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Research paper

Development of a heat storage panel for micro/nano-satellites and demonstration in orbit

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HIGHLIGHTS

- A new thermal control device called the HSP was proposed.
- In the thermal vacuum test, the HSP could decrease the temperature range of itself.
- The HSP exhibited a performance in accordance with a design on orbit.

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ABSTRACT

This study describes the proposal, fabrication, testing, and demonstration of a new thermal control device called a heat storage panel (HSP) for micro/nano-satellites. The HSP consisted of a phase change material (PCM) and a thin panel-shaped container made of a high-thermal-conductivity pitch-based carbon-fiber-reinforced polymer (CFRP). The internal PCM was used to increase the apparent heat capacity with a small mass gain, whereas the high-thermal-conductivity CFRP was used to enhance heat dissipation. The HSP was examined using thermal vacuum tests and thermal analysis. The HSP's continuous phase change reduced the temperature fluctuation in the space chamber. Furthermore, the HSP was loaded and examined on a Japanese micro-satellite called Hodoyoshi-4. In this on-orbit test, the HSP functioned as designed, and the temperature profile obtained on orbit agreed well with the thermal analysis. These results show the HSP's high potential for the thermal control of micro/nano-satellites.

1. Introduction

Over the past 10 years, a more severe demand for reducing costs and shortening development periods in the satellite industry has stimulated research and development of micro/nano-satellites weighing less than 50 kg. The number of micro/nano-satellites launched in 2013 was more than nine times that in 2003 [1]. On the other hand, the thermal condition of a micro/nano-satellite is quite different from that of a conventional large satellite because of (i) limited power resources, (ii) small heat capacity, (iii) insufficient radiator area, (iv) high-density packing of electronics, and (v) mass limitations. Thus, micro/nano-satellites are generally less thermally controllable than larger satellites. For example, NASA's Edison Demonstration of Smallsat Networks (EDSN) nanosatellite is restricted in its operating time because of heat dissipation from mission devices [2]. To improve the thermal controllability for micro/nano-satellites, we require a new methodology and a new thermal control device that is smaller than that on conventional satellites and that needs no electrical power.

Heat storage using phase change materials (PCMs) is a strong candidate for solving micro/nano-satellites' thermal difficulty because PCMs can increase a satellite's apparent heat capacity with little mass gain and no electrical power. In other words, PCMs can absorb or generate heat in the form of latent heat, changing their phase and minimizing the temperature fluctuation around the phase change point. Research on the utilization of PCMs for spacecraft has flourished in recent years. For example, NASA has studied several types of PCM heat storage. For manned spacecraft, the Johnson Space Center is studying a “water-based PCM heat exchanger”; water is a typical PCM [3]. For Mars rovers, the Jet Propulsion Laboratory proposed a thermal storage system using dodecane [4]. Furthermore, for the ExoMars 2016 mission, the European Space Agency plans to use a “phase change thermal capacitor” with several types of paraffins [5]. However, the

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Nomenclature

HSP	Heat Storage Panel
CFRP	Carbon-Fiber-Reinforced Polymer
PCM	Phase Change Material
DSC	Differential Scanning Calorimetry

abovementioned devices are designed for large (over 100 kg) spacecraft and are very heavy for small satellites. The major factor increasing the mass is the additional components of PCM devices; these components include (i) a thermal conduction member to compensate for PCMs' low thermal conductivity and (ii) a strong container to bear the volume change that arises with phase change. For example, to gain better thermal conduction, the phase change thermal capacitor has aluminum foams beside the PCM container [5]. Therefore, to decrease the mass of the PCM devices, one big challenge is to make up for the PCMs' low thermal conductivity.

At Nagoya University, a new thermal control device called a “heat storage panel” (HSP) is currently under development [6–8]. The HSP is a thin carbon-fiber-reinforced polymer (CFRP) panel with an encapsulated PCM. The HSP is attached to an electronic device that exhausts heat temporally or is exposed to cyclic heat flux. The HSP's PCM can increase a satellite's apparent heat capacity and moderate the temperature fluctuation of installed devices. Thus far, the HSP has been examined using space-based and terrestrial tests. The HSP's on-orbit demonstration was conducted on the Japanese micro-satellite called Hodoyoshi-4. Before the on-orbit test, the HSP was examined using model analysis and thermal vacuum tests. This study presents the results of these tests and analysis, in addition to the concept of the HSP.

2. Heat storage panel

2.1. Concept of a heat storage panel

The HSP is a thin CFRP panel with a PCM injected into it. The high-thermal-conductivity CFRP panel compensates for the low thermal conductivity of the PCM. The HSP is shown in Fig. 1. In satellites, some components such as communication systems generate heat periodically. This heat sometimes changes the temperature of the satellite components drastically. If the HSP is attached to such components, it can increase the apparent heat capacity of the attached device, and this increased capacity enables the satellite to change temperature over a small range. Thanks to such functionality, the HSP can deal with abnormal heat without any additional radiators, thereby simplifying the thermal design of spacecraft. For example, additional oversized radiators are equipped in some satellites to deal with heat generated temporally; the HSP can be substituted for such additional radiators. This means that heat from the radiators at a low temperature can be cut off, and the power for the heaters may be significantly reduced.

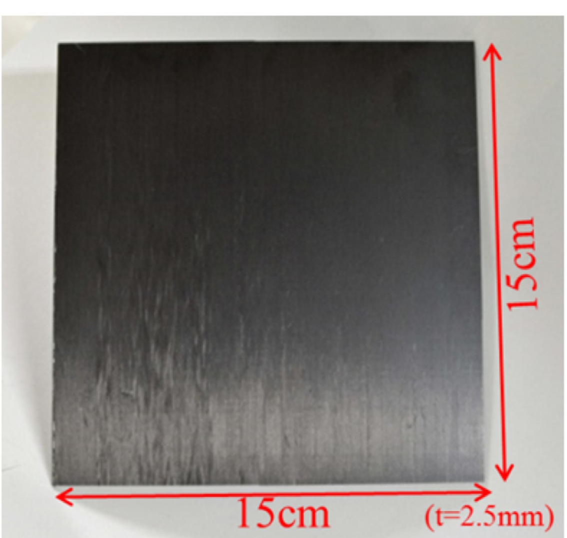

Fig. 1. Heat storage panel.

Compared with other PCM heat storage devices, the HSP has the three features as follows: thinner shape, higher specific strength, and higher thermal diffusivity. While utilizing these features, the HSP can be used not only as a heat storage device but also as a honeycomb face stem/sheet or thermal doubler. Such multifunctional equipment is greatly advantageous for small satellites. Furthermore, the three features enable the container to function as a thermal conductor for the PCM, which may contribute to the HSP's lightness.

2.2. Structure of the heat storage panel

Basically, the HSP comprises a thin pitch-based CFRP panel that has been injected with the PCM. As shown in Fig. 2, the HSP consists of three parts: one center container part that has four rooms for the PCM and two cover parts that are placed on both sides of the center part. Each part is fabricated by molding several layers of prepreg; prepreg is a unidirectional carbon fiber sheet soaked in composite resin. To obtain a uniform in-plane thermal conductivity, the carbon fiber of each prepreg layer is orthogonal to that of the adjacent layer. The specifications of each part of the HSP are shown in Table 1. The thicknesses are designed to bear the internal pressure caused by the changing volume of the PCM [9]. The HSP's pitch-based CFRP container functions as a thermal conduction member because of its high thermal conductivity and thin shape (2.5 mm thickness). The CFRP for the HSP, NT91500-525s by the Nippon Graphite Fiber Corporation, has a thermal conductivity of 347 W/m K, which is higher than aluminum alloy's 237 W/m K, in the carbon fiber direction, and the thermal conductivity in the cross-sectional direction is 3.0 W/m K. The thermal conductivity of this prepreg was estimated from thermal diffusivity that was measured by the cyclic heat method [10]. Furthermore, this type of CFRP is better than an aluminum alloy in terms of mass-specific strength rigidity. This pitch-based CFRP's excellent characteristics realize a thermally conductive container with a small mass. The HSP is 40% lighter than an aluminum heat storage device with the same storage capacity.

For the PCM inserted into the HSP, eicosane ($C_{20}H_{42}$), a type of paraffin, is adopted because of its high latent heat capacity (226 J/g) [6]. Moreover, the phase change point of eicosane (36.4 °C) [11] is

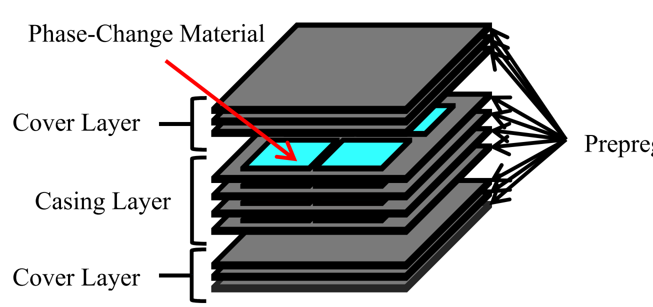

Fig. 2. Structure of HSP.