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Proton Irradiation Effects on Thermophysical Properties of High-Thermal-Conductivity Graphite Sheet for Spacecraft Application[1]

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This paper describes an evaluation of the proton irradiation effects on the thermal characteristics of a pyrolytic graphite sheet (PGS), which has characteristics of high thermal conductivity, light weight, and flexibility, in order to apply this material to an advanced spacecraft thermal control device, the reversible thermal panel (RTP). The results show slight changes in the in-plane thermal diffusivity and total hemispherical emittance of the PGS for 2.0 MeV proton irradiation. An RTP prototype model based on the PGS was designed and fabricated, and its thermal performance was evaluated. The effects of changes in thermal characteristics of the PGS on the thermal performance of the RTP were also discussed.

KEY WORDS: graphite sheet; high thermal conductivity; proton irradiation effects; reversible thermal panel; solar absorptance; spacecraft thermal control; thermal diffusivity; total hemispherical emittance.

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1. INTRODUCTION

The current spacecraft trend toward high density packing of payload electronics and the resulting increased waste heat flux will require development of lightweight high thermal conductive materials and innovative thermal control techniques. In addition, new and challenging missions, such as interplanetary, deep space, and lander missions, will require the use of new techniques to adapt to a variety of environmental conditions. To this end, a new passive, lightweight, and environmentally adaptive thermal control device—a reversible thermal panel (RTP)—which changes its function from a radiator to an absorber by deploying/stowing a reversible fin, upon changes in heat dissipation and thermal environment, has been investigated at the Institute of Space and Astronautics and Science (ISAS/JAXA) and Keio University [1, 2]. The RTP consists of a base plate, heat transport units, and a passively reversible rotary actuator. The radiator side has a low solar absorptance (α_S) to the total hemispherical emittance (ε_H) ratio (α_S/ε_H), while the absorber side has a high α_S/ε_H. By deploying/stowing the reversible absorber/radiator fin under different equipment temperatures, the RTP reverses its function from that of a radiator to that of a solar absorber (Fig. 1).

As the base material of the RTP, the application of a new conductive material—a pyrolytic graphite sheet (PGS)—which has characteristics of high thermal conductivity, light weight, and flexibility, has been considered [2]. The PGS, which has been developed by Matsushita Electric Industrial Co., Ltd., is prepared from aromatic polyimide films by heat treatment at 2900–3300 K in an inert atmosphere. The dimensions of this sheet are 500 mm × 360 mm × 0.1 mm, its density is $0.84\,\mathrm{g\cdot cm^{-3}}$, and the root-mean-square roughness of its surface is about 2.5 μm. In order to use the PGS as a spacecraft thermal control material, it is essential to determine its temperature dependence of thermal diffusivity, specific

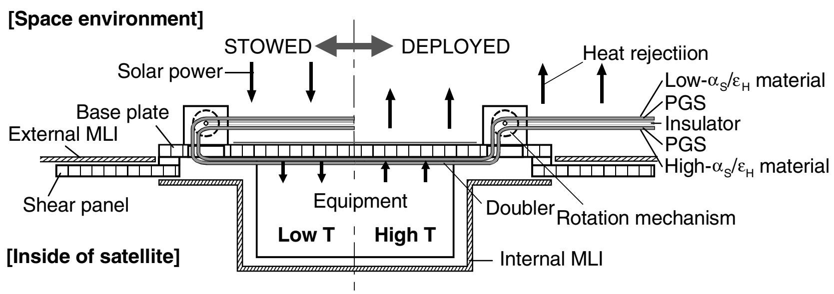

Fig. 1. Schematic view of reversible thermal panel (RTP).

heat, and total hemispherical emittance, and incident angle dependence of solar absorptance. The durability of the thermal characteristics of the PGS against proton, electron, and UV irradiation in severe space environments is also to be evaluated. The in-plane and out-of-plane thermal diffusivities have been measured over the temperature range from 100 to 350 K using a laser heating ac calorimetric method [3]. The total hemispherical emittance has been measured over the temperature range from 173 to 373 K using a calorimetric method [4]. The solar absorptance has been measured using a spectroscopic method at incident angles ranging from 5° to 60° [4]. It was confirmed that PGS has strong potential for application as a material for RTP on the grounds of its high thermal conductivity, high α_S/ε_H value, flexibility, and light weight.

This paper reports on the effects of 0.5–2.0 MeV proton irradiation onto the thermal characteristics of the PGS in order to evaluate the use of this material in an actual space environment. Additionally, an RTP prototype model based on the PGS is designed and fabricated, and the thermal performance of the RTP based on the PGS is evaluated. The effects of the changes in thermal characteristics of the PGS on the changes in the RTP's thermal performances are also discussed.

2. BASIC THERMAL CHARACTERISTICS OF PGS

2.1. Thermal Diffusivity

The thermal diffusivity of PGS has been measured by a laser heating ac calorimetric method. This graphite sheet has large anisotropy, high thermal diffusivity, and it is only 100 μm thick. It is thus difficult to apply a conventional ac technique to this material. Therefore, we propose and adopt a simultaneous measurement method for the in-plane and out-of-plane thermal diffusivities, by analyzing the three-dimensional heat conduction process, which contains the effects of anisotropy and thermal wave reflections. The uncertainty of the present measurement is estimated to be within ±3.5% (in-plane) and ±11 to 52% (out-of-plane). A detailed explanation and description of the measurement method and equipment has been reported elsewhere [3, 5]. Figure 2 shows the measurement results of the in-plane thermal diffusivity, out-of-plane thermal diffusivity, and the anisotropy ratio for the PGS, which is defined as the in-plane thermal diffusivity divided by the out-of-plane thermal diffusivity. Their maximums occur at about 100 and 70 K, respectively. The anisotropy ratio of their thermal diffusivities increases from 25 to 50 as the temperature increases. The in-plane anisotropy between the x direction and the y direction was also measured but was not confirmed [5].

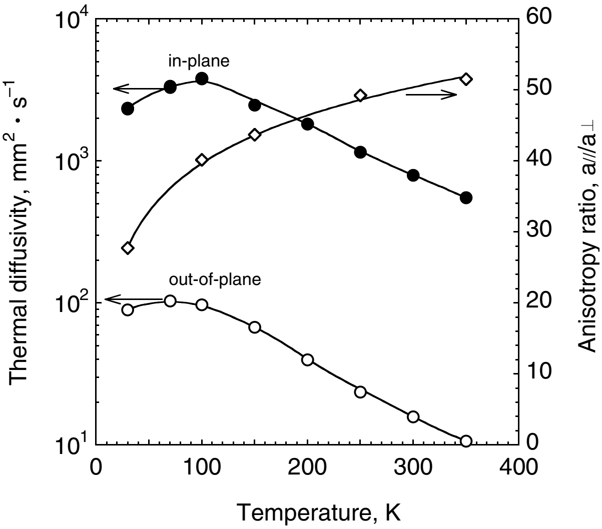

Fig. 2. Temperature dependence of the in-plane and out-of-plane thermal diffusivities of the PGS, and its anisotropy ratio.

2.2. Total Hemispherical Emittance and Solar Absorptance

The total hemispherical emittance of the PGS has been measured over a temperature range from 173 to 373 K by using a calorimetric method. The solar absorptance of the PGS has been measured by using a spectroscopic method over a wavelength range from 0.26 to 2.5 μm, which contains about 96% of the solar radiation intensity. The uncertainties of the present measurements are estimated to be within ±3.0% for the total hemispherical emittance, and ±2.0% for the solar absorptance. A detailed explanation and description of the apparatus have been reported elsewhere [4]. The results of the measurements of the total hemispherical emittance in the temperature range from 173 to 373 K are shown in Fig. 3. The total hemispherical emittance increases as the temperature increases. The value of the total hemispherical emittance changes from 0.22 to 0.32 with an increase of the temperature. Figure 4 shows the incident angle dependence of the solar absorptance calculated using the measured spectral reflectance of the PGS in a wavelength range from 0.26 to 2.5 μm. The values of the solar absorptance for incident angles of 5°, 30°, and 60° are 0.72, 0.72, and 0.67, respectively.

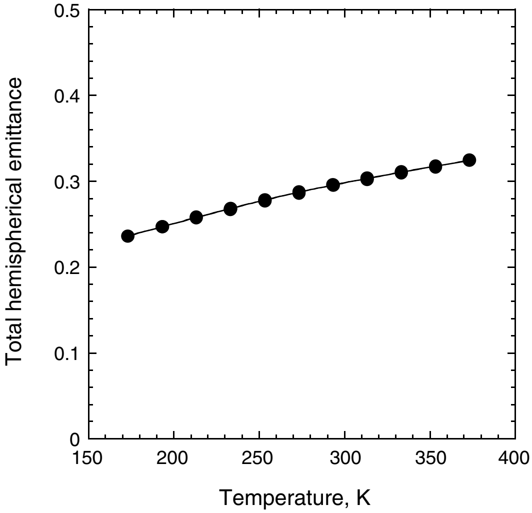

Fig. 3. Temperature dependence of the total hemispherical emittance of PGS.

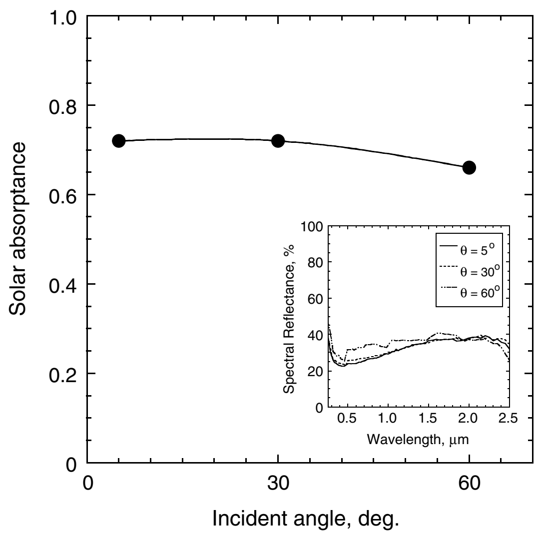

Fig. 4. Incident angle dependence of solar absorptance of PGS.

Table I. Proton Irradiation Test Conditions

Radiation energy (MeV)	Fluence ratio ($p^+ \cdot cm^{-2} \cdot s^{-1}$)	Fluence ($p^+ \cdot cm^{-2}$)
0.5	6.0×10^{11}	3.5×10^{13}
1.0	6.0×10^{10}	3.5×10^{11}
2.0	6.0×10^{11}	3.5×10^{13}

3. PROTON IRRADIATION TESTS

3.1. Test Facility and Conditions

The proton irradiation test was performed using a tandem accelerator at the National Institute of Advanced Industrial Science Technology Kansai. Protons were accelerated to energies of 0.5, 1.0, and 2.0 MeV at fluences of 3.5×10^{13}, 3.5×10^{11}, and 3.5×10^{13} $p^+ \cdot cm^{-2}$, respectively, corresponding to more than 20 years at 0.5 and 1.0 MeV in geostationary orbit, and 20 years at 2.0 MeV around Mercury [6, 7]. Table I gives an overview for the proton irradiation test conditions. The uncertainty of the irradiation energy is within 1.0%. The samples were mounted on a heat sink in a vacuum of less than 1.33×10^{-3} Pa, and their temperature was kept under 323 K during proton irradiation. After proton irradiation, samples were kept in a dark vacuum because recovery from degradation in atmosphere has been reported [8].

3.2. Irradiation Test Results

Figure 5 shows the relation between the proton irradiation energy and the in-plane thermal diffusivity of the PGS at room temperature. The differences in thermal diffusivity values among 0 MeV (non-irradiated), 0.5, and 1.0 MeV proton irradiation are very small, and are within the range of measurement uncertainty. On the other hand, the thermal diffusivity value for 2.0 MeV proton irradiation at a dose of 3.5×10^{13} $p^+ \cdot cm^{-2}$ is decreased by 4.1%. This change is considered to be due to the proton-induced degradation. Kitajima et al. [9] reports that the positive ion irradiation onto a graphite material creates point defects, and, as a result, the mean distance between defects decreases. Since the phonon mean free path, which determines the lattice thermal conductivity of the graphite materials, is limited by these detects, the degradation of the thermal conductivity of the PGS by proton irradiation is considered. In order to evaluate the relation between the degradation of PGS and irradiation energy, the penetration depth of the proton was calculated by

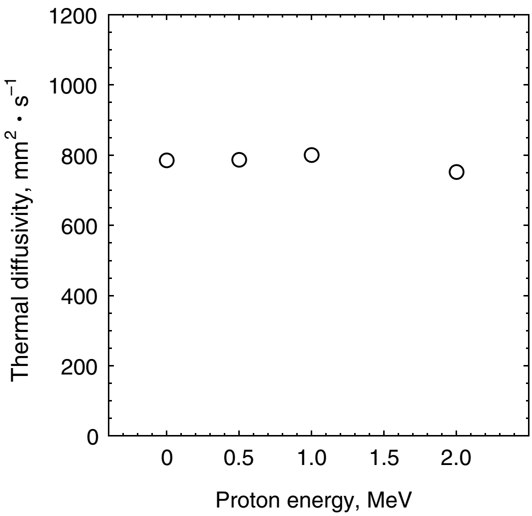

Fig. 5. Acceleration energy dependence of in-plane thermal diffusivity for proton-irradiated PGS.

using the TRIM code [10]. The penetration depth of 0.5, 1.0, and 2.0 MeV proton irradiation is calculated to be 0.472, 1.42, and 4.12 μm, respectively. Taking into account that the thickness of PGS is about 100 μm, it is clear that only its surface is damaged. Therefore, the measurement of the in-plane thermal diffusivity includes the combination of the thermal diffusivity of the degraded surface and that of the non-degraded inner part.

In order to use the PGS as a spacecraft thermal control material, more than a few pieces of PGS are to be laminated, as described later. Therefore, it is considered that the degradation of thermal diffusivity in a geostationary orbit and around Mercury does not practically affect the thermal system's performance. On the contrary, the total hemispherical emittance and solar absorptance are strongly dependent on the changes of the surface conditions, and the degradation of surface properties directly affects the thermal performance of the thermal system. Figure 6 shows the measurement results of the total hemispherical emittance and solar absorptance of proton-irradiated PGSs. The value of the total hemispherical emittance increases with the irradiation energy; it increases by 9.1% for 2.0 MeV proton irradiation at a dose of $3.5 \times 10^{13}\,p^+ \cdot cm^{-2}$. On the other hand, the degradation of solar absorptance is not confirmed since the changes of solar absorptance are less than 0.3%, which is within the range of measurement uncertainty.

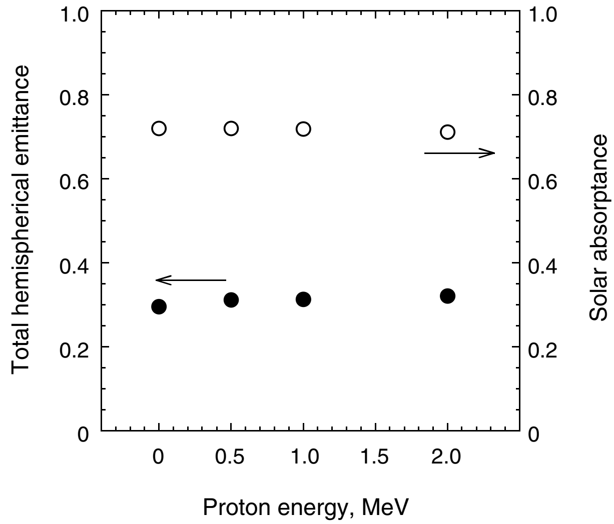

Fig. 6. Acceleration energy dependence of emittance and solar absorptance for proton-irradiated PGS.

4. APPLICATION TO RTP AND THERMAL PERFORMANCE EVALUATION

4.1. Application of PGS to Reversible Thermal Panel

A half-symmetrical, reversible-thermal-panel prototype model based on the PGS has been fabricated as shown in Fig. 7. The dimensions, shape, and thickness of the base plate and reversible fin were determined by parametric studies in order to satisfy the following thermal requirements [11]:

- The heat rejection capability, when the reversible fin is deployed and the equipment temperature is 333 K, is more than 100 W in the full-size model.
- The specific heat rejection, when the reversible fin is deployed and the equipment temperature is 333 K, is more than $150\,\mathrm{W \cdot kg^{-1}}$.
- The change in radiator fin efficiency with a change in the reversible fin position from the deployed position to the stowed position is about 0.4.

The RTP prototype model consists of a base plate, heat transport units, surface material, insulation film, an equipment simulator, solar simulators, and a passively reversible rotary actuator. A honeycomb sandwich

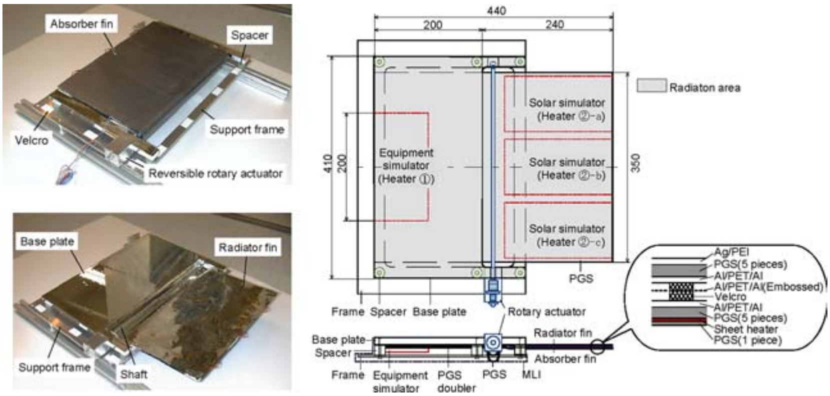

Fig. 7. RTP prototype model.

panel is used as the base plate. Ten sheets of PGSs are used as the heat transport units; five sheets are used as a radiator fin, and the other five sheets are used as an absorber fin. Each PGS sheet is attached with adhesive tape. Between the radiator fin and absorber fin, embossed double-side-aluminized Mylar is installed for thermal insulation in the out-of-plane direction. On the surfaces of the honeycomb base plate and PGS radiator fin, silverized polyester imide film (Ag/PEI) with a low α_S/ε_H value is attached for radiation. At the absorber fin side, the high α_S/ε_H value of the PGS is used. A detailed explanation and description of the test facilities and experimental conditions have been described elsewhere [2]. The thermal analysis was performed using a thermal network model in steady state. A three-dimensional numerical model, which is discretized into 299 nodes, was developed based on the prototype RTP model. The temperature dependence of the thermal conductivity of the PGS, which is calculated using the thermal diffusivity, the specific heat, and the bulk density, and total hemispherical emittance, was taken into account in the calculation. The thermophysical properties of aluminum alloys and the three-dimensional effective thermal conductivity of the honeycomb sandwich panel were obtained from Ref. 12. In advance, it had been confirmed that the anisotropy of the thermal conductivities for the PGS does not affect the thermal performance of the RTP because the thickness of the PGS fin is very thin relative to the length of the fin [1]. The thermal analysis was performed under the conditions listed in Table II. Figure 8 shows the analytical and experimental results of the fin-angle dependences of heat rejection under constant equipment temperatures of 253, 293, and 333 K. The analytical and experimental results agree within 3.0%.

Table II. Thermal Analysis Conditions

Equipment temperature	253–333 K
Environmental temperature	77 K
Solar heat input	0 W
Fin position	0° (stowed) to 180° (deployed)

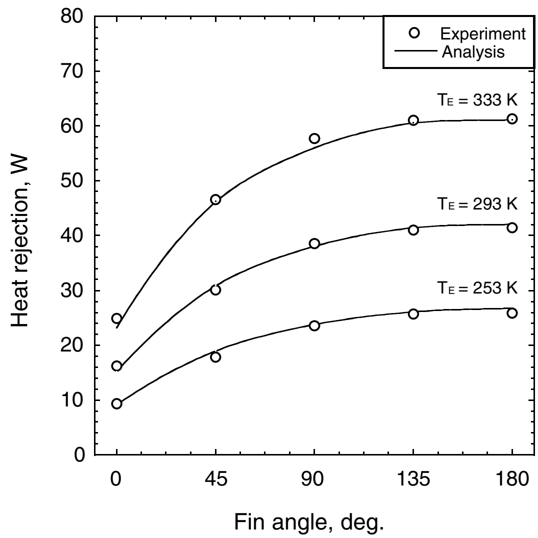

Fig. 8. Fin angle dependences of the RTP's heat rejection capability.

4.2. Effect of Properties Change of PGS on Thermal Performance of RTP

Next, using this analytical model, the thermal performance change of the RTP was evaluated with regard to the changes of the in-plane thermal conductivity and total hemispherical emittance of the PGS from −20% to +20%, when the reversible fin is stowed and deployed, respectively. Figure 9 shows the relation between the change ratio of thermophysical properties for the PGS and the change ratio of the thermal performance of the RTP when the equipment temperature is 333 K. The thermal performance varies from −6.2% to +6.1% with changes in thermal characteristics from −20% to +20%. It was confirmed that the heat rejection performance of the RTP when the reversible fin is deployed is sensitive to the in-plane thermal conductivity changes. On the other hand, the heat retention performance of the RTP when the reversible fin is stowed is sensitive

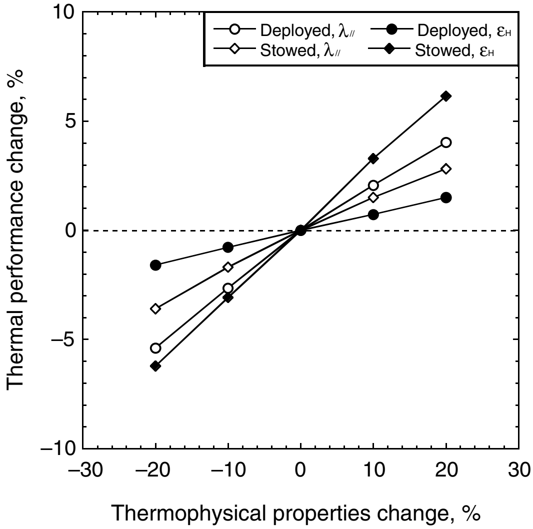

Fig. 9. Relation between the change ratio of thermophysical properties for the PGS and the change ratio of the thermal performance of the RTP.

to changes in the total hemispherical emittance. Proton irradiation test results, which show the degradation of total hemispherical emittance to be +9.1% at maximum for 2.0 MeV irradiation at a dose of $3.5 \times 10^{13}\,p^+ \cdot cm^{-2}$, confirmed that the change in the RTP's thermal performance, when the fin is deployed and stowed, is estimated to be less than +1.0% and +4.0%, respectively.

5. CONCLUSION

In order to apply a pyrolytic graphite sheet (PGS)—which has characteristics of high thermal conductivity, light weight, and flexibility—as a base material for a reversible thermal panel (RTP), the effects of 0.5–2.0 MeV proton irradiation on such thermal characteristics as the in-plane thermal diffusivity, total hemispherical emittance, and solar absorptance were experimentally evaluated. The results showed a slight degradation of total hemispherical emittance for 2.0 MeV proton irradiation at a dose of $3.5 \times 10^{13}\,p^+ \cdot cm^{-2}$. An RTP prototype model based on the PGS was designed and fabricated, and its thermal performance was evaluated. The relation between the ratio of thermophysical property changes of the PGS and the ratio of the thermal performances of the RTP was clarified analytically, and the change in the thermal performance of the RTP caused by proton irradiation to the PGS was evaluated. As a subject of future study, the effects of electron and UV irradiation to the PGS are to be examined.

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