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Development of a new multi-layer insulation blanket with non-interlayer-contact spacer for space cryogenic mission

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ABSTRACT

For conventional Multi-Layer Insulation (MLI) blankets, it is difficult to control the layer density and the thermal insulation performance degrades due to the increase in conductive heat leak through interlayer contacts. At low temperatures, the proportion of conductive heat transfer through MLI blankets is large compared to that of radiative heat transfer, hence the decline in thermal insulation performance is significant. A new type of MLI blanket using new spacers; the Non-Interlayer-Contact Spacer MLI (NICS MLI) has been developed. This new MLI blanket uses small discrete spacers and can exclude uncertain interlayer contact between films. It is made of polyetheretherketone (PEEK) making it suitable for space use. The cross-sectional area to length ratio of the spacer is 1.0×10^{-5} m with a 10 mm diameter and 4 mm height. The insulation performance is measured with a boil-off calorimeter. Because the NICS MLI blanket can exclude uncertain interlayer contact, the test results showed good agreement with estimations. Furthermore, the NICS MLI blanket shows significantly good insulation performance (effective emissivity is 0.0046 at ordinary temperature), particularly at low temperatures, due to the high thermal resistance of this spacer.

1. Introduction

Thermal insulation performance requirements are intensifying, particularly for exploration spacecraft such as the lunar surface rover and cryogenic astronomy satellite. The Japan Aerospace Exploration Agency is planning a next-generation infrared astronomy mission; the Space Infrared Telescope for Cosmology and Astrophysics (SPICA), which must meet a stringent thermal insulation performance requirement. Multi-Layer Insulation (MLI) blankets are the most efficient thermal insulation element. Conventional MLI blankets comprise multiple layers of low-emissivity films and netting spacers, the latter of which prevent direct contact between films to reduce conductive heat leaks. Instead of netting spacers however, embossed films are sometimes used to decrease the contact area between films. However, neither netting spacers nor embossed films can exclude interlayer contact between film and the netting spacer or films, which has a major impact on conductive heat leak through the MLI blankets, depending on the degree of contact. The thermal insulation performance of MLI blankets is thus strongly dependent on the mounting arrangements. For conventional MLI blankets, the degree of interlayer contact is difficult to control. Consequently, the thermal insulation performance of conventional MLI blankets installed on spacecraft degrades relative to the MLI blanket, the layer density of which is well-controlled in the laboratory, and it is difficult to quantify the thermal insulation performance before thermal balance testing of the spacecraft. Many equations are proposed to estimate the thermal performance of conventional MLI blankets [4–7]. However, since these equations must take the kind of spacer, sewing condition and so on into account, it is difficult to apply them to each MLI blanket. In addition, the performance of conventional MLI blankets declines significantly in cryogenic systems. At low temperatures, the proportion of radiative heat transfer through MLI is small relative to that of conductive heat transfer, hence conductive heat pass must be minimized.

In this study, a new MLI blanket using 'non-interlayer-contact' spacers has been developed. While conventional spacers such as netting spacers are inserted in the whole surface layer, these new spacers are intermittently arranged and hold up the film to

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Nomenclature

σ	the Stefan–Boltzmann constant	T_{cold}	cold boundary temperature
ε_{eff}	effective emissivity	N	number of layers
ε_s	emissivity of the layer surface	R	thermal resistance of a spacer
q_{total}	total heat flux through MLI	l_p	pitch between spacers
q_{rad}	radiative heat flux	$\dot{m}$	evaporation rate of liquid nitrogen
q_{cond}	conductive heat flux	h_{lg}	latent heat of evaporation
q_{conv}	convective heat flux	S_{BT}	heat transfer surface area of the boil-off tank
T_{hot}	hot boundary temperature		

exclude any incidental interlayer contact. Consequently, conductive heat leaks can be easily estimated because only conduction through the spacer need be considered, not interlayer contact, and thermal performance can be more precisely quantified. This type of spacers has also been developed by Dye et al. [1,2]. Their MLI using an intermittent-type spacer has been tested and the result shows a lower heat leak than conventional MLI [1,2]. However, the cross-sectional area to length ratio of their spacer is 1.1×10^{-4} m, which remains insufficient for the SPICA satellite requirement. In cryogenic systems, it is important for the spacer to have sufficient thermal resistance.

2. Design of a non-interlayer-contact spacer

2.1. Target and requirements

The effective emissivity ε_{eff} of an MLI blanket defined by the following equation is one of the parameters of thermal insulation performance:

$$\varepsilon_{eff} = \frac{q_{total}}{\sigma(T_{hot}^4 - T_{cold}^4)} \quad (1)$$

Effective emissivity can be achieved of 0.005 or lower in well-controlled laboratory tests [3]. However, experience has shown that when a blanket is configured for spacecraft applications, effective emissivity closer to 0.015–0.030 is representative of the current design, manufacturing, and installation methods for medium-area applications. For spacecraft requiring high thermal insulation performance, maintaining high performance is important.

Japan Aerospace Exploration Agency is planning a next-generation infrared astronomy mission; Space Infrared Telescope for Cosmology and Astrophysics (SPICA). The SPICA satellite has a cryogenically-cooled (<6 K), large telescope (in the 3 m class). To reduce heat leak from the sun, the SPICA satellite has a sun shield, plus outer, middle and inner shields around the telescope, on which MLI blankets are mounted. The strictest requirements for the MLI blanket are shown in Table 1. The heat flux from the outer to middle shield should be less than 0.04 W/m^2, in other words, the effective emissivity of the MLI blanket should be less than 0.0042, while the thickness of the MLI blanket must be less than 20 mm due to the distance between the shields. In this study, the MLI blanket requirements on SPICA's shields set a target value for the thermal insulation performance, and the new MLI blanket has been developed to be installable between the narrow space of the shields.

Table 1
Requirements of the MLI blanket on the SPICA satellite.

Temperature of the outer shield, K	120.6
Temperature of the middle shield, K	81.5
Heat flux, W/m^2	<0.04
Effective emissivity, –	<0.0042
Distance between the shields, mm	Min. 20

2.2. Concept of a non-interlayer-contact spacer

One of the problems of a conventional MLI blanket is the uncertainty of the thermal insulation performance, which arises from the variation in contact area and contact pressure between films. With conventional netting spacers, the contact area and contact pressure between the film and netting spacer can vary significantly depending on the satellite mounting method used. Therefore, to eliminate uncertainty in the thermal insulation performance, the contact area between the film and spacer must be stabilized and all contact between the films prevented. If the interlayer spacing can be controlled, the thermal insulation performance will no longer depend on the mounting method. The schematics of a conventional MLI and one with intermittent spacers are shown in Fig. 1.

The method of fastening films is crucial for thermal insulation performance. A conventional MLI blanket is fastened by stitching, which becomes one of the major causes of degradation of thermal insulation performance [10,11]. By stitching the MLI blanket, not only threads become a conductive thermal path, but also significant contact between the film and netting spacer become conductive thermal paths. To reduce the heat leak via stitches, films are sometimes seamed up loosely. However, the thermal insulation performance of the MLI blanket fastened by loose-stitching varies widely according to the mounting method. In this study, instead of fastening MLI blanket films by stitching, each spacer has a function of fastening films, similar to tying a tag to clothes. Fig. 2

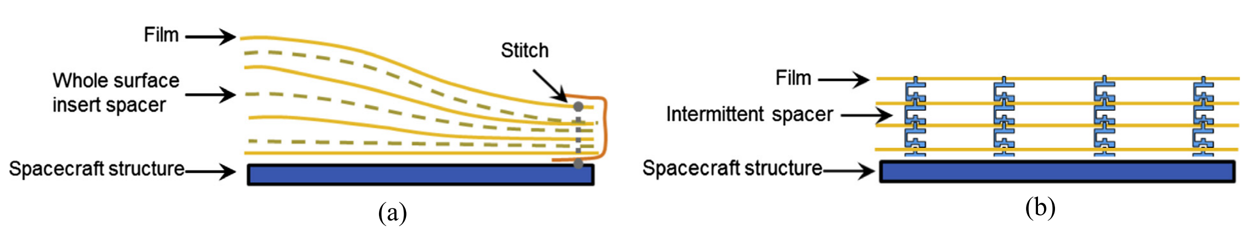

Fig. 1. Schematics of a conventional MLI (a) and MLI with intermittent spacers (b).