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Design of a multi-layer insulation(MLI) measurement system with a G-M cryocooler

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Abstract. Multi-layer insulation (MLI) is widely used in cryogenic systems such as Aerospace propulsion systems and various cryostats. The effective thermal conductivity of MLI used in lab is measured by typical systems using bath cryostat, which is only able to maintain boundary temperatures at critical point of cryogen. A liquid cryogen-free apparatus based on a two stage G-M cryocooler has been developed to measure the effective thermal conductivity of multi-layer insulation(MLI) materials at temperatures ranging from 20-300 K. Unlike traditional measurement systems utilizing evaporation rate of liquid cryogen, a calorimeter supported by a calibrated rod is installed in this system to determine the heat flow through the testing blanket. This design eliminates the error caused by variation of environment pressure to the measured evaporation rate, and meanwhile, simplifies the system structure.

1. Introduction

Heat insulation is a key element for long-running operation in cryogenic systems such as spaceflight, superconducting systems and other systems. Relatively small heat leak can cause significant boil-off, pressure increase, and thus shorten the operating time. Multi-layer insulation is considered as the most effective way of heat insulation in high vacuum cryogenic systems and is widely utilized in these systems [1,2,3]. However, the performance of MLI shows great difference in different situations, such as boundary temperatures, density, number of layers and other situations. So it is crucial for us to determine its heat insulation performance in different cases before use.

Systems designed for measuring effective thermal conductivity of MLI are mostly using the rate of evaporation of a cryogen [4,5,6,7]. Although calorimeters filled with cryogenes are more similar to the actual dewar, the cold boundary temperatures are determined by cryogen in these systems and cannot be regulated. Moreover, the heat through the MLI is calculated by the evaporation rate, thus atmospheric pressure has an influence on the measuring result.



In order to solve this problem, a MLI measurement system cooled by a two stage G-M cryocooler is designed in this article. Different from cryogen systems that measuring the volume flow rate of evaporated liquid cryogen, the heat flow through the measurement section is determined by a calibrated rod and the boundary temperatures are determined by the cold heads. This unique design enables a variable boundary temperatures and eliminates the potential problems caused by cryogens.

2. Experimental principle

The design of the cryogen-free MLI measurement system is based on the idea of the thermal conductivity measurement systems, described in references [8,9]. As is shown in figure 1, heat flow through MLI blankets can be calculated by using a calibrated rod provided that the cold boundary exchange heat with calibrated rod and 1st stage thermal shield only. The relationship between the temperature gradient at the rod and heat flow can be summarized in a graphic, and this is the calibration of the rod. The heat load through tested MLI blanket equals to the heat transfer through the calibrated rod. The performance of tested MLI blanket is determined by heat flux in this article and it is obtained from the following equation.

$$q = \frac{Q}{A} \quad (1)$$

Where q (W/m^2) is the heat flux through the tested MLI blanket, Q (W) is the heat load through MLI blanket, which is calculated from the calibrated rod, and A (m^2) is the area of MLI blanket;

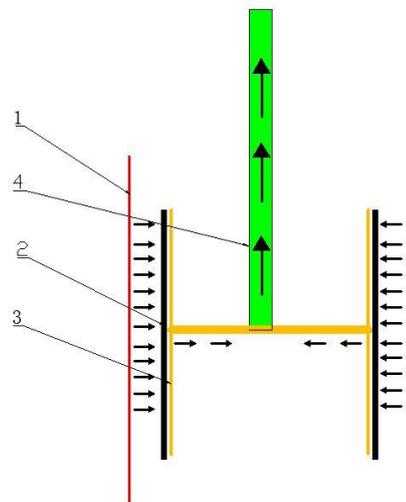


Figure 1. Schematic of MLI measurement system

1-1st stage thermal shield; 2-MLI blanket; 3-cold cylinder; 4-calibrated rod

3. System design

The measurement system is consisted of a calorimeter, an isothermal protector, a higher vacuum pumping unit, a temperature measurement and control unit and a supporting unit. Figure 3 shows the structure of the MLI measurement system. Two cylindrical oxygen-free copper thermal shields cooled by the cold heads are set as the boundaries for testing. The heat flow through the MLI blanket is absorbed by the 2nd stage cold head.



Figure 2. Photograph of MLI measurement system

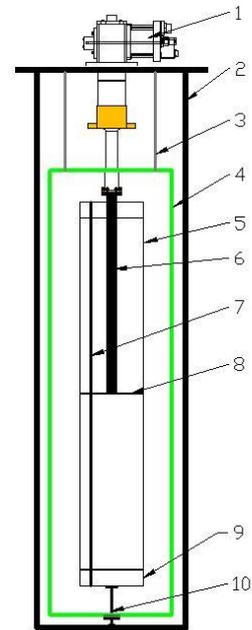


Figure 3. Structure of MLI measurement system

1-two-stage G-M cryocooler; 2-vacuum chamber; 3-support rod; 4-1st stage thermal shield; 5-cold cylinder; 6-calibrated rod; 7-heat conducting rod; 8-support plate; 9-lids of cold cylinder; 10-locator.

The whole system is cooled by a RDK-415D two-stage G-M cryocooler and the specifications of this cryocooler are: 35 Watts @ 50 K on the 1st stage and 1.5 Watts @ 4.2 K on the 2nd stage, the cooldown time to 4.2 K of the 2nd stage cold head is 60 minutes without load. Three stainless steel cylinders with a top flange are joined together to provide a 10^{-5} Pa vacuum environment for the calorimeter and the thermal shields.

A thermal shield, worked as the warm boundary, thermally contacted with the 1st stage cold head through eight 150 mm long copper braids. This thermal shield is consisted of a flange and two cylinders, and they are made of OFHC (oxygen-free high-conductivity copper) to ensure a uniform temperature. the top cylinder and the bottom cylinder are connected by 16 bolts for a convenient installation. The cylinder is 1420 mm in length and have a diameter of 384 mm. Two PT-100 platinum resistance thermometers are placed at the warm cylinder to monitor the temperature and a temperature controller is utilized to control the warm boundary temperature.

The cold boundary is a 1102 mm long, 192 mm in diameter OFHC cylinder, MLI blankets being tested is wrapped around the cold boundary. In order to decrease the thermal radiation from the top and the bottom, the cold boundary is designed as a long and thin tube. Heat flow through the MLI blankets is absorbed by the cold boundary and then delivered to the 2nd stage cold head through a calibrated rod. Radiation from the vertical space result in a 3-dimension heat transfer issue which complicates the mathematical analysis and leads to greater error. To prevent this kind of radiation, two lids maintained at the same temperature with this cold cylinder are set at the top and the bottom. The lids are connected by two OFHC rods and both of them are thermally isolated from the cold boundary.

Four copper braids are set between the top lid and the 2nd stage cold head to transfer heat. Temperature sensors and controllers are placed at the two lid, which are employed to monitor and control the temperature of the lids.

A metal rod, set between the cold boundary and 2nd stage cold head, is calibrated before MLI measurement. The replaceable rod has a diameter of 30 mm and a length of 623 mm. Two rods with the same dimensions have been made by copper and aluminium respectively, and they are used in different cold boundary temperatures. Two rhodium iron resistance thermometers are inserted into the rod and their vertical distance is 550 mm. The relationship between temperature gradient of the rod and heat flux through the rod is draw in a graph so that the heat Q in the test can be obtained easily from the graph.

To reduce thermal contact resistance, we use high-conductivity grease and indium slices between contacting surfaces.

4. Theoretical analysis of the heat load and errors analysis

In order to insulate heat leakage from ambient, the vacuum chamber provides vacuum environment up to 10^{-5} Pa for the system to eliminate heat leakage through convective heat transfer. Heat load for the 1st stage thermal shield is heat transfer through three austenite 304 stainless steel support rods and radiation from vacuum chamber. The 1st stage thermal shield is wrapped with MLI for a better heat insulation. Cold cylinder suspended below the top lid which maintain at the same temperature with it, so that heat load for the cold cylinder is radiation from 1st stage thermal shield, and it is the heat through tested MLI blanket. The top and bottom lids is also cooled by 2nd stage cold head and the top lid is suspended by 1st flange through 3 epoxy resin rods. The heat load is calculated as shown in table 1.

Table 1. heat load of 1st stage thermal shield and cold cylinder

Items	Components	Heat load /Watt
1 st stage thermal shield	Support rods	1.164
	Radiation	1.702
	Total	2.866
Cold cylinder	Radiation	0.203
Lids	Support rods of lids	0.00174
	Radiation	0.036
	Total	0.241

The total heat load of 1st stage thermal shield is 2.866 W, while the cooling capacity of the 1st cold head at 50 K is 20 W; Meanwhile, the total heat load of the cold cylinder and the lids is 0.241 W, and the cooling capacity of the 2nd stage cold head at 10 K is about 13 W. This means that the MLI measurement system is achievable. The cold cylinder and the 1st stage thermal shield can reaches blow 10 K and 50 K at the experiment, respectively.

The measuring error in this system mainly comes from the temperature measurement and the heating power measurement. According to the specifications of the manufacturers, the maximum values of the errors are shown in table 2. It can be concluded from table 2 that the total measuring errors is about 0.908%. This indicates the superiority over the traditional measurement systems based on cryogen, which have a measurement error about 4% [10] due to the large error from the gas flow

rate measurement. The statistical errors are reduced through placing more temperature sensors on the boundaries and taking the values until an equilibrium obtained in the test. Repetitive experiment is also used to minimize the statistical error.

Table 2. The measuring errors in the system

Positions	Thermometer of the cold cylinder	Thermometer of the warm boundary	Thermometers of the calibrated rod	Power supply of the heater	Total
errors	0.088%	0.39%	0.42%	0.01%	0.908%

5. Conclusion

A newly designed MLI (multi-layer insulation material) measurement system cooled by a two-stage G-M cryocooler is introduced in this article. The temperatures of cold and warm boundary of this system are adjustable so that effective thermal conductivity test of MLI can be carried out at any set of temperature ranging from 10 K to ambient temperature, which is unreachable in traditional cryogen systems. Additionally, the structure of this system is simple comparing with cryogen systems. Thermometers and temperature controllers are working and experimental data obtained in difference cases will be published in the future.

6. Future

The future work will be continued in three steps. The rods made by copper and aluminium will be calibrated and a graph of the relationship between temperature difference and heat flow will be made for them. Then MLI blanket with different kinds, boundary temperatures, densities and other parameters will be tested and analysed. For discovering better thermal insulation structures, composite structures containing MLI and other insulation materials will be tested and analysed by this system.

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