Numerical simulation and experimental investigation of the thermal insulation performance of multi-layer insulation material at 20-298 K

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Abstract. Thermal insulation plays a major role in the use of cryogenic systems. Due to its superior thermal insulation property, Multi-layer insulation materials (MLI) are widely used in various cryogenic systems, such as superconducting magnets, space propellant storage, satellites and so on. Thus, it is crucial to estimate and measure the insulation performance of it. This paper has carried out a numerical simulation of the performance of one kind of MLI through a modified Layer-by-Layer model. The thermal insulation propriety of the test specimen is also measured by a newly designed measurement system, which is based on the steady-state axial heat flux method. Finally, the simulation and test results are compared and discussed.

1. Introduction

Multi-layer insulation (MLI) system is a kind of thermal insulation system, which normally consists of several metal foils or metal coating polymeric films with high reflectance and thin spacers with low thermal conductivity [1, 2]. Due to the excellent property in thermal insulation, MLI systems are widely used in cryogenic systems such as cryogenic liquid transportation, spacecraft and superconducting system to reduce heat leakage.

The insulation performance of MLI is affected by the material of spacer and metal coating, layer density, the temperature of cold and warm boundary, etc. Thus, it is essential to measure the thermal property of MLI at different conditions and improve the thermal performance of the MLI system.

As a traditional thermal property testing method of MLI at cryogenic temperature, measurement by evaporation rate is usually carried out with cryogenic liquid [3, 4]. Because of the difficulty of temperature regulation, evaporation has a limited boundary temperature. Moreover, it is expensive to use liquid helium and dangerous to use liquid hydrogen. Therefore, cryocoolers have been applied as cold sources of the MLI measurement systems. This method has many advantages such as simple
temperature regulation and low cost of measurement, etc.

In this paper, the thermal property of one kind of MLI has been studied through a kind of MLI measurement system cooled by a G-M cryocooler. By using a modified layer-by-layer model, the property is also simulated and compared with the result of the experiment.

2. Experiment
2.1. Apparatus and test specimen
The measurement system is shown in Figure 1. It is cooled by an RDK-415D two-stage G-M cryocooler and has two thermal shields made of OFHC (oxygen-free high-conductivity copper). The outer shield function as the warm boundary of the MLI measurement system, is thermally attached to the 1st stage cold head of cryocooler through some copper braids. While the inner shield functions as the cold boundary, and is thermally attached to the 2nd stage cold head through a support plate and a calibrated rod. The temperature of the cold and warm boundary is controlled by a temperature controller.

The heat flow through MLI is absorbed by the cold boundary and transmitted to the 2nd stage cold head through the calibrated rod. By placing the rhodium-iron resistance thermometer on the calibration rod, the temperature gradient on the calibration rod is measured. Comparing the test data to the calibration data of the calibrated rod, the heat flow can be calculated. It was calculated that the total measuring error is about 9.47%, which is better than the error of the traditional measurement systems of MLI.

The detailed description and measurement principle of the device is described in the article [5].

Figure 1. Schematic diagram of the MLI measurement system
The test specimen is a commercial MLI material (provided by Wuhan Yang-Ge-En Technology Co., Ltd.) composed of double aluminized-Mylar (reflector) and polyester non-woven fabric (spacer). The size of it is 1220mm×700mm, and the layer density is 29.4 layers/cm. The number of layers is 30 and the area of the cold boundary is 0.76m².

2.2. Experiment result
Set the temperature of the cold boundary as 20K, and the warm boundary as the ambient temperature. Record the temperature of the upper and lower location of the calibrated rod when the system reached thermal equilibrium. The temperatures of these two locations during the thermal equilibrium are shown in Figure 2.

It was calculated that the temperature difference between the upper and lower calibrated rod is 0.921K when the system reaches thermal equilibrium, and the vacuum degree is 3.4×10⁻⁴ Pa. According to the calibration data of the calibrated rod, the heat flow is 1.07 W. Treating the area of cold boundary as the heat transfer area of the MLI, the heat flux is 1.41 W/m² by calculation.

![Figure 2. Temperature histories of the upper and lower calibrated rod](image)

3. Calculation
3.1. Modified calculation model
The Layer-by-Layer model is a classical calculation model of thermal properties of the MLI materials [6]. It divided the heat transfer through MLI into three parallel parts, including solid conduction \( (k_s) \), gas conduction \( (k_g) \) and thermal radiation \( (k_r) \) [7]. The total thermal conductivity can be expressed as:

\[
k = k_s + k_g + k_r
\]

(1)
3.1.1. **Solid conduction.** The solid conduction of MLI mainly from the thermal contact between spacers and reflectors, and it can be calculated through the following equation:

\[ k_s = \frac{C_1 f k}{d} \]  

Where,
- \( k_s \) – solid conduction, [W/m²·K];
- \( C_1 \) – an empirical constant, 0.008 for the specimen;
- \( f \) – relative density of the spacer compared to the solid material, 11.6 for the specimen;
- \( k \) – thermal conductivity of the spacer, \( 0.17 + 7 \times 10^{-6}(800 - T) + 0.0228 \cdot \ln(T) \) [W/(m·K)] for the specimen [7], \( T \) represents the temperature, K;
- \( d \) – thickness of a piece of spacer, 1.8 [μm] for the specimen.

3.1.2. **Gas conduction.** The thermal conductivity of the residual gas conduction can be written as follows:

\[ k_g = C_2 p \alpha \]  

Where,
- \( k_g \) – gas conduction, [W/m²·K];
- \( C_2 \) – \( [(\gamma + 1)/(\gamma - 1)] \cdot [R/8\pi M T]^{1/2} \), \( \gamma = c_p/c_v \), \( R = 8.314 \) J/mol·K, \( M \) represents the molecular weight of the gas, [g/mol]. For this experiment, \( C_2 = 1.1666 \) [7];
- \( p \) – gas pressure, [Pa];
- \( \alpha \) – accommodation coefficient, 0.9 for air [6];

In this experiment, the pressure of the vacuum chamber under cryogenic temperature reaches \( 10^{-5} \) Pa, considering that the gas pressure of the interlayers is higher than the pressure of the chamber, the gas pressure of the interlayers can be considered to be \( 10^{-3} \) Pa.

3.1.3. **Thermal radiation.** The coefficient of thermal radiation is as the following equation:

\[ k_r = \frac{\sigma(T_{N+1} + T_N)\varepsilon T_{N+1}^2}{\varepsilon_{N+1} + 1 - \frac{1}{\varepsilon_{N+1}}} \]  

Where,
- \( k_r \) – coefficient of thermal radiation, [W/m²·K];
- \( \sigma \) – Stefan-Boltzmann coefficient, \( 5.67 \times 10^{-8}[W/m^2·K^4] \);
- \( T_N, T_{N+1} \) – temperature of layer \( N \) and layer \( N + 1 \), [K];
- \( \varepsilon_N, \varepsilon_{N+1} \) – emissivity of layer \( N \) and layer \( N + 1 \);

Because the temperature difference between adjacent layers is small, the emissivity of adjacent layers can be considered the same, thus \( \varepsilon_{N+1} = \varepsilon_N \).

According to the previous studies, emissivity of the double aluminized-Mylar has an approximate positive correlation with temperature at cryogenic temperature, and it can be described by the following equation roughly [8]:

\[ \varepsilon = 0.0131 + 4.643 \times 10^{-5}T \]
3.2. Calculation procedure

The relation between $k$ and $T_N, T_{N+1}$ (temperature of layers) is established through the above mathematical processing. Based on the above equations, the temperature of each layer of MLI can be calculated through an iterative process. The calculation process is shown in Figure 3.

![Figure 3. Calculation flow chart](image)

3.3. Results and discussion

The temperature of layers of MLI has been calculated, and compared to the result of measurement. The comparison is shown in Figure 4.

![Figure 4. Comparison of the temperature of layers between measurement and calculation](image)
As can be seen in Figure 4, the calculation result of the difference in temperature between the first ten layers is larger than that in the measurement. Due to the larger preload at the internality of the MLI in the measurement, the internal layer density is higher, thus the solid thermal conduction is higher than that in the calculation. Past studies have shown that leakage of solid conduction and thermal radiation account for different share of total heat leakage [9]. The change of temperature has more influence on thermal radiation. While at the lower temperature zone, the solid conduction accounts for the major part of the total heat transfer, and the thermal radiation accounts for the major part of the total heat transfer at the higher temperature zone. Thus, the temperature difference between the measurement and calculation results is larger at the internal layers, and diminishes at the outer layers.

4. Conclusion
By using the MLI measurement system cooled by a G-M cryocooler, the heat flux of one kind of commercial MLI material has been measured when the temperature of cold boundary is 20 K and warm boundary is 298 K in this article.

The temperature of layers of MLI is also calculated by using a modified layer-by-layer model, and the calculation result has been compared with the experiment result. The difference between experiment and calculation result has also been analyzed in this article.

On one side, the obtained result is instructive to the design and construction of cryogenic cryostat. On the other side, the analyze for the contribution of different heat transfer mode in different temperature range is also important for the optimization of the high-performance MLI.

5. Future
In order to provide guidance for the MLI application, the heat flux of MLI when the temperature of the cold boundary and the warm boundary changed will be measured in the future, and the changing law will also be summarized. The thermal property of more different kinds of MLI materials will be tested to find better MLI materials. In addition, on the basis of the measurement and calculation analysis, new MLI materials will be developed.

6. Reference
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