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Emissivity of black plated open honeycomb and black coatings at cryogenic temperatures

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Abstract. A cryogenic radiator with high emissivity is required for ultra-sensitive astronomical observation missions. The use of a three-dimensional structure as well as black coatings is effective to achieve high emissivity at cryogenic temperatures. We focused on an open honeycomb with black plating, which has an advantage of low outgassing compared to painting. The emissivity of the open honeycomb with or without black plating and the flat surface with several black coatings was measured using calorimetric methods at 20-80K. The emissivity of the flat surface with a black coating showed a strong dependence on temperature. The black-plated open honeycomb had the highest emissivity up to 0.9, while the emissivity was around 0.5 in the case without black plating. The results suggest that the combination of an open honeycomb and black plating offers a promising solution to achieving high emissivity.

1. Introduction

Ultra-sensitive astronomical observation missions require the optical sensors to be maintained at cryogenic temperatures for thermal noise reduction. Such missions have recently employed a cooling system using cryocoolers and radiation to deep space instead of expendable cryogen. In such a system, it is essential to maximize radiation cooling to suppress the cooling capacity requirement of the cryocoolers. In other words, a high emissivity surface is desired as a radiator surface from room to cryogenic temperatures. However, a high emissivity surface at room temperature does not necessarily have high emissivity even at cryogenic temperatures, because the dominant wavelengths of infrared radiation become longer with decreasing temperature in accordance with Wien's displacement law.

High emissivity surfaces at cryogenic temperatures have been investigated for such astronomical observation missions as the Herschel/Planck spacecraft and the James Webb Space Telescope (JWST). As for Planck, the emissivity of various kinds of black paints was measured using calorimetric methods, and a black-painted open honeycomb was employed as the surface of the telescope baffle and a part of the V-groove radiators [1–4]. As for JWST, the emissivity of black coatings such as Z306, black anodize, and Ball IR BlackTM was measured at cryogenic temperatures using calorimetric methods [5]. In addition to the black coatings on the flat surface, the emissivity of the black-painted open honeycomb was also measured, recording emissivity greater than 0.95 in a temperature range above 30K.

Several ultra-sensitive astronomical observation missions such as SPICA are being studied at the Japan Aerospace Exploration Agency (JAXA), and thus require a cryogenic radiator with high



emissivity [6]. This paper describes the emissivity measurements of a flat surface with several kinds of black coatings and an open honeycomb with or without black plating, using calorimetric methods at cryogenic temperatures ranging from 20K to 80K.

2. Approaches for emissivity enhancement

The approaches for emissivity enhancement are classified as the following two methods.

2.1. Coatings

The emissivity of the surface can be enhanced by selecting a proper coating material and thickness. In this study, the following coating materials were selected: black paint, carbon nanotubes (CNT), and black plating. Black paint is commonly used to achieve high emissivity at room temperature. CNT is well known as the blackest surface, and reportedly has extremely low reflectance of 0.01-0.02 at the wavelength range from UV to mid IR [7]. Black plating is also a common blackening method, which has an advantage of low outgassing since it uses no organic compound.

2.2. Three-dimensional structures

Assuming a cavity as a three-dimensional structure, the incident light can be repeatedly reflected and trapped inside the cavity, resulting in an increase of apparent emissivity. The emissivity enhancing effect can be achieved without wavelength dependence as long as the wavelength is shorter than the aperture size of the cavity. Additionally, the cavity resonance can enhance the emissivity at specific wavelengths. It has been reported that as for a surface with periodic microcavities, the emissivity increased at wavelengths close to the cavity aperture dimensions and at those predicted by a simple theory of the cavity resonator [8]. This study selected an open honeycomb, a very common structure in space use, as a three-dimensional structure.

3. Emissivity measurements

3.1. Test pieces

Test pieces with different surface structures and coatings were prepared. Table 1 lists the details of the test pieces. The aluminium plate with dimensions of 50 mm × 50 mm × 3 mm was used as the flat surface except for CNT. As for CNT, a titanium plate was used due to the constraints regarding the formation process of CNT. The test piece of the open honeycomb was made of aluminium and had dimensions of 50 mm × 50 mm × 10 mm. The aluminium plate of 50 mm × 50 mm × 3 mm was adhered to back side of the honeycomb core.

Thickness of the black paint is usually on the order of several tens of μm . This study selected a larger thickness (130 μm) in considering that the targeted wavelength became longer at cryogenic temperatures. The test pieces of CNT with different heights (100 μm and 500 μm) were prepared to investigate the effect on emissivity. Tough Black® is the black plating having high emissivity at near IR wavelengths.

Table 1. Details of the test pieces.

Name of test piece	Surface	Coating
Desothane®-Flat	Flat surface	• Black paint (PPG Aerospace, Desothane®) • 130 μm in thickness
CNT100-Flat		• Carbon nanotubes, 100 μm in height
CNT500-Flat		• Carbon nanotubes, 500 μm in height
TB-Flat		• Black plating (Ebina Denka Kogyo, Tough Black®) • 20 μm in thickness
TB-OH	Open honeycomb • Cell size: 1/8"	• Black plating (Ebina Denka Kogyo, Tough Black®) • 20 μm in thickness
AL-OH		• No coating

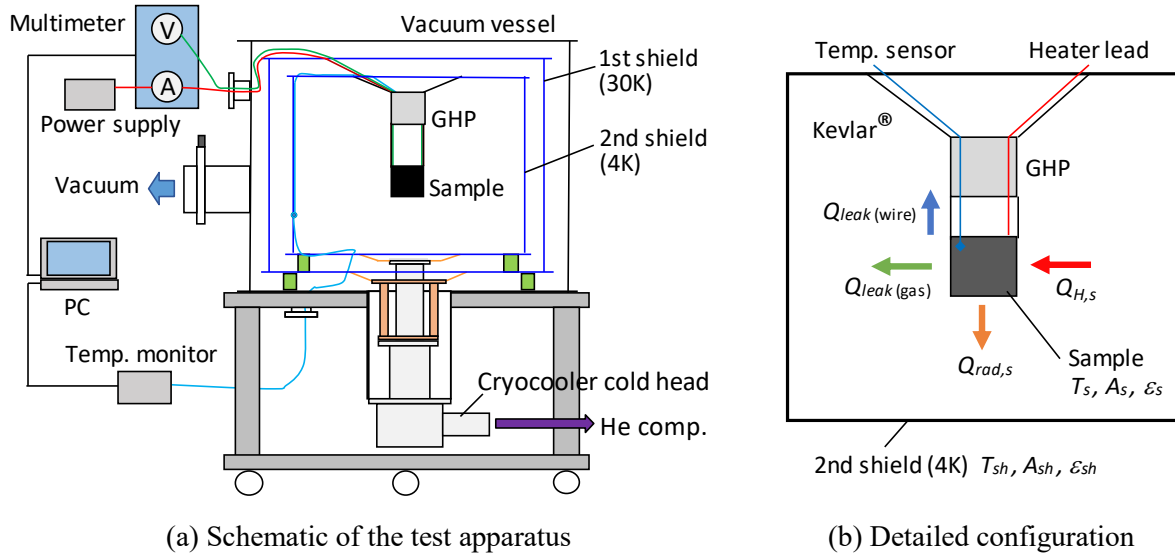


Figure 1. Test apparatus for the emissivity measurements.

The selected cell size of the honeycomb core was 1/8" because it could almost fully cover the dominant wavelength range of infrared radiation at cryogenic temperatures down to 7K. And in the case of a cylindrical cavity having a diffusive material surface, the emissivity enhancement effect is known to reach a plateau at an aspect ratio (i.e., the height divided by cell radius) above 6 [9]. For this reason, the height of the honeycomb core was set as 10 mm, and the aspect ratio was set as 6.3, which satisfied an aspect ratio > 6 .

3.2. Measurement configuration

The total hemispherical emissivity of the test sample was measured using a calorimetric method. Figure 1 (a) shows the developed test apparatus. The two-layer cylindrical shields of aluminium alloy were equipped in the vacuum vessel. The 1st and 2nd shields were connected to the 1st and 2nd stages of the cold head of the GM cryocooler (SHI RDK-408D2) via the copper thermal straps, respectively. During the test, those shields were kept at cryogenic temperatures (i.e., 1st shield at 30K, 2nd shield at 4K). The ultimate vacuum of the vacuum vessel was 1.8×10^{-6} Pa.

The test sample was suspended with Kevlar® thread as shown in Figure 1 (b). The test sample consisted of two test pieces, with the polyimide film heater adhered by Stycast™ placed between them. The temperature of the test sample was measured using Cernox™ resistance temperature sensors on both sides of the test sample. Because the Kevlar® thread, lead wires of the heater, and temperature sensors are possible the heat leak paths, a guard heater plate (GHP) kept at the same temperature as that of the test sample during the test was adopted to reduce such potential heat leaks.

3.3. Defining equations

In the measurement configuration, the following equations are applied at the steady state.

$$Q_{rad,s} = \varepsilon_{eff} \sigma A_s (T_s^4 - T_{sh}^4) \quad (1)$$

where,

$$\varepsilon_{eff} = \left[\frac{1}{\varepsilon_s} + \left(\frac{1}{\varepsilon_{sh}} - 1 \right) \frac{A_s}{A_{sh}} \right]^{-1} \quad (2)$$

In equation (2), it is assumed that:

$$\text{if } A_s/A_{sh} \ll 1, \varepsilon_{eff} = \varepsilon_s \quad (3)$$

Actually, A_s/A_{sh} was approximately 1/200 in this measurement, and thus not so small as to always accept the assumption above. In case of small ε_{sh} and large ε_s , the error caused by the assumption

could not be negligible. The 2nd shield surface was coated with black paint (Desothane®, 130 μm in thickness), but the value of ε_{sh} at 4K was not precisely identified. Therefore, error due to the assumption should be considered. The expected value of ε_{sh} at 4K was assumed to be a minimum of 0.1 based on extrapolation using the emissivity measurement results of Desothane® above 20K. The error, which was estimated using equation (2), could be +4.4% at maximum.

Q_{rad} in equation (1) is expressed as equation (4) as follows:

$$Q_{rad,s} = Q_{H,s} - Q_{leak} = I_H V_H - Q_{leak} \quad (4)$$

Q_{leak} includes heat leak due to conduction heat transfer by the residual gas as well as heat leak via the Kevlar® threads and the lead wires. In this study, Q_{leak} was determined according to a preliminary heat leak test. The configuration of the heat leak test was the same as for the emissivity measurements except for the test sample; the reference sample with low emissivity ($\varepsilon_{ref} < 0.025$) was used instead of the test sample. Q_{leak} measured in the heat leak test can be regarded as the same as that in the emissivity measurement, provided that the reference and the test samples have the same temperature. The following equation is applied in the heat leak test.

$$Q_{H,ref} = Q_{leak} + Q_{rad,ref} = Q_{leak} + \varepsilon_{ref} \sigma A_{ref} (T_{ref}^4 - T_{sh}^4) \quad (5)$$

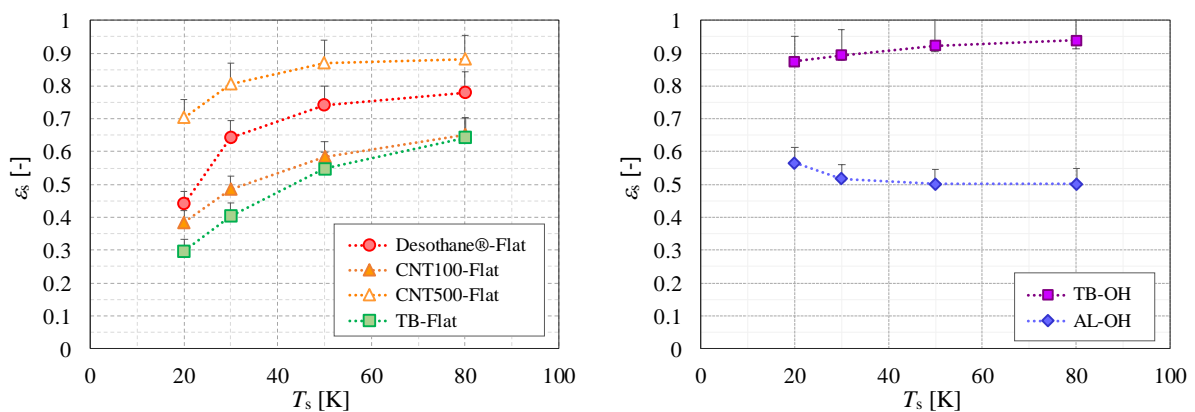
Strictly speaking, a highly accurate value of ε_{ref} is not identified at the various cryogenic temperatures. The uncertainty of ε_{ref} is ultimately considered in the error analysis of ε_s .

4. Results and discussion

Figure 2 shows the emissivity measurement results at 20-80K; (a) for the flat surface, and (b) for the open honeycomb.

The emissivity of any test sample with a flat surface decreased significantly with temperature. CNT500-Flat had the highest emissivity due to the large thickness of the CNT coating. Its emissivity was above 0.86 at 50-80K, but decreased to 0.7 at 20K because the influence of wavelengths longer than the coating thickness could not be negligible at this temperature. Emissivity dependence on the coating thickness was clearly observed according to the CNT samples with different coating thicknesses. TB-Flat showed relatively high emissivity for its thickness of only 20 μm . The surface of Tough Black® has a complex texture formed by the micro particles, which can function as a three-dimensional structure and contribute to emissivity enhancement.

Conversely, the emissivity of the open honeycomb was less dependent on temperature. In other words, the measurement results suggested that a three-dimensional structure can enhance emissivity without any dependence on the wavelength. The emissivity of AL-OH was around 0.5. The emissivity of AL-OH could be estimated from the emissivity of the aluminium surface (0.01-0.03 as typical) and the aspect ratio of the honeycomb cell (6.3 in this case). The expected value was approximately 0.2,



(a) Test samples with flat surface

(b) Test samples with open honeycomb

Figure 2. Emissivity measurement results of various test samples.

which differed from the measurement results. The possible reasons for this difference can be explained as follows: Although the estimation above assumed that the material surface was perfectly diffuse, many real surfaces possess both specular and diffuse reflectance components. The emissivity enhancement effect was reported to increase as the specular component became a larger fraction of the surface reflectance [10]. It is possible that the measured emissivity of AL-OH was larger than that estimated because the specular component was dominant rather than the diffuse component. Moreover, the cavity resonance effect at specific wavelengths possibly contributed to the measured value. At this point, further detailed analysis is required. The emissivity of the open honeycomb increased drastically when Tough Black® was applied. The emissivity of TB-OH was more than 0.86 at 20-80K, and it showed a slight decrease with temperature, due to the characteristics of Tough Black® itself.

5. Conclusion

The emissivity of a flat surface with several kinds of black coatings and an open honeycomb with or without black plating was measured using calorimetric methods at cryogenic temperatures from 20K to 80K. The emissivity of the flat surface with black coatings showed a strong dependence on temperature, where emissivity decreased significantly with temperature. Conversely, the emissivity of the open honeycomb was less dependent on temperature. The emissivity was enhanced up to 0.5 even without any black coating, and the black-plated open honeycomb had the highest emissivity up to 0.9 at 20-80K. The results suggested that the combination of an open honeycomb and black plating offered a promising solution to achieving high emissivity.

Nomenclature

Symbols	Subscripts
A area, m ²	eff effective
I electric current, A	H heater
Q heat transfer rate, W	$leak$ leak
T temperature, K	rad radiation
V voltage, V	ref reference
ε emissivity, -	s sample
σ Stefan-Boltzmann constant, 5.67×10^{-8} W/m ² K ⁴	sh shield

References

- [1] Jamotton P, Cucchiario A, Demaret D and Balbeur H 2000 *Proc. 30th Int. Conf. on Environmental Systems (Toulouse)* No. 2000-01-2568.
- [2] Jamotton P, Delree C, Cucchiario A and Liebecq S 2004 *Proc 5th Int. Symp. on Environmental Testing for Space Programmes (Noordwijk)* ESA SP-558.
- [3] Valentini D and Gavila E Planck passive cooler thermal design, test and performance 2007 *3rd European Space Cryogenic Workshop*.
- [4] Ade P A R *et al.* 2012 *Astronomy and Astrophysics manuscript* Planck2011-1.3.
- [5] Tuttle J and Canavan E Recent NASA/GSFC cryogenic measurements of the total hemispheric emissivity of black surface preparations 2015 *Proc. Int. Cryogenic Materials Conf.*
- [6] Ogawa H, Shinozaki K and Nakagawa T 2016 *Proc. 46th International Conference on Environmental Systems (Vienna)* ICES-2016-305.
- [7] Mizuno K, Ishii J, Kishida H, Hayamizu Y, Yasuda S, Futaba D N, Yumura M and Hata K 2009 *Proc. the National Academy of Sciences of the United States of America* **106** (15) pp 6044–47.
- [8] Maruyama S, Kashiwa T, Yugami H and Esashi M 2001 *Applied Physics Letters* **79** (9) pp 1393–95.
- [9] Sparrow E M, Albers L U and Eckert E R G 1962 *J. Heat Transfer* **84** (1) pp 73–79.
- [10] Sparrow E M and Lin S L 1965 *Int. J. Heat Mass Transfer* **8**, pp769–79.