Thermal Analysis on a Satellite Box during Launch Stage by Analytical Solution

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Abstract

Simple methods are developed to predict temperatures of a satellite box during launch stage. The box is mounted on outer surface of satellite and directly exposed to space thermal environment for the time period from fairing jettison to separation. These simple methods are to solve a 1st order ordinary differential equation (ODE) which is simplified from the governing equation after applying several assumptions. The existence of analytical solution for the 1st order ODE is determined depending on treatment of time-dependent molecular heating term. Even for the case that the analytical solution is not available due to the time dependent term, the 1st order ODE can be solved by relatively simple numerical techniques. The temperature difference between two different approaches (analytical and numerical solutions) is relatively small (less than 1 °C along the time line) when they are applied to STSAT-I launch scenario. The present methods can be generally used as tools to quickly check whether a satellite box is safe against space environment during the launch stage for the case that the detailed thermal analysis is not available.

Key Word : Analytical Solution, Launch, Thermal Analysis, Satellite, STSAT-I

Introduction

A satellite is exposed to severe space thermal environment as soon as fairing of launcher is jettisoned. Under cold space environmental condition, heaters installed in the satellite provide thermal energy to keep its components above their acceptance temperatures. However, under hot space environmental condition, there is no other choice but having balanced thermal design for a satellite which adopts passive thermal control system. This should be verified by thermal analysis as well as thermal vacuum test. This study is about finding relatively simple thermal analysis methods to judge whether a satellite component is thermally balanced to overcome the hot space environment during launch stage (specifically, from fairing jettison to separation). The first analytical approach for this purpose was recently shown in the Ref [1].

The present methods are to predict temperatures of a satellite box for the time period from fairing jettison to separation. To apply this methods, the box should be mounted on outer surface of satellite and directly exposed to space thermal environment. Hereafter, "considered launch period" in this study stands for the time period from fairing jettison to separation.

As long as fairing of launcher encloses a satellite, the satellite may be placed under

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thermally mild condition. However, after fairing is jettisoned during launch stage, the satellite is directly exposed to severe hot space environment depending on launch time. The major factors which contribute to hot space environmental condition during launch stage are direct solar flux, Albedo, earth IR, and molecular heating by air.

To convince that the satellite is thermally safe under launch thermal environment, detailed thermal analysis should be conducted. For this purpose, full integrated thermal model of satellite and launcher should be developed. Obviously, this kind of thermal analysis takes considerable effort and time. However, frequently, quick temperature prediction is needed before the full model is developed. The quick prediction method should be simple as well as reliable. This is the motive to start this study.

In this study, 1st order ordinary differential equation (ODE) is derived after applying several assumptions to the governing equation. For some cases, analytical solutions exist for the ODE. Even for the case that analytical solutions do not exist, the ODE is easily solved by applying well known numerical methods (e.g. Runge-Kutta method).

The simplified governing equation is applied to launch scenario of real satellite, namely, STSAT-I (launch date : 2003. 9. 27). In this practical application, the most vulnerable box mounted on external surface of satellite is selected as a reference. If this box is predicted thermally safe against the space environment by the thermal analysis, it can be concluded that all the boxes in the satellite could be safe against the space environment. To give conservative prediction and compensate the uncertainties which inhere in the simple analysis, the thermal analysis is conducted based on reasonably worst hot conditions.

With proper assumptions and reliable information, the present methods can be generally adopted to predict temperature of any element exposed to space for the considered launch period.

Nomenclature

Q : heat flux

Q_{Sun} : direct solar flux

$Q_{Earth\ IR}$: Earth IR

Q_{Albedo} : Albedo

Q_{MH} : Molecular heating by air

$Q_{Radiation}$: radiation heat exchange with neighbor boxes

$Q_{Irradiation}$: irradiation to space

Q_{Gen} : internal heat generation, $Q_{Gen} = Q_{heating} - Q_{cooling}$

$Q_{heating}$: internal heating

$Q_{cooling}$: internal cooling

α : solar absorptance

q_s : solar constant

ε : IR emittance

q_E : Earth IR heating

β : reflection rate of solar energy by earth

q_{MH} : molecular heat flux by air

σ : Stefan-Boltzmann constant

Thermal Analysis by Analytical Approach from Fairing Jettison to Separation

Simplification of Governing Equation

The goal of this study is to obtain analytical solution to predict temperature increase for the considered launch period. During the considered launch period, the satellite is directly exposed to external heating environment and boxes or elements which are installed in ram direction experience the molecular heating as well. To verify the balanced thermal design of satellite, one box installed in ram direction is focused in this study since the box is considered most vulnerable against space thermal environment. For conservatism, the box is assumed to be thermally isolated from the satellite bus (no heat exchange with the satellite bus) and only the box surface mass is considered rather than the box total mass. The above assumptions let the box temperature change easily along with the external environment so that the box temperature may be predicted hotter than nominal one.

As a starting point, the governing equation is expressed as follows:

$$mC_p\frac{dT}{dt} = Q$$

The term Q includes all kinds of heat fluxes (positive quantity for in-flux and negative quantity for out-flux) to the box (specifically, surface mass) assuming a single mass. The heat fluxes are direct solar flux, earth IR, Albedo, molecular heating by air, radiation heat exchange with neighbor boxes, irradiation to space, and internal heating or cooling. Each heat flux term can be expressed in following equation:

$$Q = Q_{Sun} + Q_{Earth\ IR} + Q_{Albedo} + Q_{MH} + Q_{Radiation} - Q_{Irradiation} + Q_{Gen}$$

$Q_{Sun} = \alpha q_s A_s$: direct solar flux

$Q_{Earth\ IR} = \varepsilon q_E A_E$: Earth IR

$Q_{Albedo} = \beta \alpha q_s A_s$: Albedo

$Q_{MH} = q_{MH}(t) A_{MH}$: molecular heating by air

$Q_{Radiation}$: radiation heat exchange with neighbor boxes

$Q_{Irradiation} = \sigma\varepsilon A_{Irr}(T^4 - T^4_{space}) = \sigma\varepsilon A_{Irr}T^4$

: irradiation to space (T_{space} = $0\ K$)

$Q_{Gen} = Q_{heating} - Q_{cooling}$: internal heating and cooling

where A_S, A_E, A_A, A_{MH}, and A_{Irr} are areas which are participated in corresponding heat transfer.

If radiation heat exchange with neighbor boxes is neglected, the governing equation is simplified as follows:

$$a\frac{dT}{dt} = b_1 + f(t) - cT^4$$

where $a = mC_p$, $c = \sigma\varepsilon A_{Irr}$, $b_1 = Q_{Sun} + Q_{Earth\ IR} + Q_{Albedo} + Q_{gen}$, $f(t) = q_{MH}(t) A_{MH}$

Analytical Approach of Governing Equation

The existence of analytical solution of the simplified governing equation is determined by how to handle time-dependent molecular heating term. If $f(t)$ remains time-dependent, the analytical solution does not exist and the solution should be obtained numerically. Consequently, $f(t)$ should be treated as a constant to get analytical solution. With this assumption, the simplified governing equation is rewritten as follows:

$$a\frac{dT}{dt} = b - cT^4$$

where $b = b_1 + f(t)$ assuming $f(t)$ is constant.

The above 1st order ODE have three different analytical solutions depending on the sign of constant b. The each solution is classified as follows[2]:

(I) $b > 0$

Let $b/c = d^4$

$$-\frac{c}{a}t + F = \frac{1}{d^3}\left(\frac{1}{4}\ln\left|\frac{T-d}{T+d}\right| - \frac{1}{2}\tan^{-1}\frac{T}{d}\right)$$

(II) $b = 0$

$$-\frac{c}{a}t + F = -\frac{1}{3}\frac{1}{T^3}$$

(III) $b < 0$

Let $-b/c = d^4$

$$-\frac{c}{a}t + F = \frac{1}{4d^3\sqrt{2}}\ln\left|\frac{T^2 + dT\sqrt{2} + d^2}{T^2 - dT\sqrt{2} + d^2}\right| - \frac{1}{2d^3\sqrt{2}}\left(\tan^{-1}\left(1 - \frac{T\sqrt{2}}{d}\right) - \tan^{-1}\left(1 + \frac{T\sqrt{2}}{d}\right)\right)$$

where F is an integral constant.

The internal cooling rate $Q_{cooling}$ which is in Q_{Gen} is a unique term which can make the constant b negative. If internal cooling rate is big enough to make constant b negative, the analytical solution (III) would be used. However, since constant b is positive in most cases, the analytical solution (I) is only considered hereafter.

Applications

Description of Example

For the analytical approach, one box is selected which is mounted on top platform of STSAT-I carried by COSMOS launcher. The box is placed in ram direction so that it can experience the most serious external heating such as direct solar flux, Earth IR, Albedo and molecular heating (Fig. 1 and Fig. 2). Fig. 3 shows the schematic of the box and its specific surfaces which are influenced by external heating environment.

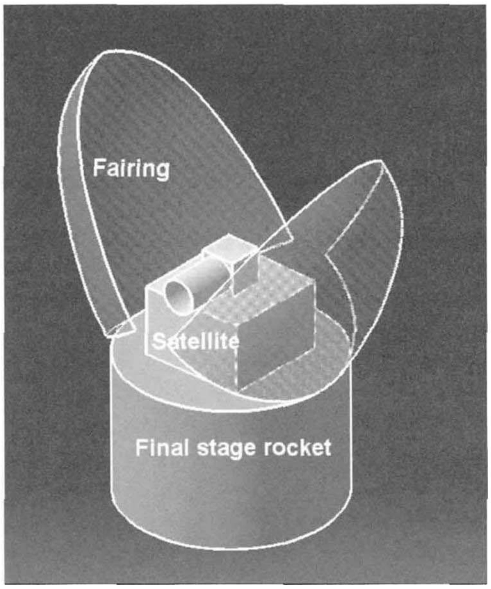

Fig. 1. Configuration of example

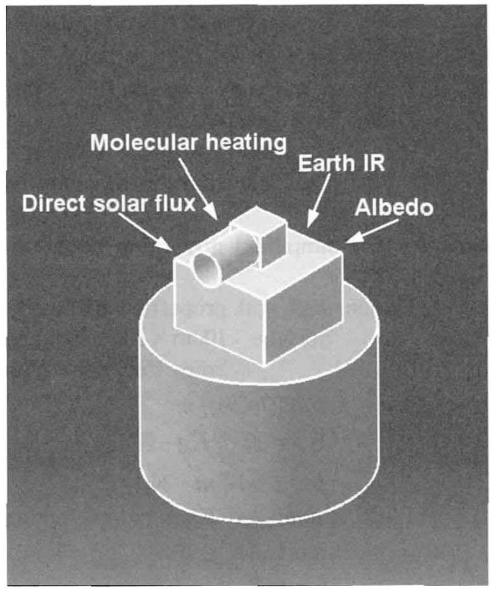

Fig. 2. Environmental heating

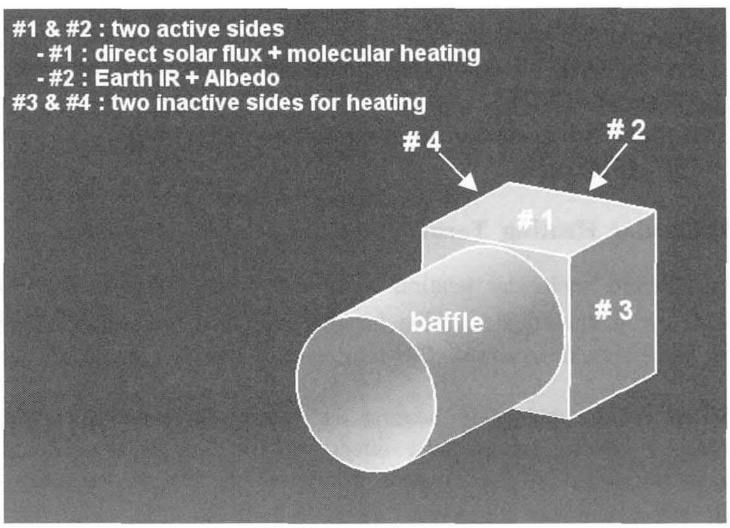

Fig. 3. Heating conditions on box surfaces

Assumptions and Conditions

External heating factors on the box surfaces are illustrated in Fig 3. For the thermal analysis, only four out of five surfaces are considered among the box external surfaces because the front surface has a baffle and the baffle is thermally isolated from the box while a single mass is considered by summing four surfaces. All the box surfaces are wrapped with 1 Mil (1/1000 inch thickness) Aluminized Kapton tape. The heating conditions for four surfaces are summarized as follows:

- Two Active Sides :
  Incident heat flux condition
  Surface #1 : direct solar flux + Molecular heating
  Surface #2 : Earth IR + Albdeo
- Other Two Inactive Sides :
  No heat flux in for surface #3 and #4
  Only contribution to mass increase and irradiation to space for this example

Constants for the simplified governing equation are summarized as follows:

- Dimensions and properties of box :
  Surface : 10cm×10cm square (total : 4 surfaces)
  2mm thickness aluminum
  $\rho = 2702 kg/m^3$
  $C_p = 903 J/Kg \cdot K$
  $k = 237 W/m \cdot K$
- 1 Mil aluminized Kapton tape optical properties :
  $\alpha = 0.41$
  $\varepsilon = 0.8$
- Worst hot conditions :
  $q_S = 1420 W/m^3$
  $\beta = 35\%$
  $q_E = 249 W/m^3$
- Temperature at fairing jettison :
  For 1st ODE governing equation, initial condition is required.
  $T(t=0) = 35\ ^\circ C$
- Duration from fairing jettison to separation for STSAT-I
  $\Delta t = 1518(\sec)$

Treatment of Molecular Heating Term

As mentioned before, molecular heating term $f(t) = q_{MH}(t) A_{MH}$ is the important factor to determine the existence of analytical solution for the simplified governing equation. If molecular heating term can be assumed constant, the temperature can be predicted with the analytical solution (I).

In real launch stage, molecular heating is commonly time-dependent. However, the duration that molecular heating significantly effects on the box temperature is relatively short since the fairing is jettisoned at the altitude where air density is very low. If this is true, molecular heating effect can be neglected, $q_{MH}(t) = 0$. If not the case, the term should be considered. Hence, the simplified governing equation is divided in two situations as follows:

(I) *Under molecular heating after fairing jettison*

$$a\frac{dT}{dt} = b_1 + f(t) - cT^4$$

(II) *No more molecular heating*

$$a\frac{dT}{dt} = b_1 - cT^4$$

In fact, the situation (II) can be applied for the cold case thermal analysis with proper

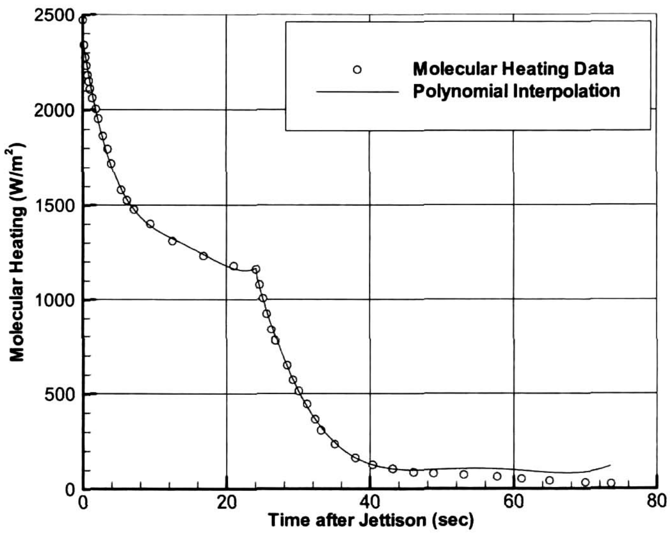

Fig. 4. Time-dependent molecular heating

environmental conditions. Fig. 4 shows the estimated molecular heat flux of STSAT-I along with time after the fairing is jettisoned [3]. In Fig. 4, the practical duration of molecular heating is about 75 sec while the total time is 1518 sec from fairing jettison to separation. Although the duration of molecular heating is relatively short compared with the total time, thermal effect of molecular heating on the box may not be neglected in this example.

In this study, molecular heating term $Q_{MH}(t)=q_{MH}(t)A_{MH}$ is taken into account in two different ways as follows:

(Method I) *Time averaged molecular heating*
Under molecular heating condition (up to 75 sec), time averaged molecular heating is considered and after 75 sec, no more molecular heating is considered. For given molecular heating data of STSAT-I, the total molecular heating is $55000\ J/m^2$. Hence, the time averaged molecular heat flux is $55000/75 = 773.33\ W/m^2$ and molecular heating term in the simplified governing equation becomes $q_{MH}(t)=(q_{MH})_{ave}=733.33$ and $f(t)=(q_{MH})_{ave}A_{MH} = constant$. In this case, analytical solution is possible for all time range because the right side of simplified governing equation always becomes constant.

(Method II) *Time-dependent molecular heating*
Time varying molecular heating are interpolated by 4th order polynomial. In Fig. 4, the solid line is represented by two 4th order polynomial interpolation lines due to discontinuity. Consequently, the simplified governing equation should be solved numerically.

Temperature Result of Applications

The simplified governing equation is solved by three ways such as method I, method II, and no molecular heating assumption. For method I and no molecular heating assumption, the solutions are obtained from analytical solution (I) of simplified governing equation. For method II, the 1st order ODE is solved numerically by applying the 4th order Runge-Kutta method.

Table 1. Temperature result for applications

	t = 75 *sec* At the end of molecular heating	t = 1518 *sec* Separation
(Method I) Time averaged molecular heating	38.3 °*C*	43.6 °*C*
(Method II) Time dependent molecular heating	37.8 °*C*	43.4 °*C*

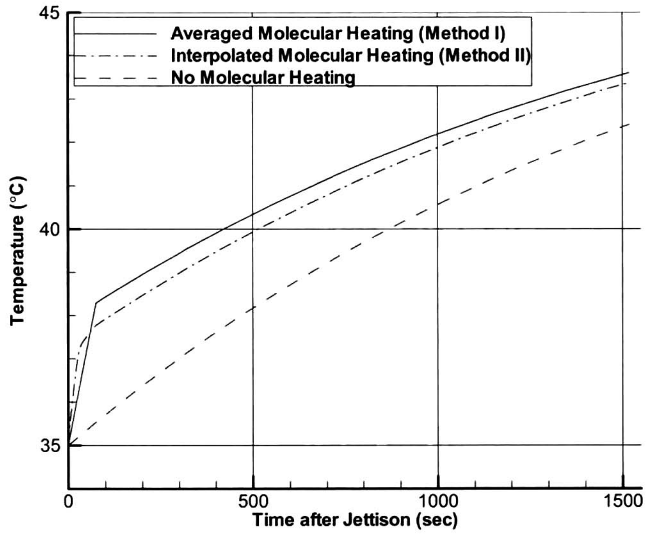

Fig. 5. Temperature time history for applications

The results are shown in Fig. 5. The temperatures at 75 sec as well as the ones at 1518 sec for two methods are shown in Table 1. It tells that the temperature differences between two method results are small. From this fact, it is concluded that the accurate calculation for molecular heating by numerical methods is not absolutely necessary and the analytical solution by using time averaged molecular heat flux is good enough to predict the box temperature for the considered launch period. This means that the analytical solution can be a useful tool to predict a box temperature in all time as long as the proposed assumptions are valid. If the molecular heating is not taken into account, the temperature at separation(Δt=1518 sec) becomes 42.4 °*C* as shown in Fig. 5. This means that the molecular heating contributes to the final temperature raise by about 1 °*C*.

Conclusion

Simple methods have been developed to quickly check whether a satellite box is safe against space environment during the launch stage for the case that the detailed thermal analysis is not available. The simple methods are focused on how to solve the 1st order ODE which is simplified from the governing equation.

For real application, the most vulnerable box of STSAT-I was selected and its temperature was calculated under reasonably worst conditions. If this box is safe against space environment, other boxes will be also safe. From the thermal analysis results, the temperature difference between analytical solution and numerical solution is less than 1 $^{\circ}C$ along the time line. Consequently, it is concluded that the analytical solution is comparable with the numerical solution. For STSAT-I case, the thermal analysis predicts that the final temperature is additionally raised by about 1 $^{\circ}C$ due to molecular heating by air.

With proper assumptions and space environmental information, the present methods can be expended to general tools for first-cut thermal analysis of launch stage.

References

1. Choi, J. M., Kim, H. K., and Hyun, B. S., 2003, " Thermal Analysis on Satellite during Launch Stage by Analytical Solution", *Proceedings of the KSAS Spring Annual Meeting*, pp. 694-697

2. Spiegel, M. R., 1985, *Mathematical Handbook of Formulas and Tables*, Schaums Outline Series, Korea Student Edition, McGraw-Hill, pp. 73-74

3. *Cosmos Launch System-Payload User's Manual-2.1*, 1999, OHB System-TEAM