Heat Storage Material with Crystal Transformation for Micro- and Nano-satellites

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The thermal analysis of a micro cubic satellite pointing to the Earth on a sun-synchronous and circular orbit has been carried out using one-nodal analysis. The altitude of the orbit is 500 km. The local time of descending node of the orbit is 11 AM. The combination of the solar absorptivity and the infrared emissivity on the surface of the satellite under which the temperature of the satellite is kept within the allowable temperature range, from 0 to 40 degree Celsius, has been clarified. As the heat capacity is getting larger, the number of the combinations of the solar absorptivity and the infrared emissivity increases. In order to increase the heat capacity of micro- and nano-satellites, the development of a heat storage material has been performed. It is desirable that the heat storage materials for micro- and nano-satellites have the characteristic of not phase-change but crystal transformation at heat storage because a container for heat storage material is not required. Trans-1,4-polybutadiene transforms crystal structure at the temperature of heat storage. Trans-1,4-polybutadiene is produced and the heat storage performance is measured. The produced trans-1,4-polybutadiene has the amount of heat storage of about 80 J/g at the heat storage temperature of 74 °C This amount corresponds to about 70% amount of heat storage of a literature data (112 kJ/kg). The density of the produced trans-1,4-polybutadiene is 706 kg/m^3.

Nomenclature

a = albedo factor, -
A_p = projected area, m^2
c = specific heat, J/(kg K)
F = configuration factor, -
G_s = solar constant, W/m^2
H = altitude, km
l = length of side of satellite, m
m = mass, kg
q_{IR} = Earth IR radiation, W/m^2
R_e = radius of Earth, 6378.14 km
t = time, s
T = temperature, K
α = solar absorptivity, -
ε = infrared emissivity, -
θ_s = true anomaly, rad
π = circular constant
σ = Stefan-Boltzmann constant, 5.67×10-8 W/(m^{2}K^4)
Subscripts
$ns\text{-}e$ = from Earth-pointing surface of a satellite to Earth

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ps-e	=	from the surface parallel to the position vector of a satellite to Earth

I. Introduction

Micro- and nano-satellites of not more than 100 kg in mass have been developed actively. It is expected that the micro- and nano-satellites realize the mission in a short period after the acceptance of order. The design, the analysis, the fabrication, and the tests of micro- and nano-satellites are required to complete for a short time.

The temperature control of micro- and nano-satellite is difficult. The temperature of micro- and nano-satellite changes easily because the heat capacity of micro- and nano-satellite is small. Heaters, thermal louvers, heat switches, phase-change materials, pumped fluid loops, thermoelectric coolers and heat pipes are well known as thermal control devices in the satellites more than 100 kg.[1] The resource of electricity assigned to the temperature control subsystem is not enough to control the temperature of all units mounted in a micro- and nano-satellite actively. There is a severe restriction in mass of a micro- and nano-satellite in the case that the micro- and nano-satellite is launched by utilizing the piggyback system. It is difficult to mount traditional thermal louvers and pumped fluid loops from the viewpoint of the restrict in mass. The space for integrating a thermal control device is limited because the units are crowed in the micro- and nano-satellite. The pipe arrangement of heat pipe is quite difficult in micro- and nano-satellites. There are some units in micro- and nano-satellites which generate large amount of heat for a short time such as a radio transmitter. The radio transmitter used in micro- and nano-satellites generates several dozen watts for maximum 10 minutes to communicate between a ground station and the micro- and nano-satellite.

Ueno et al. is developing a MEMS-based small heat switch utilizing a near-field effect.[2] Hiroki et al. is developing a MEMS-based small thermal louver that works with an elastic force of a torsion bar and an electrostatic force.[3] We pay attention to the thermal control device which store heat temporarily because there are some units in micro- and nano-satellites which generate large amount of heat for a short time such as a radio transmitter. The traditional heat storage materials store heat with the phase-change from solid to liquid. The liquid storage material needs a container that leads to the increase in mass. The liquid phase does not contact with a wall of the container in a micro gravity condition in the case that the wetting characteristic between the heat storage material and the wall of the container is not good. We believe that the heat storage material not with phase-change but with crystal transformation has big attraction as the thermal control device for micro- and nano-satellites.

The final goal of this study is to simplify the thermal design by developing the thermal control device fitting to micro- and nano-satellites and to complete the thermal design of a micro- and nano-satellite for a short period less than 1 year. In this paper, first, the sensitive parameter for the temperature control is found out by the thermal analysis of a micro satellite. Then, a heat storage material with crystal transformation is focused as the temperature control device fitting to micro- and nano-satellites. Finally, the amount of heat storage and the temperature at the heat storage of the heat storage material with crystal transformation are examined.

II. Sensitive Parameter for Temperature Control of Micro- and Nano-satellite

Table 1 shows the specifications of the micro satellite used in a thermal analysis. The combinations of the solar absorptivity and the infrared emissivity which keep the temperature of the micro satellite within the allowable temperature range under the worst cold case and the worst hot case shown in Table 2 are calculated by means of a one-nodal analysis method.[4]

Table 1. Specifications of micro satellite for thermal analysis.

Shape	Cube
Dimensions	0.30 m × 0.30 m × 0.30 m
Mass	25 kg
Heat capacity	17,200 J/K
Orbit	Sun-synchronous and circular
Altitude	500 km
Local time of descending node	11:00 AM
Attitude	Earth-pointing

Setting method of solar cell	Body-mounted
Allowable temperature range	0 to 40 °C

Table 2. Worst cold and hot cases.

	Worst cold case	Worst hot case
Earth IR radiation	140 W/m^2	258 W/m^2
Solar flux	1309 W/m^2	1399 W/m^2
Albedo	0.15	0.6
Initial temperature	10 °C	25 °C
Initial position	Entrance of shadow region	Exit of shadow region

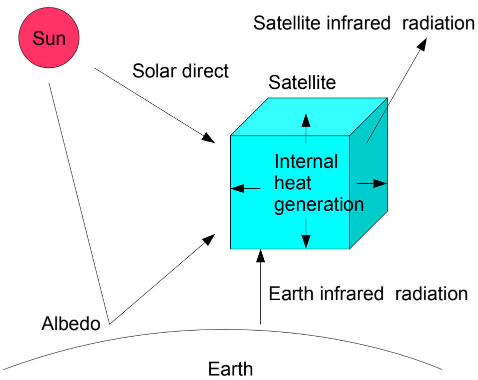


Figure 1. Schematic of heat input to satellite and heat output from satellite.

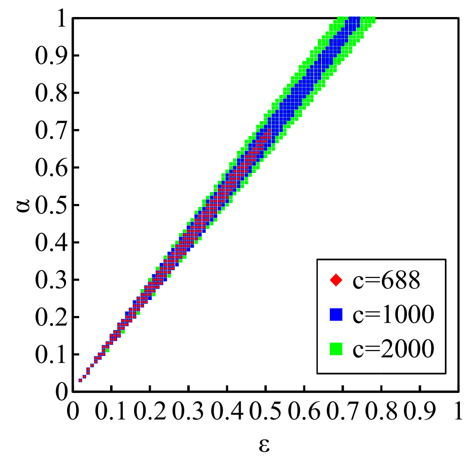


Figure 2. Combinations of solar absorptivity and infrared emissivity on outside surface of micro satellite that keep temperature of micro satellite within allowable temperature range under worst cold case and worst hot case. Solar absorptivity and infrared emissivity are calculated at the intervals of 0.01.

Figure 1 shows the schematic of heat input to and heat output from the micro satellite. The solar direct, the albedo, and the Earth infrared radiation are considered as the heat input to the micro satellite. The heat output from the micro satellite is the infrared radiation from the micro satellite. The energy equation of the micro satellite in the sunshine region and in the sunshade region are expressed by Eq.(1) and Eq.(2), respectively.

$$G_s A_p \alpha + q_{IR}(F_{ns-e} l^2 + 4F_{ps-e} l^2)\varepsilon + G_s a(F_{ns-e} l^2 + 4F_{ps-e} l^2)\alpha\cos\theta_s - \varepsilon 6 l^2 \sigma T^4 = mc\frac{dT}{dt} \ . \quad (1)$$

$$q_{IR}(F_{ns-e} l^2 + 4F_{ps-e} l^2)\varepsilon - \varepsilon 6 l^2 \sigma T^4 = mc\frac{dT}{dt} \ . \quad (2)$$

The first term in the left hand side in Eq. (1) shows the heat transfer rate of solar direct. The second term indicates the heat transfer rate of Earth infrared radiation. The third term means the heat transfer rate of albedo. Bannister approximation[5)] is used in the albedo factor. The fourth term is the heat transfer rate of the infrared radiation emitted from the whole surface of micro satellite. It is known that the configuration factors in the second and the third term are expressed as the following equation, respectively:[6]

$$F_{ns-e} = \left(\frac{R_e}{R_e + H}\right)^2 , \quad (3)$$

$$F_{ps-e}=\frac{1}{\pi}\left(\tan^{-1}\frac{1}{\sqrt{\left(\frac{R_e+H}{R_e}\right)^2-1}}-\frac{\sqrt{\left(\frac{R_e+H}{R_e}\right)^2-1}}{\left(\frac{R_e+H}{R_e}\right)^2}\right). \quad (4)$$

Figure 2 shows the combinations of solar absorptivity and infrared emissivity which keep the temperature of the micro satellite within the allowable temperature range under the worst cold case and the worst hot case. The solar absorptivity and infrared emissivity are calculated at the intervals of 0.01. The red diamonds, the blue squares, and the light green squares indicate the combinations in the case of the specific heat of 688, 1000, and 2000 J/(kg K), respectively in Fig. 2. The specific heat of 688 J/(kg K) corresponds to 80% of Aluminum Alloy A7050-T7451. The specific heat of 2000 J/(kg K) means about a half of the specific heat of water. As shown in Fig. 2, the number of the combinations increases with the larger specific heat. It means that the increase of the specific heat in the whole micro satellite leads to the increase of the number of the combinations and the easiness of a thermal design of the micro satellite.

The projected area A_p in Eq. (1) includes the square of the length of one side of the micro satellite l^2. It is clear from Eq. (1) and (2) that the temperature change rate dT/dt depends on the parameter of mc/l^2. It is clarified that the increase of the mass of the micro satellite, the increase of the specific heat, and the decrease of the length of one side of the micro satellite are effective to decrease the temperature change rate. There is a restrict in the mass of the micro satellite in the case that the micro satellite is launched with the main satellites. Most of micro-satellites have been launched with the main satellites. There is a lower limit about the size of micro satellite that the micro satellite does not become smaller than the size of the units mounted in the micro satellite. We believe that the increase of the whole specific heat of the micro satellite contributes most effectively to decrease the temperature change rate. The decrease of the strength of the structures with the increase of the specific heat is not accepted because the micro satellite need to hold with respective to the large vibration and shock in the launch of a rocket. A structural material mixed the material with a high specific heat without the decrease of strength of the material and the setting of the material with a high specific heat at the units with a high waste heat are effective to decrease the temperature change rate.

III. Requirements of Heat Storage Material for Micro- and Nano-satellite

Table 3 shows heat storage materials which storage heat the temperature between 6 degree Celsius and 72 degree Celsius. Most of the heat storage materials store heat by means of the phase change from solid to liquid. The liquid phase does not contact with a heat transfer surface in a micro gravity condition in the case that the wetting characteristic between the heat storage material and the heat transfer surface is not good. The heat transfer between the heat storage material and the heat transfer surface decreases extremely in that case. A liquid has a trend that a liquid produces more outgas than a solid. A trans-1,4-polybutadiene is suitable for the heat storage material in the space use from viewpoints of the outgas and the contact between the heat storage material and the heat transfer surface.

Table 3. Heat storage materials.[7, 8]

Materials	Temperature of heat storage	Amount of heat storage	Method of heat storage
n-Tetradecane ($C_{14}H_{30}$)	6 °C	228 kJ/kg	Phase change from sold to liquid
n-Hexadecane ($C_{16}H_{34}$)	17 °C	237 kJ/kg	Phase change from sold to liquid
n-Octadecane ($C_{18}H_{38}$)	28 °C	244 kJ/kg	Phase change from sold to liquid
n-Eicosane ($C_{20}H_{42}$)	37 °C	246 kJ/kg	Phase change from sold to liquid
n-Octacosane ($C_{28}H_{58}$)	62 °C	253 kJ/kg	Phase change from sold to liquid
Trans-1,4-polybutadiene	72 °C	112 kJ/kg	Crystal transformation

Table 4. Purity of initial chemical components.

Chemical components	Purity
Irganox 1076	98.0% minimum
Butadien	99% minimum
Diethylaluminum chloride	15% in Hexane
Ethanol	99.5%
Toluene	99.5%
Vanadium oxytrichloride	99%

IV. Trans-1,4-polybutadiene

A. Process of manufacture

Trans-1,4-polybutadiene has been produced by means of the same way with the previous report.[8] The recipe for making the trans-1,4-polybutadiene is shown as follows: 1) Put toluene 37.5 L and butadien 12.5 L in the autoclave substituted for nitrogen. 2) Put vanadium oxytrichloride 250 mmol as a catalyst in the autoclave. Put diethylaluminum chloride 1250 mmol as a promotor in the autoclave and start the polymerization. The polymerization is carried out in the nitrogen at -5 degree Celsius for 30 minutes. 3) Put twice volume of ethanol with respect to the polymerization solution in the autoclave, precipitate the polymer and filter the polymer. 4) After the filtering polymer is washed in ethanol, oxidation inhibitor Irganox 1076 3 wt% is mixed in the solution, the polymer is finally desiccated.

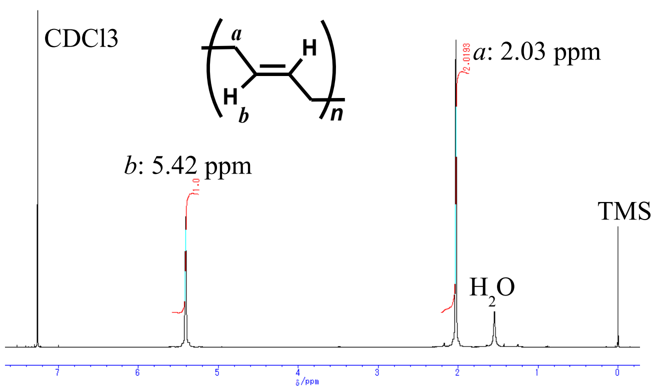


Figure 3. 1H NMR spectrum of produced trans-1,4-polybutadiene measured in CDCl3.

The purity of initial chemical components is indicated in Table 4. Figure 3 shows the ^{1}H NMR spectrum of the produced trans-1,4-polybutadiene measured in CDCl3. The reference material is TMS. Water is included in CDCl3. The ratio of integral vales of hydrogen corresponds to Trans-1,4-polybutadiene. Figure 3 means that the impure substance is not almost included in the produced trans-1,4-polybutadiene. The influence of the purity of initial chemical components is small.

The mass and the volume of the produced trans-1,4-polybutadiene have been measured. The density of the produced trans-1,4-polybutadiene is 706 kg/m.^{3}

B. Measurement of storage of heat

The amount of heat storage of produced trans-1,4-polybutadiene was measured using Differential Scanning Calorimeter (DSC), METTLER TOREDO DSC 1. The measurements are carried out after the temperature of trans-1,4-polybutadiene rises from 25 °C to 200 °C under nitrogen atmosphere, the temperature keeps at 200 °C for 10 minutes and trans-1,4-polybutadiene melts perfectly, the temperature is dropped from 200 °C to 25 °C. In

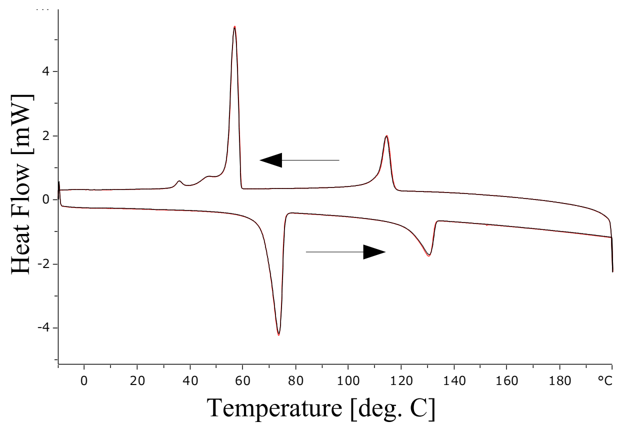
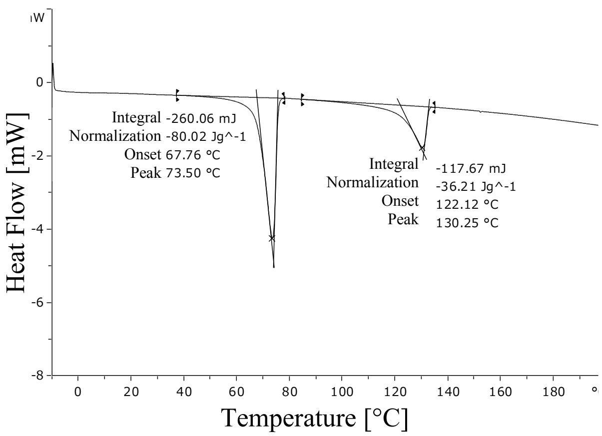


Figure 4. Comparison of DSC curves between 1st and 2nd measurement at 5 °C/min. temperature rising and -5 °C/min. temperature falling.



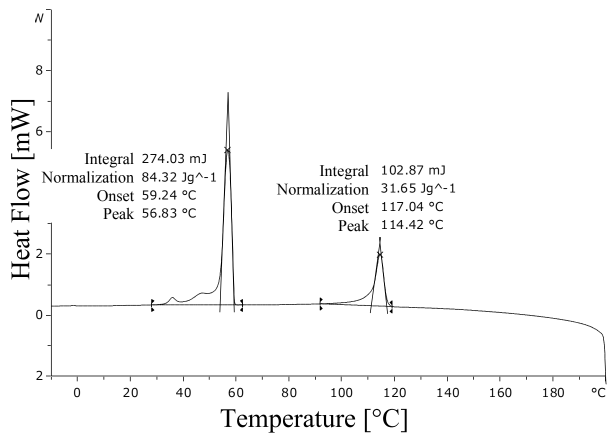


Figure 5. DSC curve at 5 °C/min. temperature rising. Figure 6. DSC curve at -5 °C/min. temperature falling.

measurements of storage of heat, the temperature rises from -10 °C to 200 °C at a constant rate and is dropped from 200 °C to -10 °C at a constant rate.

C. Results and discussion of storage of heat

Figure 4 shows the DSC curve in the case that the temperature rises at +5 °C per minute and the temperature drops at -5 °C per minute. The lower curve indicates the DSC curve at the temperature rise. The another curve is the DSC curve at the temperature drop. The left endoergic reaction in the lower curve and the left exoerginc reaction in the higher curve means heat storage and heat release by the crystal transformation from a solid phase to the other solid phase, respectively. The right endoergic reaction in the lower curve and the right exoerginc reaction in the higher curve means heat storage by the phase change from a solid phase to a liquid phase and heat release by the phase change from a liquid phase to a solid phase, respectively. Figure 4 has the first (black line) and second (red line) measurement. The two curves correspond to each other. It is clear that repeatability is good.

Figure 5 shows the DSC curve at the temperature rise of +5 °C. per minute and the amount of heat storage at the crystal transformation from a solid phase to the other solid phase and at the phase change from a liquid phase to a solid phase. It is clarified that the amount of heat storage is about 80 J/g at the crystal transformation and 36 J/g at the phase change. The obtained amount of heat storage at the crystal transformation corresponds to 71% of the previous reported amount of heat storage, 112 kJ/kg.[8]

Figure 6 shows the DSC curve at the temperature drop of -5 °C per minute and the amount of heat release at the crystal transformation from a solid phase to the other solid phase and at the phase change from a liquid phase to a solid phase. It is clarified that the amount of heat release is about 84 J/g at the crystal transformation and about 32

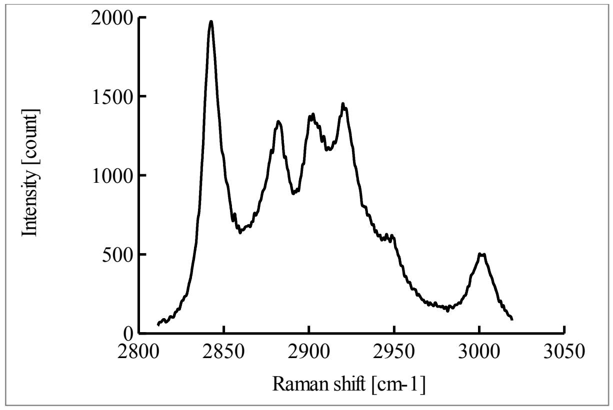


Figure 7. Raman shift of CH2 band of trans-1,4-polybutadien in Figs.4-6.

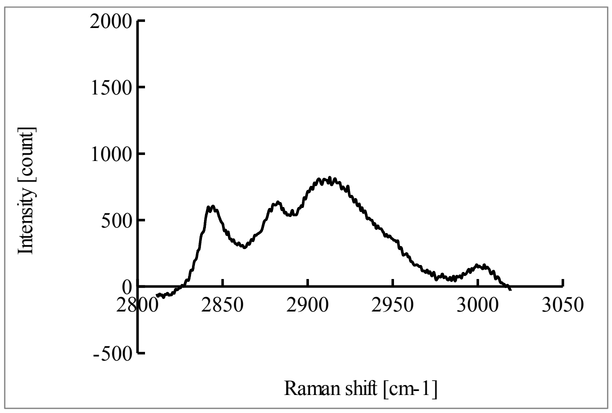


Figure 8. Raman shift of CH2 band of tran-1,4-polybutadien with much degradation.

J/g at the phase change. The measured peak temperature of about 57 °C at the crystal transformation in the case of the temperature drop. It is clarified that the peak temperature in the case of the temperature drop is quite different from one in the case of the temperature rise.

Figures 7 and 8 show raman shifts of -CH_2 band of trans-1,4-polybutadien in Figs. 4 to 6 and with much degradation. The amount of storage heat of trans-1,4-polybutadien with much degradation was less than 10% of the literature data. The measurement equipment was Renishaw Raman Micro Scope inVia Rellex. It is clarified that two peaks between 2900 cm^{-1} and 2950 cm^{-1} in Fig. 7 change to one peak in Fig. 8. This means that the structure of -CH_2 changed. It is known that H dissociates from -CH_2 group adjacent to the double bond between C and C by autoxidation in the case of the degradation of a polymer.[9] The storage time from production to the measurement was about 1.5 years. The storage temperature was the room temperature. It is suspected that the degradation of the produced trans-1,4-polybutadiene causes the difference of the amount of heat storage between the measurement data and the literature data.

Table 5 shows the transition temperature of the crystal transformation and the amount of endoergic or exoergic heat at some rates of temperature rise or temperature drop. The transition temperature shifts to the higher temperature as the higher rate of temperature rise and shifts to the lower temperature as the higher rate of temperature drop. It is known that these phenomena is a typical characteristic of DSC measurements. It is suspected that the difference of transition temperature at temperature rise and temperature drop could be caused by the supercooling phenomena and superheating phenomena.

The heat storage temperature about 50 °C is desirable for the heat storage material of micro- and nano-satellites. The decrease of the transition temperature is a future work. The endoergic heat bottoms out at about 70% of a literature data, 112 kJ/kg.[8] The increase of endoergic heat is a future work. Although it is clarified from Fig. 3 that trans-1,4-polybutadiene has a good repeatability, the endoergic and exoergic process from one thousand times to ten thousand times is required for the heat storage material of micro- and nano-satellites. A future work is to study the dependency on the number of heat storage and heat release. The thermal conductivity of trans-1,4-polybutadiene was measured by using Kyoto Electronicsis Manufacturing Co., Ltd. Thermal Measuring Instrument TPS 2500 S. The thermal conductivity is 0.38 W/(m K), which is comparable to that of a glass epoxy plastic, 0.47 W/(m K), that is a insulator. It is recommended to set a thin plate of trans-1,4-polybutadien on a chasis and to mix the powder of trans-1,4-polybutadien in a thermo-setting resin of carbon fiber reinforced plastic. The increase of thermal conductivity of trans-1,4-polybutadien is a future work.

Table 5. Transition temperature and exoergic or endoergic heat.

Temperature rising or falling rate, °C/min.	Transition temperature, °C	Exoergic or endoergic heat, J/g
+2	72.63	-79.63
+5	73.50	-80.02
+10	75.00	-80.07
-2	58.00	+87.57
-5	56.83	+84.32
-10	54.83	+83.36

V. Conclusion

The thermal design of micro- and nano-satellites is difficult because the temperature of micro- and nano -satellites changes easily and enough electricity to control the temperature of all units actively can not be assigned. The thermal analysis of a micro satellite and the development of a heat storage material are carried out to overcome the difficulty of thermal design of micro- and nano-satellites. It is clarified that as the heat capacity over the square of the length of one side of the micro satellite is larger, the temperature change rate of the micro satellite decreases. Trans-1,4-polybutadiene has the attractive characteristic of heat storage by crystal transformation from viewpoint of relaxing the difficulty of the thermal design of micro- and nano-satellites. The produced trans-1,4-polybutadiene has the amount of heat storage of about 80 J/g at the heat storage temperature of 74 °C. This amount corresponds to about 70% amount of heat storage of a literature data (112 kJ/kg). Future works are: 1) to study the change of the amount of heat storage under the large number of heat storage and heat release; 2) to decrease the heat storage temperature; 3) to increase the amount of heat storage.

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