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Experimental Estimation of the Effective Emissivity (ε^*) of a Space-borne MLI (Multi-Layer Insulation) Based on Design Parameters

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Abstract
Space-borne MLI is applied on the outermost of satellites. Generally, evaluation of a MLI performance is estimated with the effective emissivity (ε^*). To increase the reliability of test results, temperature stabilization criteria were defined. As a result of experiments, twenty filler layers MLI showed the highest performance compared to other filler layers. Also, in case of the MLI affixing by 4 and 8 patterns, the two-step stand-off showed lower effective emissivity compared to the standard stand-off. In future works, an empirical equation will be constructed, and it will be validated with experimental results.

1. Introduction

A satellite in the space mission is exposed to extremely hot (~ +100 ℃) and cold (~ -100 ℃) space environments. To develop a reliable and sustainable satellite, thermal control is required for sensors and satellites. Also, it is required to minimize the required heater power for thermal control of a satellite. For these reasons, a space-borne MLI (Multi-Layer Insulation) is generally applied on the outermost of satellites. The required heater power can be decreased by minimizing the radiative heat loss from the satellite to the surrounding by a space-borne MLI. The typical composition of a space-borne MLI is as shown in Figure 1. It generally consists with an inner layer and an outer layer, which acts as a skin, and filler layers between them were acts as a radiative shield.

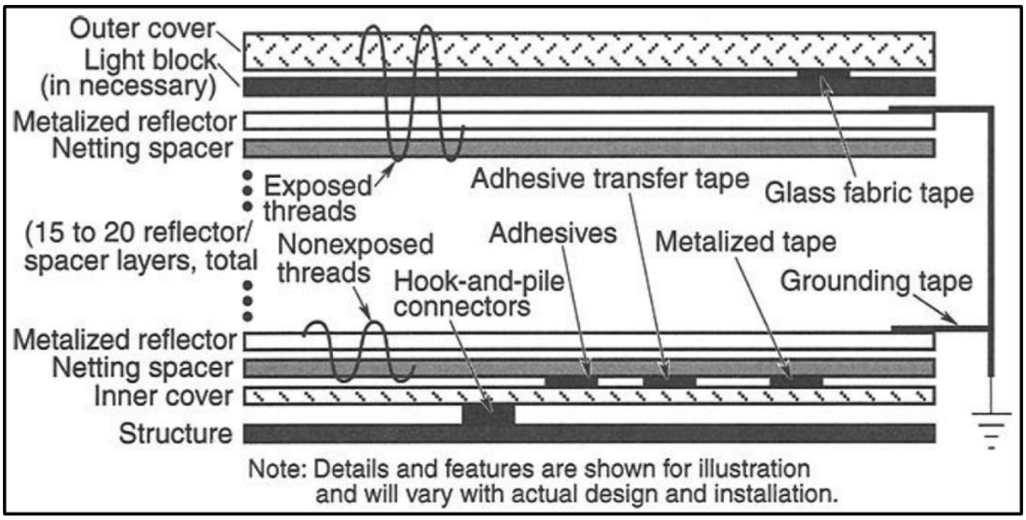

Figure 1: Typical Composition of Space-borne MLI [1]

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In case of filler layers, to minimizing the radiative heat exchange, a metalized reflector which has low emissivity is generally used. Also, the VDA[Vacuum Deposited Aluminum] is commonly used in filler layers for ease of manufacturability and reduction of development cost [2]. Additionally, in filler layers, polyester netting spacers are applied between the metalized reflector to prevent the conductive heat transfer [3]. For these reasons, number of filler layers could be a key parameter for an insulation effects of a space-borne MLI. Therefore, in many countries, performance estimation and constructing of an empirical equation of a space-borne MLI had been conducted before [4]. However, in previous studies, it only optimized for a certain size and shape. For this reason, it has an unsatisfactory things such as various sizes and shapes in the actual design and development. Therefore, in an aspect of the actual design process, the performance of a space-borne MLI should be performed with a various of design parameters.

Generally, the performance evaluation of a MLI has been conducted by estimating the effective emissivity (ε^*). In this work, an experimental set up to estimate the effective emissivity of MLI were constructed, and experimentally evaluated the performance of MLI samples according to a various design parameters such as number of filler layers, double composition of MLI, different types of stand-off and the effective distance of a stand-off which clip on a MLI sample. The performance test of a space-borne MLI was performed in a high vacuum level, which kept below the level of 3.75×10^{-5} torr. Also, for reliable test results, evaluation of the measurement uncertainty was performed, and a standard stabilizing condition of temperature was conducted by 0.5 ℃/hr. In this work, we constructed the test configuration with different design parameters, and we proposed the effective way to improve the performance of a space-borne MLI.

2. Experimental setup

2.1 Vacuum chamber

In order to measure the effective emissivity of MLI samples in a similar environment that sattelites actual operating, a vacuum chamber which simulating a high altitude environment was constructed. The vacuum chamber consisted of a main chamber with a diameter of 1.2 m and a length of 1.8 m, and vacuum pumps were consisted for low and high vacuum conditions. The configuration of a vacuum chamber which capable of simulating a high-altitude vacuum environment was shown in Figure 2 [5]. A rotary pump makes a low vacuum environment and three number of turbo pumps are operated for a high vacuum environment with turbo pump controller, and the high vacuum chamber reaches at the level of 3.00×10^{-5} torr, which simulating about a 120 km altitude space environment, within about 1 hour after turbo pumps were operating. In addition, a control box of the vacuum chamber controlled all of the signal and components.

Figure 2: Vacuum chamber test equipment (CNU HPCL)

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However, the vacuum chamber does not include facilities that adjust the temperature of the internal vacuum container. Therefore, in this work, a radiation shelter, which applied the VDA, was designed to adjust the temperature around the control volume of tests, as shown in figure 3. Figure 3 appeared the schematic of a test section configuration. Three number of heaters were used in a test, one of them were mounted in the radiation shelter to regulate the outer wall of the test control volume, and the others were mounted in the baseplate which MLI samples were placed [6]. Heaters which mounted on the baseplate act as a heat source, and in a vacuum environment, it transfers the heat to the inner layer of MLI samples as a radiative heat transfer and a conductive heat transfer mechanism. Accordingly, by measuring and comparison the temperature difference between the inner and outer layer of MLI samples, it can estimate the insulation performance and effective emissivity of each MLI specimens. In addition, thermocouples were located to each component in the test section as shown in figure 3, and the effective emissivity of MLI samples were estimated based on an experimental result.

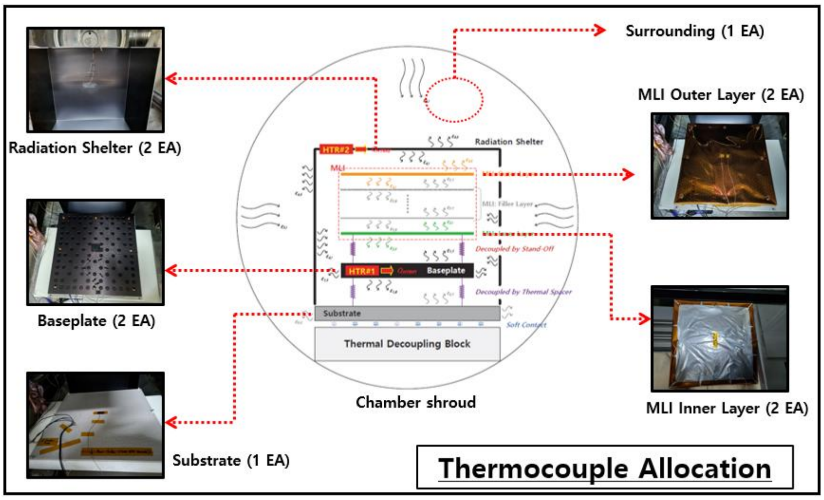

Figure 3: Schematic of test section configuration

2.2 Test equipment configuration

The test equipment configuration is shown in Figure 4. Thermocouples which placed like Figure 3, they measured the temperature on each component and receive date through the Agilent's 34970A DAQ logger. Pressure sensors were consisted with a low vacuum gauge and a high vacuum gauge, depending on the vacuum condition of the inner place of the chamber. The convectron gauge measured a low vacuum condition (999 ~ 1.0×10^{-4} torr), and the ion-gauge mounted to measure a high vacuum condition (2.0×10^{-2} ~ 4.0×10^{-9}). The vacuum level of the chamber could be measured in a real-time state through the vacuum gauge as shown in Figure 4, which transfer the data from gauge to PC by USB communication. Table 1 summarized detailed specifications for each test equipment.

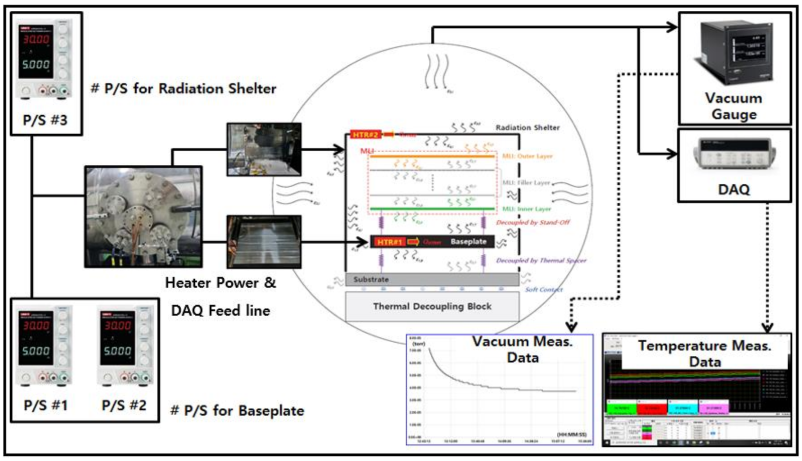

Figure 4: Test equipment configuration

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Table 1: Specification of test equipment

Category	Items (Model: Company)	Specification
Simulating vacuum environment	Rotary pump: Low vacuum (E2M275-Edwards)	· Exhaust speed: 4,876 lpm · Reaching pressure $< 3.8 \times 10^{-3}$ torr
	Turbo pump: High vacuum (TURBOVAC 1000-Leybold)	· Pump speed: 36,000 RPM · Reaching pressure $< 7.5 \times 10^{-2}$ torr
Sensors & Guages	Thermocouples (T Type-OMEGA)	· Measuring range [℃]: -250 ~ 350 · Standard error: ± 0.75%
	Convectron gauge: Low vacuum	· Measuring range [torr]: 999 ~ 1.0×10^{-4}
	Ion-gauge: High vacuum	· Measuring range [torr]: 2.0×10^{-2} ~ 4.0×10^{-9}.
Data acquisition & Logger	Agilent DAQ Logger (34970A: Agilent)	· Accuracy: ± 0.5% ·
	Vacuum Data acquisition (230680V01: Leybold)	· Display range: 10 ~ 2000 mbar
Power supply	DC power supply (UTP3315TFLII: UNI-T)	· Output voltage: 0~30 V · Accuracy: 0.5% + 20 mV · Output current: 0~5 A · Accuracy: 0.5% + 10 mA

Table 2: Test condition according to applied power

Test case	Heating area	Applied power (W)	Target temperature
Case 1	Baseplate #1	5.03	~ 70 ℃
	Baseplate #2	-	
	Radiation Shelter	2.17	~ 25 ℃
Case 2	Baseplate #1	5.08	~ 110 ℃
	Baseplate #2	4.60	
	Radiation Shelter	2.05	~ 25 ℃
Case 3	Baseplate #1	5.13	~ 110 ℃
	Baseplate #2	4.67	
	Radiation Shelter	5.05	~ 30 ℃

DC Power supplies control the power in a capacity of 0~30V and 0~5A, to adjust different temperatures on the base plate and the radiation shelter, respectively. In order to increase the reliability of an estimated effective emissivity of MLI samples, this work estimated the effective emissivity of MLI samples in three different temperature cases as shown in Table 2. Comparing the temperature condition of the test case 1 and 2, the temperature of the radiation shelter

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conducted in the same temperature, but the temperature of the baseplate was set up differently. And in case of 2 and 3, the baseplate temperature conducted at the same temperature, but this time, the radiation shelter temperature was set up differently. By setting the temperature condition as above, the effective emissivity for one MLI specimen could be measured under the condition, in which the temperature of surrounding and baseplate were different.

Theoretical study on estimating the effective emissivity for evaluating the performance of a space-borne MLI has been conducted in many countries [4]. However, in previous studies, they were only optimized for a certain size and shapes of a space-borne MLI, for this reason, it has an unsatisfactory things such as various shapes in the actual design and development process. Therefore, in this study, the effective emissivity of a MLI sample was estimated based on design parameters as shown in Figure 5. Table 3 summarized design parameters which applied to MLI samples in this study. Filler layers of a space-borne MLI can be manufactured in various composition of filler layers. Therefore, by estimating the effective emissivity for each number of filler layers of MLI samples, it can be using for selecting an effective filler layer composition. According to previous MLI performance studies, most of these studies applied 20 number of filler layers in MLI samples. Also, based on a preliminary experiment result, the MLI with 20 number of filler layers showed the lowest effective emissivity, which means the highest insulation performance. In case of 20 number of filler layers, it can be designed another method by configuring it as a double MLI composition. For instance, the 20 filler layers single MLI specimen could be composed with 5 layers & 15 layers MLI or 10 layers & 10 layers MLI. Therefore, by dividing 20 single layers of MLI into a double MLI compositions, the effectiveness of double composition on MLI insulation performance can be identified. Other design parameters are about the stand-off type and the effective distance which clip-on the MLI. Stand-off types were separated in a standard, long and two-step type, and the shape of each types were shown in figure 5. The two-step stand off type is especially useful when it constructing as a double MLI composition. Accordingly, the effective emissivity for MLI samples with different types of stand-off were estimated, and an effective type of stand-off could be selected. Last design parameter is about effective distance according to the number of stand-off as shown in figure 5. Number of stand-off was fixed to 8 or 4 EA, and the performance of MLI samples were compared according to the distance of the stand-off. By estimating the effective emissivity according to variable design parameters, the effectiveness of each design parameters on MLI performance was confirmed.

Table 3: Applied design parameter list

Design parameters	Test condition	Purpose
Number of filler layers	5, 10, 15, 20, 25, 30 layers	· Performance comparison according to the number of filler layer · Selection of effective layer
Double MLI composition	20(5+15, 10+10) layers	· Identification effectiveness of double MLI composition
Different types of stand-off	Standard, Long, Two-step	· Performance comparison according to different types of stand-off · Selection of effective stand-off types
Number of stand-off	4 EA, 8 EA	· Performance comparison according to effective distance

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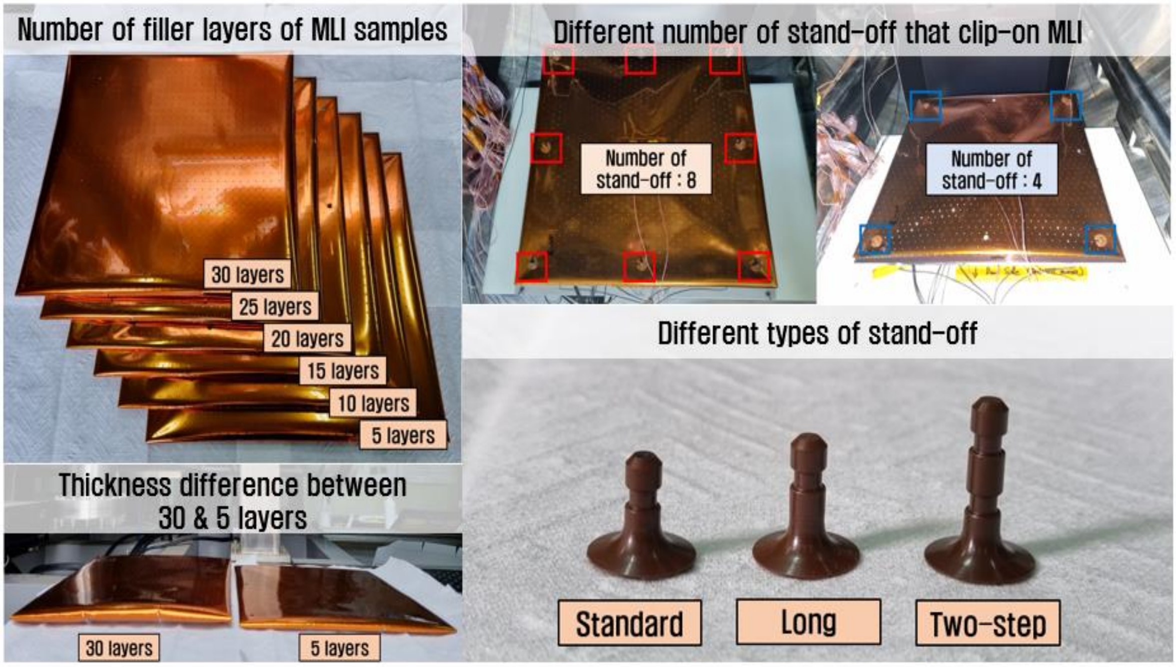

Figure 5: Design parameters of MLI samples

Test setup of the chamber inside is shown in Figure 6. The test stand was designed to evaluate the performance of MLI samples according to various design parameters. Double MLI composition 5 & 15 layers MLI and single 20 layers MLI configuration were shown in figure 6.

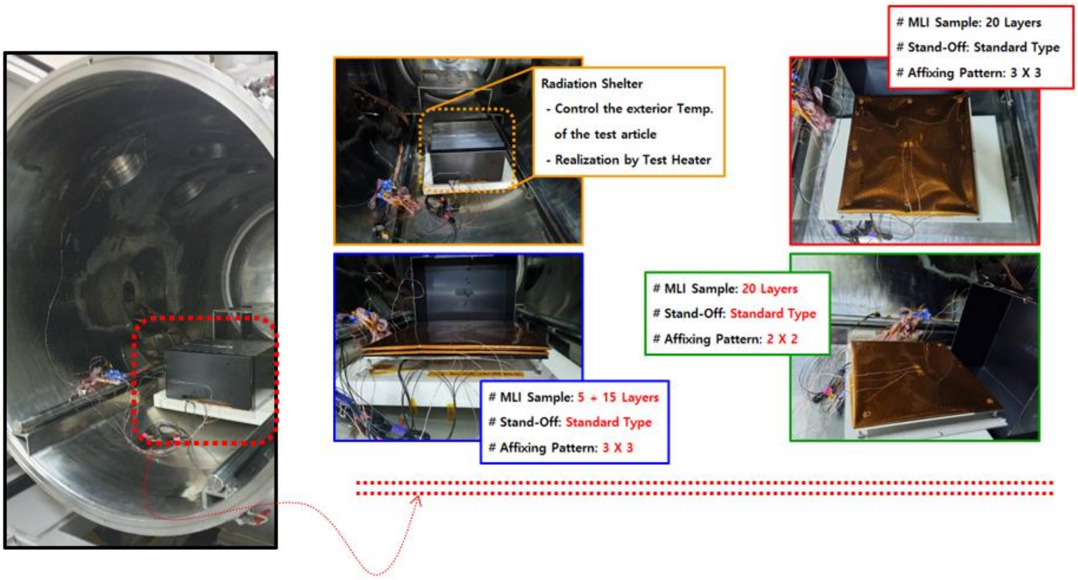

Figure 6: Experimental setup of MLI performance test

3. Post Proceedings

Prior to the analysis of test results, test criteria, such as a temperature stabilizing and a vacuum condition were defined to increase the reliability of test results. In space environment thermal vacuum testing, the vacuum level of the chamber and the temperature stabilization condition of specimens are considered most important things. Table 4 summarized the temperature stabilization criteria for a space environment testing that conducted by research institutes. Although each organization had selected the different temperature stabilization condition, they usually selected the

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temperature stabilization criteria as a temperature deviation lower than 0.5 ℃ / hr. In this regard, as the temperature stabilization criteria selected lower, the reliability of the test result can be increased. However, in this work, various design parameters were conducted, also effective emissivity of the MLI sample is measured for three different temperature conditions. Due to its many time of tests, this work selected the temperature stabilization criteria within an acceptable range than a precise control of the temperature. Therefore, in this study, as a temperature stabilization critea '< 0.5 ℃ / hr as measured over 1 hours' was selected same as the NASA Langley institution. Figure 7 showed the temperature stabilization and vacuum conditions of this study. After the vacuum level dropped below 3.75×10^{-5} torr, heaters were operated and power sources were controlled to set the temperature condition by referring to the test case. As shown in Figure 7, the temperature of each component was measured by real time state through sensors and PC program, and the data is stored by checking whether the temperature converges in 0.5℃ / hr.

Table 4: Summary of temperature stabilization criteria for thermal balance testing [7]

Organization	Temperature stabilization criteria
U.S. Air force	< 0.2 ℃ / hr as measured over 5 hours
NASA Goddard	< 0.05 ℃ / hr as measured over no less than 6 hours
NASA Langley	< 0.5 ℃ / hr as measured over 1 hours
NASA Marshall	Tenths or hundredths of a degree
Jet Propulsion Laboratory	< 0.3 ℃ / hr as measured over 3 hours
European Space Agency	< 0.1 ℃ / hr as measured over 5 hours
JAXA	< 0.3 ℃ / hr

Figure 7: Temperature stabilization and vacuum level criteria

Referring to previous studies on estimating the effective emissivity of a space-borne MLI, there are many approach method to estimate the effective emissivity such as theoretical approach, experimental equation, empirical equation, radiative heat exchange equation etc. In this paper, the effective emissivity of a space-borne MLI was estimated based on the radiative heat exchange equation as shown below[8]. Figure 8 shown the schematic of the radiative heat exchange process through a space-borne MLI. Following the process as shown below eq. 1 to 4, this paper estimated the effective emissivity of MLI samples [8, 9, 10]

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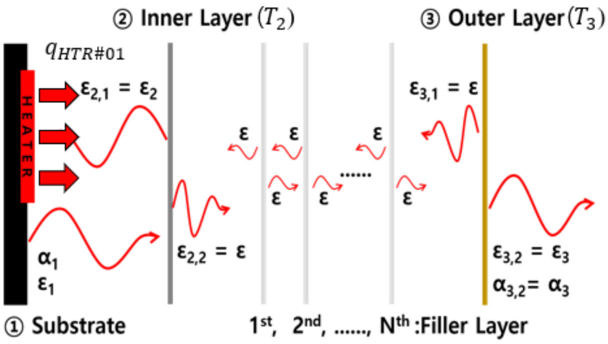

Figure 8: Schematic of radiative heat exchange through a space-borne MLI [2]

$$A_1 = A_2 = A_3 = \cdots = A_N \tag{1}$$

$$q_{23} = q_{12} = q_{HTR\#01} - q_{10} - q_{14} \cdots \approx q_{HTR\#01} \tag{2}$$

$$q_{23} = \sigma \cdot A \cdot \varepsilon^*_{MLI} \cdot \left(T_2{}^4 - T_3{}^4\right) \tag{3}$$

$$\varepsilon^*_{MLI} = {q_{HTR\#01}}\Big/{\sigma \cdot A \cdot \left(T_2{}^4 - T_3{}^4\right)} \tag{4}$$

4. Experimental results

Experimental results were shown in figure 9 and figure 10. Figure 9 showed the effective emissivity of MLI samples according to number of filler layers. As a result of experiments, both test conditions showed the lowest effective emissivity in the number of 20 filler layers, which means the highest performance of a space-borne MLI. In addition, the test condition of standard No. 8 showed lower effective emissivity than the standard No. 4. That is, as the number of stand-off that clip on a MLI increases, and the degree of compression getting increases on MLI samples, the effective emissivity getting decreases. Figure 10 compared the effective emissivity by configuring various combinations (standard type: 5 & 15 layers, 10 & 10 layers, two-step type: 5 & 15 layers, 10 & 10 layers) of double MLI composition for a 20 layers MLI configuration. As a result, both conditions in standard No. 8 and No. 4, the effective emissivity of a single 20 filler layers getting reduced when the 20 layers MLI configured by double MLI composition with standard stand-off and two-step stand-off. In addition, compared to two step stand-off double MLI composition, MLI with standard stand-off showed lower effective emissivity. Accordingly, configuring of a space-borne MLI with double MLI composition showed advantageous than the standard type single stand-off.

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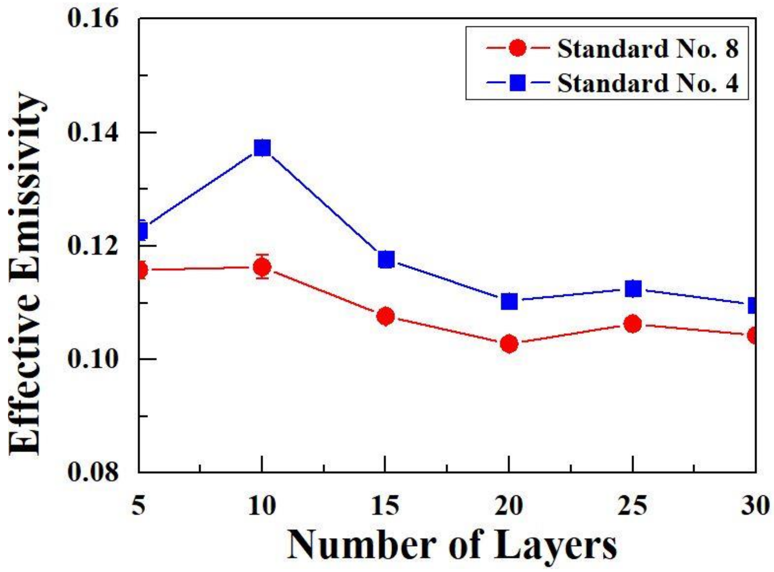

Figure 9: Estimation of ε^* variance with MLI layers

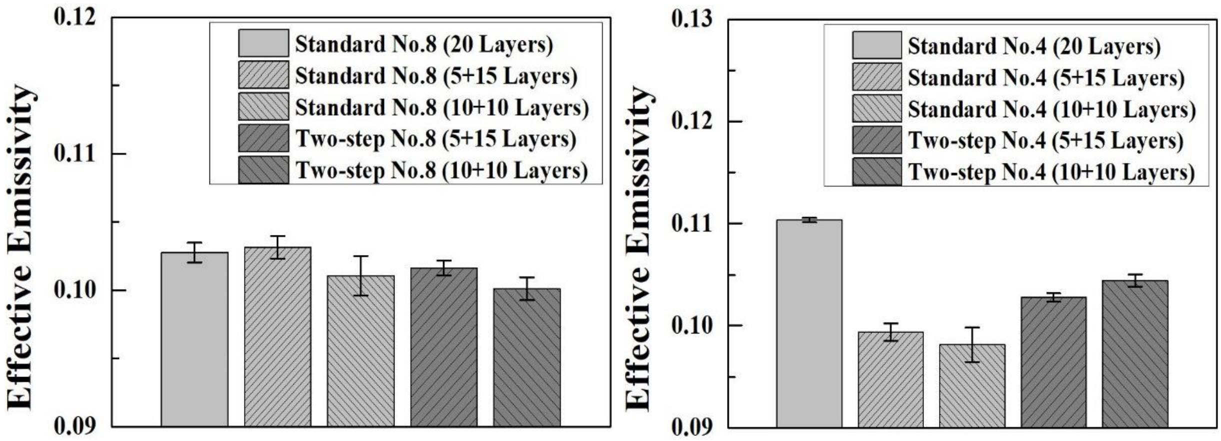

Figure 10: Comparison ε^* variance with 20 layers composition

5. Conclusion

In this work, an experimental system to estimate the effective emissivity of MLI samples were constructed. The vacuum level of the chamber was kept below the level of 3.75×10^{-5} torr. Also, the standard stabilizing condition of the temperature was conducted by 0.5 ℃/hr. As a result of experiments, twenty filler layers MLI showed the highest performance compared to the other filler layers. To improve the performance of MLI, several experiments were performed with other design parameters. As a result, double MLI composition MLI layers showed lower effective emissivity compared to the single 20 layers, which means MLI performance increase. Other design parameters were conducted with stand-off types (standard, two-step, long), and the number of stand-off (8 pcs., 4 pcs). In case of the MLI affixing by 4 and 8 patterns, the two-step stand-off showed lower effective emissivity compared to the standard stand-off. Based on experimental results, 20 double MLI composition (10+10) with 8 number of two-step types of MLI showed the highest performance. In addition, to increase the reliability of the effective emissivity estimation, an equation that reflects design parameters is required. Therefore, in future works, an effective emissivity equation, which is based on heat transfer mechanism & MLI design parameters will be constructed, and an equation will be validated with experimental results.

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