Development of a new MLI for orbital cryogenic propulsion systems -thermal performance under one atmosphere to a vacuum

Takeshi MIYAKITA 1,2, Kazuya KITAMOTO 1, Kiyoshi KINEFUCHI 2, Masanori SAITOY 3, Tomoyuki HIRAI 4 and Hiroyuki SUGITA 1

1 JAXA R&D Directorate, 2-1-1 Sengen, Tsukuba, 305-8505, Japan
2 JAXA Space Technology Directorate I, 2-1-1 Sengen, Tsukuba, 305-8505, Japan
3 Orbital Engineering Inc., 1-7-8 Nishikanagawa, Kanagawa, 221-0822, Japan
4 Toska Bano’k Co., Ltd., 14 Kanda, Tokyo, 101-0042, Japan

E-mail: miyakita.takeshi@jaxa.jp

Abstract  The efficient storage of cryogenic propellants is among the key technologies for long-duration space exploration missions. For the orbital transfer vehicle, the required thermal insulation performance is more than ten times higher than that of conventional spray-on foam insulation. Conventional multi-layer insulation blankets are used as excellent insulation for spacecraft in the vacuum environment, but are not usable in the atmospheric environment. A new type of insulation-a load-bearing, non-interlayer-contact spacer MLI (LB-NICS MLI)-has been developed. The insulation performance in both air and vacuum environments is measured with a boil-off calorimeter. According to the test results, LB-NICS MLI is about 3 times superior under 1 atmosphere and 13 times superior under a vacuum, compared to foam insulation.

1. Introduction
For the long-term propulsion systems of orbital transfer vehicles equipped with cryogenic propellant tanks, insulation performance is one of the most important key technologies to reduce heat entering the propellant storage tank and minimize the boil-off losses of propellant during long-term missions. Insulation is not important for a storable propellant like hydrazine, but the propulsion systems become large and heavy due to the small specific impulse. Conversely, the specific impulse is large when using such cryogenic propellants as liquid hydrogen or liquid methane, but the boil-off of propellant must be reduced. For a mission duration of less than three days, cryogenic propulsion systems are lighter than storable propulsion systems. However, for a mission duration longer than three days, cryogenic propulsion systems require extremely high insulation for weight reduction. For the orbital transfer vehicle to the moon, the required thermal insulation performance is more than 10 times higher than that of conventional spray-on foam insulation.

2. New type of multi-layer insulation

2.1. NICS-MLI in previous research
Multi-Layer Insulation (MLI) blankets are the most efficient thermal insulation element in the space vacuum environment. 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. However, netting spacers cannot exclude interlayer contact between film and the netting spacer, resulting in a major impact on conductive heat leaks through the MLI blankets, depending on the degree

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd
of contact. When conventional MLI is actually used on a spacecraft, the degree of interlayer contact is difficult to control or predict. Many equations are proposed to estimate the thermal performance of conventional MLI blankets [1]-[4]. As the type of spacer, sewing condition, and other factors must be considered, however, it is difficult to apply such equations to each MLI blanket.

A new type of spacer—the non-interlayer-contact spacer (NICS)—has been developed [5]. While conventional spacers such as netting spacers are inserted in the whole surface layer, these new spacers are intermittently arranged on the film and prop the film up to exclude any incidental interlayer contact. NICS controls the gaps between films to be intermittently arranged on the film and props the upper film. The only contact points of the films are the top face or subsurface of the discrete interlayer and the film surfaces that do not come into contact. Consequently, conductive heat leaks can be easily estimated as only conduction through the spacers must be considered, rather than the interlayer contacts of films. As a result, thermal performance can be more precisely quantified. According to the experimental results, the insulation performance of NICS MLI is far superior to conventional MLI [5].

2.2. Concept of LB-NICS MLI
MLI blankets including NICS-MLI are not usable in the atmospheric environment. Cryogenic propellant tanks need to maintain insulation from the time of launch until orbital navigation. Therefore, orbital transfer vehicles require insulation having high thermal performance in both vacuum and one atmosphere (1 atm) environments. The concept of a new type of insulation in this research is intended to prepare a vacuum double vessel as lightweight as possible and install MLI in it to maintain thermal insulation performance, both on the ground and in orbit.

In this study, a lightweight vacuum double vessel is realized with discrete spacers, an outer layer shell, and vacuum-sealed film. The interior space is held by intermittent spacers evenly arranged on the outer layer shell, the outermost layer is covered with a thin vacuum seal film, and the interior space is evacuated to constitute a light vacuum double vessel. It is thought that when conventional MLI is installed inside this vacuum double vessel, the interlayer of conventional MLI is compressed by a compression load of 1 atm, heat leaks increase due to the conduction, and the thermal insulation performance degrades. Therefore, we propose to use MLI applying NICS-MLI. We refer to this insulation material proposed in this research as load-bearing, non-interlayer-contact spacer MLI or LB-NICS MLI. The spacer needs to withstand a compression load of 1 atm at the launch site. Because the load path is a heat path as it is, leaving the load path as is under pressure environment during orbital navigation where compression load does not work is not a promising idea. Therefore, the LB-NICS was designed so that the heat path switches at the time of compression (under pressure) and at the time of release (under a vacuum). Figure 1 shows schematics of LB-NICS MLI. The ratio of heat path length to the cross-sectional area of the LB-NICS is $2.6 \times 10^2 \text{ m}^{-1}$ at the time of compression. When under the vacuum environment and released from the compressive load, the ratio of thermal path length to the cross-sectional area improved by two orders to $3.4 \times 10^4 \text{ m}^{-1}$ by separating the load path. The spacer (10 mm in diameter and 4 mm in height) was molded using polyetheretherketone (PEEK) by injection molding.

3. Materials and method

3.1. Measurement equipment
The thermal insulation performance of insulation materials was measured by a boil-off calorimeter with liquid nitrogen. The boil-off tanks are cylindrical in shape. As shown in Figure 2, the inner tanks consist of the main boil-off tank and the upper/lower guard tanks, all of which are filled with liquid nitrogen. This configuration ensures uniform temperature distribution around the measurement tank along the axial direction. The main boil-off tank is 300 mm (height) $\times$ 318.5 mm (diameter) in size. A middle flange is installed on top of the upper guard tank for closing the upper aperture of the vacuum-sealed film of the sample. The top flange installed above the middle flange suspends these inner tanks and is equipped with a cryogen exhaust port from each tank and evacuation ports. An aluminum shroud
surrounds the test piece, while the temperature of its inner surface is maintained from 276 to 353 K by thermostat circulation. The inside and outside of the insulation sample are connected to the separate vacuum evacuation pumps, and the degree of vacuum outside of the insulation sample can be controlled from 1 atm to a high vacuum. The heat flux through the insulation sample is measured by the evaporation rate of liquid nitrogen from the main tank. Equation (1) is used to calculate the heat flux ($q$),

$$q = \frac{m \cdot h_{lg}}{S_{BT}}$$

where $m$, $h_{lg}$ and $S_{BT}$ denote evaporation rate of liquid nitrogen, latent heat of evaporation and heat transfer surface area of the boil-off tank respectively. The flow rate of nitrogen gas having evaporated from the main boil-off tank is measured using mass flow meters.

3.2. Test piece 1: LB-NICS MLI

Table 1 list the main specifications of the prototype LB-NICS MLI. The pitch of the LB-NICS spacer was arranged from a maximum of 50 mm to a minimum of 30 mm, and the double-sided aluminum vapor deposited polyester film had five layers. As the vacuum-sealed film, a heat laminate film containing an aluminium layer was used. By adopting a heat laminate film as vacuum-sealed film, even in outfitting to a large tank surface, it is possible to cope with upsizing by joining seams through thermal fusion bonding. Even in this prototype, LB-NICS MLI was divided into four parts in the circumferential direction, with both the carbon fiber reinforced plastic (CFRP) shell and radiation films designed to assume outfitting to large tanks. The overall size of the prototype LB-NICS MLI featured an inner diameter of 318.5 mm and a height of 805 mm in accordance with the test equipment tank described in Subsection 3.1.

3.3. Test piece 2: Vacuum-packed conventional MLI

To compare the performance with LB-NICS MLI developed this time, we prepared a sample containing conventional MLI in vacuum-sealed film. The vacuum-sealed film used is the same as that used for LB-NICS MLI. Table 2 lists the main specifications of the vacuum-packed conventional MLI. As the spacer,
double netting spacers were piled up and inserted between low emissivity films. There is a total of 21 low emissivity film layers and the seam is connected at one place with interleaved lapping.

3.4. Test procedure
First, the inside of the insulation is evacuated and then the vacuum chamber is evacuated. Thereafter, the vacuum chamber was again pressurized to 1 atm with dry nitrogen. To investigate the temperature dependence of thermal insulation performance, the shroud temperature was controlled to 276, 300, and 353 K. The pressure inside of the insulations after the transfer of liquid nitrogen is less than $10^{-3}$ Pa.

4. Results and discussion

4.1. Results of the boil-off tests
Figure 3 shows the heat fluxes measured by the boil-off calorimeter. The values of the mass flow rate in Equation (1) are corrected for the influence of atmospheric pressure [6]. As shown in Figure 3, the thermal performance of LB-NICS MLI is far superior to vacuum-packed conventional MLI under 1 atm. Under 1 atm, the low emissivity film of conventional MLI is strongly compressed and heat leaks due to conductive heat transfer increase, whereas LB-NICS MLI maintains low conductive heat by controlling the interlayer space with intermittent spacers.

When the outer layer is depressurized from 1 atm and a vacuum is reached both inside and outside of the insulation, the compression of the insulation layer is released. By releasing compression of the insulation layer, heat transfer due to conduction is suppressed, and both conventional MLI and LB-NICS MLI significantly improve thermal insulation performance. LB-NICS MLI does not change the contact area between the film and spacer, but by changing the heat path of the spacer, it gains thermal resistance and improves the thermal insulation performance. In addition, the thermal insulation performance does not change much in the compressed state and recompressed state, and the state of the thermal insulation layer is thought to be maintained without degradation.

4.2. Analysis of thermal insulation performance
Although the effective emissivity is often used as an indicator of MLI performance, it is difficult to consider the number of layers and temperature dependence, so here we will summarize by using the conductive heat transfer coefficient of each layer. To evaluate the thermal performance of the test pieces, the thermal mathematical model below is conceivable. The total heat flux ($q_{total}$) is expressed as the sum of radiative heat flux ($q_{rad}$), conductive heat flux ($q_{cond}$), and convective heat flux ($q_{conv}$) as follows:

$$q_{total} = q_{rad} + q_{cond} + q_{conv}$$

(2)
Here, it is assumed that radiation and conduction are not coupled, and the principle of superposition can be applied [1]. Under the condition of applicability to spacecraft, convective heat transfer via rarefied gas is negligible, and radiative heat flux is expressed in the form of radiation exchange between large parallel plates as Equation (3).

\[
q_{\text{rad}} = \frac{1}{(1/\epsilon_i) + (1/\epsilon_j) - 1} \sigma (T_i^4 - T_j^4)
\] (3)

\(\epsilon_i\) and \(\epsilon_j\) are the emissivity of the hotter and colder layer surface respectively, and both follow Equation (4) [7].

\[
\epsilon_i = 6.69 \times 10^{-4} \times T_i^{2.35}
\] (4)

The conductive heat flux is expressed as Equation (5).

\[
q_{\text{cond}} = h_c (T_i - T_j)
\] (5)

Here, \(h_c\) is the conductive heat transfer coefficient between two layers. The conductive heat transfer coefficients between each layer are assumed to be constant independent of layer. The temperatures of the outermost and innermost layers are given as boundary conditions, and the heat flux between each of the films is repeatedly calculated until the calculated heat flux matches the measured value by changing the conductive heat transfer coefficient and the temperature of each layer. Table 3 lists the calculated results of \(h_c\). In the compressed state under 1 atm pressure, the vacuum-packed conventional MLI shows that it transports heat about 30 times more than LB-NICS MLI. In addition, heat flux appeared to be not greatly different between LB-NICS MLI and vacuum-packed conventional MLI, but compared with \(h_c\) per layer, LB-NICS MLI is about 8 times better than vacuum-packed conventional MLI.

Figure 3 also shows the results of calculating the heat flux using \(h_c\) obtained in Table 3. The figure also shows the heat flux of the existing foam insulation material (polyisocyanurate foam). The thickness of PIF is 25 mm with thermal conductivity of 0.015 W/mK. The surface density of PIF is 0.84 kg/m². Although vacuum-packed conventional MLI has a lot of low emissivity film layers, radiative heat transfer is kept small, but since \(h_c\) is large, thermal insulation performance cannot be expected at low temperature where conduction is dominant. Conversely, LB-NICS MLI can keep the thermal conductance of the spacer very low, so it can maintain high performance even at low temperature, thereby increasing the difference in performance from vacuum-packed conventional MLI. When adopting the insulation of the orbital transfer vehicle, the weight is also a crucial factor. Considering the value obtained by multiplying the total heat transfer coefficient by areal density, LB-NICS MLI is about 3 times superior under 1 atm and 13 times superior under a vacuum, compared to foam insulation. Compared to vacuum-packed conventional MLI, the performance is 13 times higher under 1 atm and 4 times higher under a vacuum.

5. Conclusion

A new type of MLI using new spacers, the load-bearing, non-interlayer-contact spacer MLI or LB-NICS MLI was developed, and thermal performance tests in both atmospheric and vacuum environments were conducted using a cylindrical boil-off calorimeter. According to the experimental results, the thermal insulation performance of LB-NICS MLI is far superior to existing spray-on foam insulation and vacuum-packed conventional MLI, particularly at low temperature, where conduction dominates.

References
[1] Moshfegh, B. et al., *Advanced Computational Methods in Heat Transfer*, Vol. 3, 1990, pp. 357-368.
[2] J. Doeneche, *SAE technical paper series*, No. 932117, 1993.
[3] C. W. Keller, G. R. et al., “Thermal Performance of Multilayer Insulations,” NASA CR-134477, 1974.
[4] L. D. Stimpson et al., AIAA paper, No. 72-285, 1972.
[5] T. Miyakita et al., *Cryogenics* 64 (2014), pp. 112-120.
[6] R. Hatakenaka, T. Miyakita et al., *Cryogenics* 64 (2014), pp. 121-134.
[7] N. Inai, *Japan Society of Mechanical Engineers*, Vol. 43, No. 365 (1977-1), 217, 1977.