to measure the temperature, and a data logger measured the temperature at 10s intervals. Normally, air temperature around the equipment or equipment intake is used as reference for the ambient temperature, but in this test, the heat mass temperature was used. The heat mass temperature just before the start of the measurements was 24.6°C, and similar to the thermal analysis, temperature measurements were taken from the start of communication operation until 500s had elapsed.

In comparing the measurement result with the thermal analysis, the result of the variable heat mass temperature (1) was used due to the same condition as the measurement test. The reference temperature was 40°C in the thermal analysis and 24.6°C in the actual measurements, so an adjustment was made by adding the difference of 15.4°C to the actual measurements.

Figure 10 shows a comparison of LANPHY's analysis result and the actual measurements. It can be seen from the figure that the actual measurements were about 8°C lower than the analysis result. There are two possible reasons for this difference. The first is that the amount of heat generated by the device was set too high in the analysis. The theoretical worst value was used in thermal analysis, and it is likely that the amount of heat generated during actual operation was much lower. The second is that the measurements were taken in a low vacuum state, which may have caused a small amount of convection heat transfer to occur.

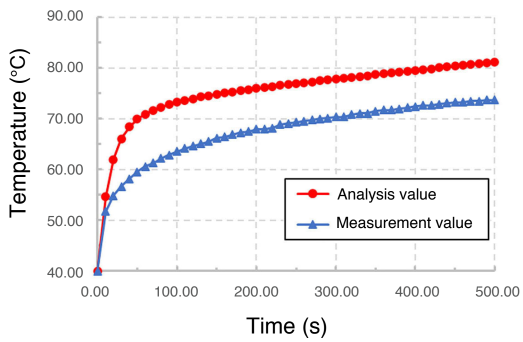

Figure 10. Comparison of Analytical and Measured Values (LANPHY)

Actual measurements also confirmed that the temperature of the entire equipment did not exceed the maximum allowable temperature, and it was determined that no additional heat countermeasures were necessary.

Precautions Dealing with Heat in Vacuum Environment

In this development, the temperature remained within the allowable range without any additional countermeasures, but in actual development, there may be situations where the temperature rises beyond the allowable range. In equipment on the ground, the temperature of a specific device can be lowered by adding a cooling fan, increasing the air flow, or adding a heat dissipation material such as a heat sink, but these methods cannot be used for equipment in a vacuum. As shown in **Figure 2**, the heat from the device needs to be transferred to the enclosure by thermal conduction. To enable this, devices that generate extreme heat must be placed close to the board fixings or arranged so that they can directly contact the enclosure via a heat transfer material.

Future Work

The article presented the analysis of unsteady heat transfer in a vacuum environment. Thermal analysis is a necessary technique in various fields, and OKI plans to continually collect data from diverse thermal analysis cases, including comparisons with actual measured values. Presently, there is no record of thermal analysis on a water-cooling method, and in this matter, OKI is currently studying how to establish a procedure. ◆◆

References

1) Haruaki Itagaki, Heat Transfer Problems in Space Systems, Vacuum (Journal of Vacuum Society of Japan), Issue 38, No. 6, pp.574-575, 1995 (in Japanese)

Authors

Naoya Tonooka, Development Department, OKI IDS Co., Ltd.

Keiichi Fujino, Development Department, OKI IDS Co., Ltd.