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Cryogenic radiator with cavity-in-cavity structure for space missions

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Abstract. A new cryogenic radiator with high emissivity under 50K has been designed, fabricated and tested for space cryogenic missions in which high emissivity radiative cooling at low temperature is proposed. In this design, a cavity is introduced in a cavity surface structure to make a low reflectivity surface at an infrared wavelength (ranging from a few tens of μm up to 1000 μm) without any black coating resulting in contamination and low reliability at low temperature. As proof of a concept demonstration, a triple-cavity surface structure was designed, and three types of test pieces with different number of surface cavities were measured. Low temperature emissivity measurement using the calorimetric method, revealed that higher emissivity was successfully obtained with the test piece having a higher number of cavities.

1. Introduction

Radiative cooling at lower than 77 K is major means for space cryogenic missions. In particular, the Space Infrared telescope for Cosmology and Astrophysics (SPICA), proposed as an infrared observatory is transferred into a halo orbit around the second Lagrangian point (L2) in the Sun-Earth system, which enabling us to use effective radiant cooling in combination with mechanical cooling in order to cool a 2.5m IR telescope as well as scientific instruments below 8 K. High emissivity radiative cooling is also proposed at around the telescope shields, along with a V-groove between 40 K and room temperature [1]. LiteBIRD – the cosmic microwave background (CMB) polarization observation satellite – is also needed to cool down the mission instruments as well as telescopes by about 5 K at L2, with a thermal design similar to that of SPICA [2].

There are several kinds of candidates to realize a high emissivity cryogenic radiator in space at lower than 77 K. One of the most common methods is to apply a black coating using thick black paint. This method is simple, easy to assemble, and has few restrictions regarding the shape on the radiator. High radiative emissivity was obtained with the black paint known as Ball IR BlackTM (or BIRBTM) that was used for the cryogenic radiator of the James Webb Space Telescope [3]. However, there are still concerns about contamination and quality control for the design of each spacecraft. An open honeycomb with thin black paint has a good heritage in the Planck mission [4][5], and is now being developed at JAXA [6]. Other methods, such as one using carbon nanotubes (CNT) [7] are also proposed and being developed.



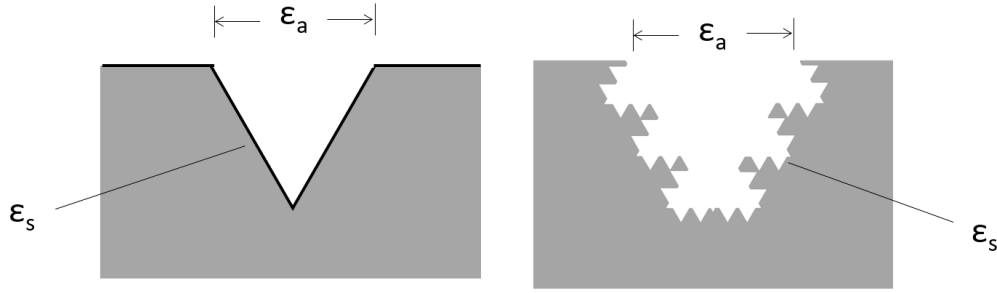


Figure 1. Enhanced emissivity with a cavity from ϵ_s to ϵ_a (left) and concept of a cavity in a cavity cryogenics radiator (right).

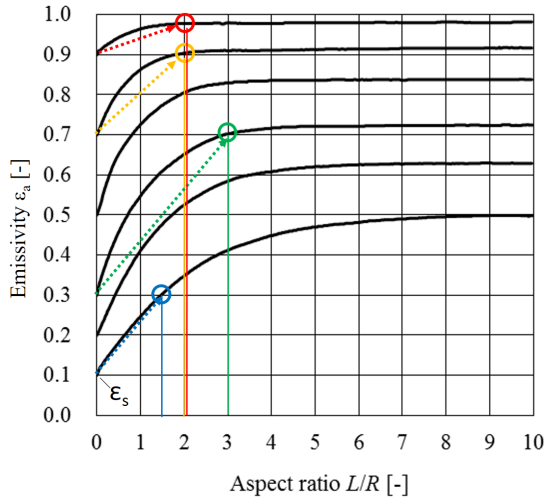


Figure 2. An expected apparent emissivity ϵ_a higher than 0.9 from ϵ_s by quadruple cavity in cavity with $1.5 < L/R < 4$.

This paper introduces a new concept of a cryogenic radiator in space with the sample emissivity being measured at between 20 K and 50 K. According to new concept, a cavity in a cavity three-dimensional (3D) structure is proposed with the possibility of providing high radiative emissivity close to 1 even at low temperature (< 20 K) without any coatings, and with the emissivity having no dependence on temperature due to a multiple cavity effect.

2. Concept of a cavity in a cavity cryogenic radiator

When there is a hole structure as shown on the left side of Figure 1, apparent emissivity ϵ_a can be higher than surface emissivity ϵ_s due to the cavity effect, with which most of photons emitted by the surface as well as photons incoming a hole structure have more than one reflection. In such a case, there is a possibility of a multiple cavity effect when a smaller cavities are introduced in a large cavity structure, as shown on the right side of Figure 1. A cavity effect depends on an aspect ratio L/R (hole depth / hole radius in case of a circular cylinder)[8]. Figure 2 shows the relation between the aspect ratio L/R and the apparent emissivity with various surface emissivities. A diffuse reflection is only considered in the figure. For instance, emissivity higher than 0.9 can be expected by quadruple cavities in a cavity with $1.5 < L/R < 4$ (red circle), even if surface emissivity ϵ_s is only 0.1 (a rough metal surface).

The emission wavelength range of blackbody radiation becomes longer and the radiative emissivity of a black-painted surface decreases at cryogenic temperatures lower than 50 K [9].

When a black paint having a few mm thickness is applied to maintain high emissivity at low temperature, it is critical to mitigate the risks of an outgas and contamination, as well as quality control to prevent thermal cracks in a spacecraft design. Even when a surface structure using one cavity effect such as the use of an open honeycomb, a black coating is needed on the surface. A radiator with a CNT and a metal formed on the surface also raises a concerns about contamination.

In the concept of a cavity in a cavity cryogenic radiator, high radiative emissivity (close to 1) is expected at cryogenic temperature without any coating or surface finishing. On the other hand, a hole size must be larger than the wavelength to be considered for a blackbody radiation spectrum at low temperature. Moreover, the mass necessary to make the structural design is also critical.

3. Sample results and discussion

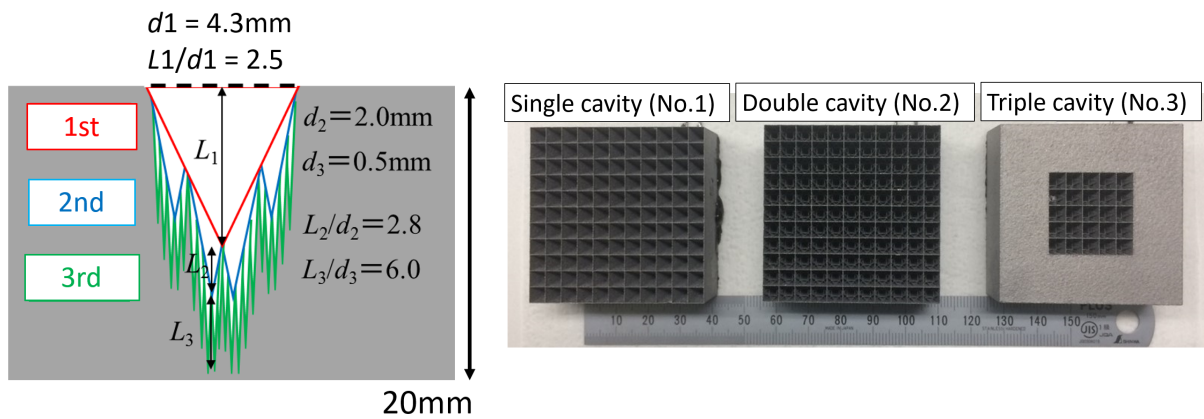


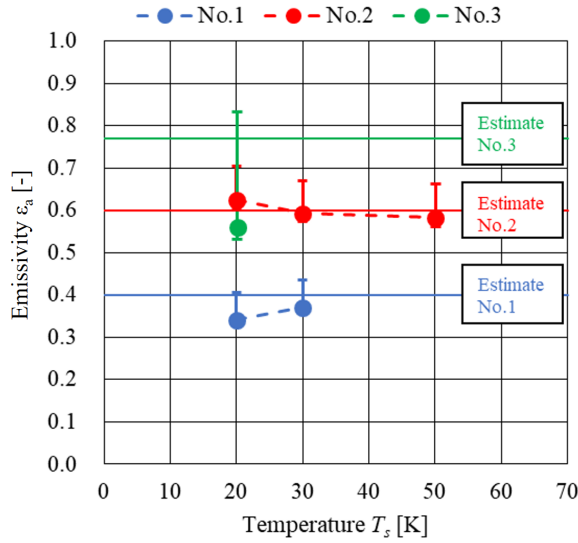
Figure 3. Cross section of the designed triple-cavity structure (left) and samples (right).

As the first trial, the triple-cavity structure has been designed and fabricated by adapting additive manufacturing using an Al-alloy AlSi10Mg. Prior to the design, a cavity effect with different hole shapes (i.e., cylinder, hexagon pole, square pole, triangle pole) were compared as a function of aspect ratio using the thermal model, and it was confirmed that the function can be the same by introducing the ratio of surface area in the hole's A_{surface} and opening area A_{open} ($A_{\text{surface}}/A_{\text{open}}$). Cavity effects with a single-pyramid and a three-pyramid shape were also estimated, and it was concluded that the cavity effects using these structures are slightly lower compared to the cavity effect with a cylinder at low $A_{\text{surface}}/A_{\text{open}}$, while peak emissivity is the same.

The left side of Figure 3 shows a cross section of the designed triple-cavity structure. As a prior condition, it was designed for a sample height of $< 20\text{ mm}$ by considering the feasibility of integrating it on a spacecraft radiator. Given the processing precision of about 0.2 mm in the additive manufacturing, 0.2 mm was used to estimate the aperture efficiency as well as to design each aspect ratio and each opening diameter. The pyramid shape was chosen for the first cavities, with the three-pyramid shape for the second and third cavities. The designed aspect ratio and opening diameters are also shown on the right side of Figure 3, and Table 1 lists the main parameters of the three samples. The samples having only single and double cavities were also fabricated to compare these emissivities with the triple-cavity sample. The opening diameter of the smallest cavity was determined to be 0.5 mm for the cavity effect with a maximum wavelength of $1000\text{ }\mu\text{m}$. As the production of samples using the manufacture had a limited data transfer rate, triple cavities were only fabricated on $23\text{ mm} \times 23\text{ mm}$.

Table 1. Main parameters of the samples.

	Size	Structure	Expected emissivity
No.1	50 mm × 50 mm	single cavity	0.26 (ϵ_s 0.1), 0.40 (ϵ_s 0.19)
No.2	50 mm × 50 mm	double cavity	0.44 (ϵ_s 0.1), 0.60 (ϵ_s 0.19)
No.3	23 mm × 23 mm (total size 50 mm × 50 mm)	triple cavity	0.68 (ϵ_s 0.1), 0.77 (ϵ_s 0.19)

**Figure 4.** The sample emissivities measured by the low temperature calorimetric experiment.

The low temperature emissivity of these samples was measured by using the calorimetric method, as described in detail by M.Ando et al. [6]. The 4K-class GM cooler (4K-GM) is used to provide an inner shield of ~ 5 K in the vacuum chamber. The guard heater plate (GHP) was used to reduce conductive heat loss from the samples, each of which was suspended from the GHP by two Kevlar[®] wires. The GHP assembly was covered by the inner shield. The sample temperature was regulated by a heater attached directly to each sample, and the GHP temperature was also heater-regulated to maintain the difference in temperature with the sample at lower than ± 0.1 K. The conductive heat loss from samples in the experimental setup was measured by another low temperature measurement with a low emissivity polished Al sheet (50 mm × 50 mm, $\epsilon_s < 0.025$), and then the cavity sample's emissivity was estimated based on the sample's heater-regulated power after subtracting the conductive heat loss.

Figure 4 shows the measured emissivities of the three samples. The estimated error is dominated by the systematic error and lower than 0.1 for No.1 and No.2. Higher emissivity was obtained with sample No.2 (double cavity) than sample No.1 (single cavity) between 20 K and 50 K. Furthermore, it is important that the dependence on temperature was low and the result shows the main feature of cavity effects. These results suggest that the surface emissivity of the Al alloy was about 0.2, which was assumed to be caused by the surface roughness. Higher emissivity with sample No.3 (triple cavity) was expected, but it has a smaller radiative area and provides a large error.

Another triple-cavity sample (No.4) was also assembled by adhesion using the stycast with the four small samples to be measured. However, the measured emissivity was about 0.25 at

20 K and about 0.45 at 30 K, and thus lower than that of sample No.1 (single cavity). The adhesion to assemble sample No.4 may be weak, which provides very low thermal conductance. Furthermore, there is possibility that the aspect ratio of the third cavity is much lower than designed, as the design shape of triple cavity particularly the opening diameter (0.5 mm) is close to the processing precision (of about 0.2 mm). The design must be improved for fabricating third cavities correctly on a 50 mm × 50 mm sample, to obtain higher emissivity by a triple-cavity structure.

As discussed above, the emissivity enhancement by multiple cavity effect of current design was apparently restricted by the processing accuracy of the additive manufacturing. Hence, a higher radiative emissivity would be predicted by the progress of the manufacturing development. On the other hand, an alternative approach to manufacturing including cutting work should be investigated. Then, a no-metal sample development must be also desirable since a mass is most critical issue for the concept.

4. Conclusion

The multiple cavity effect with a 3D structure was proposed for a spacecraft's cryogenic radiator. It offers the possibility of achieving high emissivity close to 1 without any surface coating or surface finishing, as well as easy fabrication after being designed just once. As proof of a concept demonstration, the sample with a triple-cavity structure was designed and fabricated by additive manufacturing. In the calorimetric measurement, higher emissivity was measured with the double-cavity sample than with the single-cavity sample at between 20 K to 50 K. There is a possibility of obtaining even higher emissivity with the triple-cavity sample, though it entails large uncertainty. Therefore, the design must be improved to enhance the multiple cavity effect of the new concept.

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