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Test apparatus utilizing a Gifford-McMahon cryocooler to measure the thermal performance of multilayer insulation

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Abstract

A vertical cylindrical calorimeter for measuring the thermal performance of multilayer insulation (MLI) has been developed. Two concentric oxygen-free high-conductivity copper drums are wrapped with sample MLI blankets, and are cooled using a two-stage Gifford-McMahon cryocooler. As the drums are vertically supported, the layer density of the MLI sample is unaffected by gravity. The inner drum is cooled by the 2nd stage of the cooler and is maintained at a temperature of about 6 K. The outer drum is maintained at a temperature of about 65 K by connecting it to the first stage of the cooler. The heat transfer through the blanket is determined by measuring the temperature difference across the stainless steel thermal resistance tube in a heat-flow meter placed between the drum and the cold finger of the cryocooler. The structure of the calorimeter, the calibration procedure, and results for heat flow through the MLI sample are reported.

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Keywords: multilayer insulation; Gifford-McMahon cryocooler; heat-flow meter

1. Introduction

The multilayer insulation (MLI) to be used in the Large-scale Cryogenic Gravitational Wave Telescope known as KAGRA must release as little moisture as possible into the cryostat vacuum tank, which requires the lowest possible quantity of polyester in the MLI. A new thermal insulation film for lightweight MLI was developed by Kaneka Corporation. The film (Code No. KFP-9B08) is 9 μm thick double aluminized Mylar (DAM) with very thin non-

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woven polyester spacer which is laminated to one side of the DAM, and has been measured for outgas rate in vacuum, and the outgas quantity has been found comparable to that of stainless steel, and is thus sufficiently low.[1)]

In the present study, we constructed a prototype calorimeter incorporating a two-stage Gifford-McMahon (GM) cryocooler for measurement of the thermal insulation performance of this MLI. Here we describe the essentials of this calorimeter and its application to measurement of the MLI thermal performance which is defined as the heat flux perpendicular to the surface of MLI.

In the cryostats of KAGRA, the temperature of the MLI on its cold side is approximately 10 K, which is far below that of liquid nitrogen. The thermal performance of MLI in this temperature range is generally assessed by measuring the rate of liquid helium evaporation from a boil-off calorimeter, which inherently involves certain problems. Liquid helium is a scarce resource, and it is difficult to handle. The vaporized gas flow from the boil-off calorimeter, moreover, is strongly affected by changes in atmospheric pressure,[2)] and lengthy gas flow rate measurements are required to obtain average values suitable for evaluation of MLI thermal performance.

To avoid these problems, we constructed a prototype calorimeter in which the MLI thermal performance is measured as it is cooled on one side by a GM cryocooler. The temperature of the MLI cold-side environment is thus maintained by the cryocooler, with no need for liquid helium. But this calorimeter requires a meter to measure the heat flow through the MLI to the cold side. The heat-flow meter developed for this purpose determines the heat flow based on the temperature difference between both ends of an SUS 304 thermal resistance part of the meter.

2. Apparatus and procedure

Fig. 1 shows the structure of the prototype calorimeter developed in this study. The measurements are performed with an MLI sample wrapped around two vertical oxygen-free high-conductivity copper (OFHC) drums. Each drum is connected to a cold head of the GM cryocooler via a heat-flow meter.

The first-stage cold head is attached to the high-temperature drum, and the second-stage cold head is attached to the low-temperature drum, thus enabling simultaneous determination of the MLI thermal performance at levels near 70 K (high temperature) and 4 K (low temperature). The high-temperature drum is 172 mm in outer diameter and 700 mm in height, and the low-temperature drum is 118 mm in outer diameter and 400 mm in height.

The thermal resistance part in the 70 K heat-flow meter (Fig. 2(a)) attached to the first stage is composed of two concentric cylinders formed from SUS 304 thin sheets with a thickness of 0.4 mm. Its “cold-end” flange is connected to the first-stage cold head of the cryocooler, and its “hot end” flange is connected to a flange in the 70 K drum. The temperatures of the hot and cold ends of the thermal resistance parts are each measured using a diode thermometer (DT-670-CU; Lake Shore Cryotronics, Inc.). In the 4 K heat-flow meter (Figure 2(b)), the thermal resistance part is an SUS 304 pipe 25 mm in outer diameter and 2.5 mm in wall thickness, and its temperatures at both ends are measured with a low thermal resistance germanium thermometer (GR-1400-AA; Lake Shore Cryotronics, Inc.).

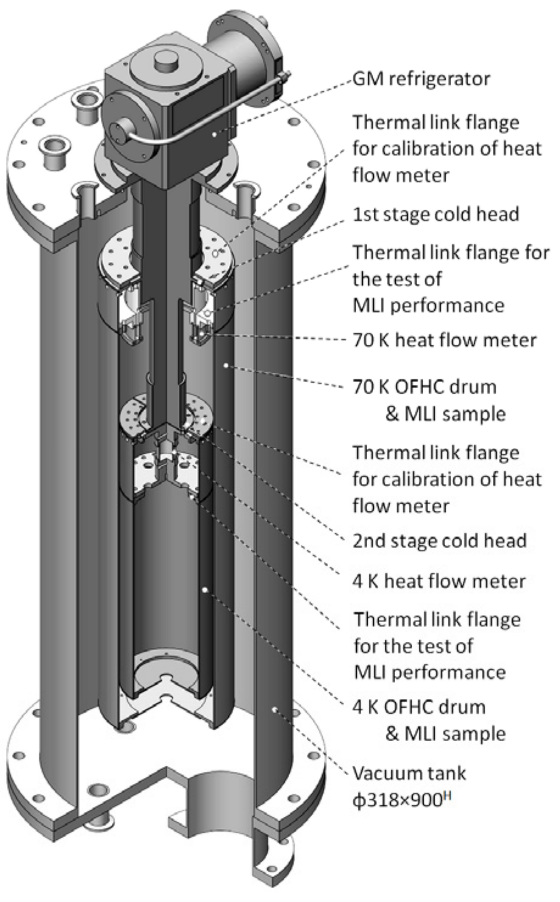
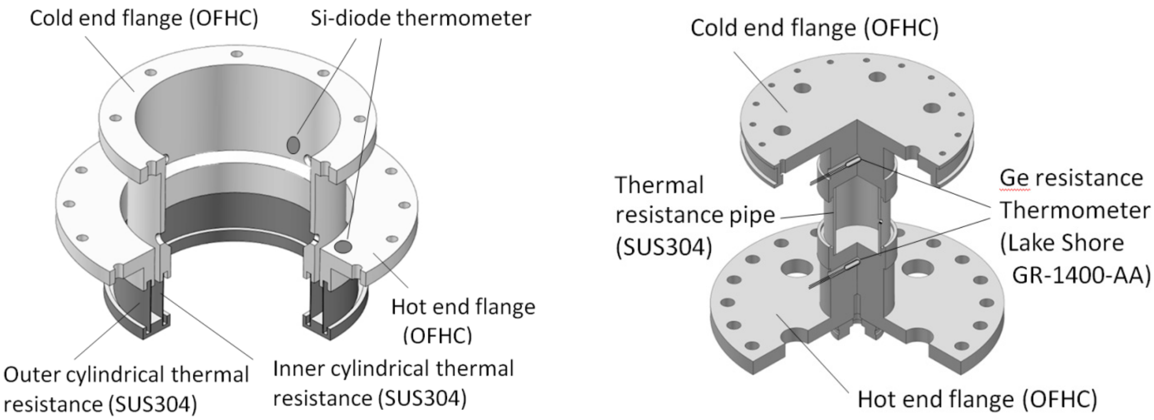


Fig. 1. Test apparatus utilizing GM refrigerator.



(a) 70 K heat-flow meter (b) 4 K heat-flow meter

Fig. 2. Schematic diagrams of the heat-flow meter.

The cold-end flange of this heat-flow meter is connected to the second-stage flange of the cryocooler, and its hot-end flange is connected to a flange in the 4 K drum.

For calibration of the heat-flow meters, the drums are disconnected from the hot-end flanges of their respective heat-flow meters and lowered axially by approximately 5 mm. The calibration flange at the top of each drum then lies on the corresponding cold head of the cryocooler and is bolted to that head. The drums are thus cooled directly by contact with the cold head. Each drum then functions as the thermal shield for its heat-flow meter. The hot end of each heat-flow meter is heated using a calibration heater consisting of a Manganin wire wound around it, in order to simulate the flow of heat through the MLI and into the drum.

For measurement of the MLI thermal performance on the drums, the cold heads are disconnected from the corresponding flanges at the top of the drums, the drums are then axially raised by 5 mm, and their internal flanges are bolted to the corresponding hot end-flanges of the heat-flow meters. In this configuration, the heat flow $\dot{Q}_1$ into the 70 K drum via the MLI wrapped around it comprises the heat flow $\dot{Q}_2$ to the hot-end flange of the 70 K heat-flow meter and the heat flow $\dot{Q}_3$ arriving at the MLI wrapped around the 4 K drum, which is measured by the 4 K heat-flow meter. The GM cryocooler used in this system is a Sumitomo Heavy Industries, Co. cryocooler RDK-415D.

3. Calibration results for heat flow meters

The electrical input to the calibration heater on the heat-flow meter for the 70 K drum, was varied and the resulting temperature changes at the cold and hot ends of the heat-flow meter in each drum were measured. Fig. 3 shows the changes in the measured temperature at the ends of the heat-flow meters while cooling the calorimeter using the GM cryocooler. As shown, the temperatures at all measured points stabilized approximately 40 h after the initiation of cooling. Electric power was then applied to the calibration heaters and the values at the heat-flow meters were recorded following their stabilization. Fig. 4 shows the change over time of the hot-end temperature T_h and the cold-end temperature T_c of the thermal resistance part in 70 K heat-flow meter while varying the electrical input to the calibration heater. Fig. 5 shows the dependence of T_h and T_c on $\dot{Q}$ in the range 0 to 1.6 W. It can be seen that T_c was almost constant at 20.4~21.5 K, because $\dot{Q}$ is far lower than the cooling capacity of the cryocooler. In contrast, T_h increased monotonically from 20.4 to 103.9 K.

In the 4 K heat-flow meter calibration test, as shown in Fig. 6, the electrical input to the calibration heater was varied in the range of 0 to 0.0187 W, and the resulting temperature changes over time at the hot and cold ends of its thermal resistance part rose as shown. Fig. 7 shows the variations in the hot- and cold-end temperatures of this heat-

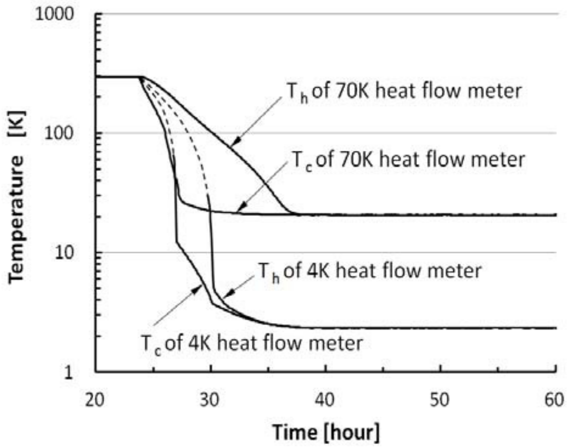


Fig. 3. Temperature variation of heat-flow meters with time during calibration.

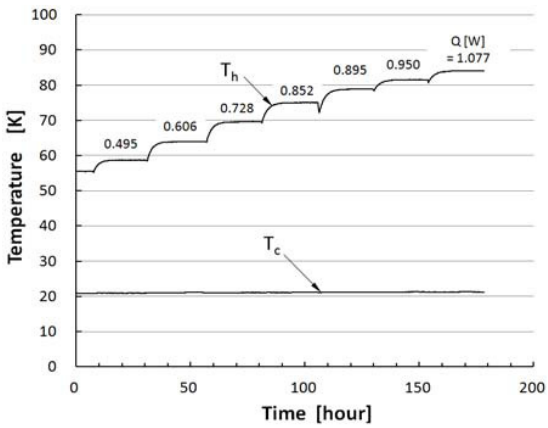


Fig. 4. Temperature dependence of 70 K heat-flow meter with time and input power to the calibration heater.

flow meter for this range of electrical input to the calibration heater. They are seen to be very similar to those for the 70 K heat-flow meter.

As also shown in Figs. 5 and 7, the experimental results of hot-end temperature for the 70 K and 4 K heat-flow meters were in very close agreement with those obtained by numerical analysis of the thermal conduction of the thermal-resistance parts of the heat-flow meters. In the numerical analysis, the thermal conductivity used for the SUS 304 was based on data published by Touloukian et al.[3] The results of the calibration tests clearly show that the heat flow through the heat-flow meter can be accurately derived from the temperature only at its hot end.

4. Thermal performance of MLI

In the present study, to measure the thermal performance of the MLI, 50- and 20-layer sample insulation films (Code No. KFP-9B08) were used on the 70 K and 4 K drums, respectively. Each sample was fabricated by cutting the film into rectangular pieces, overlaying 50 or 20 of the cut pieces, and then wrapping them around on the drum. During the wrapping process, the overlapping ends of the MLI were interlaid layer by layer to form an overlap seam. The width of the overlap was approximately 20 mm. To prevent separation of the MLI sample while winding it

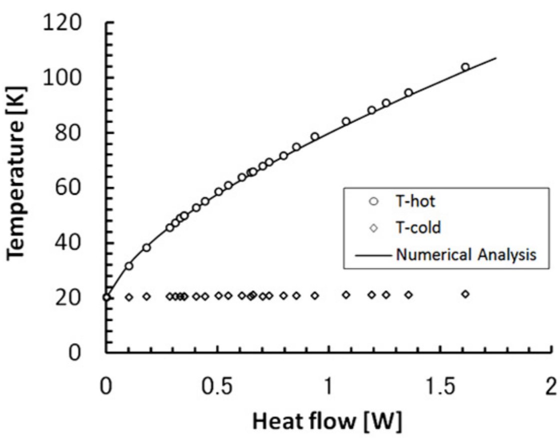


Fig. 5. Calibration results for the 70 K heat flow meter.

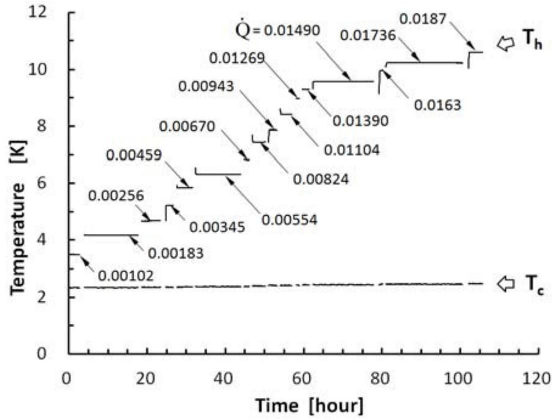


Fig. 6. Temperature dependence of 4 K heat-flow meter with time and input power to the caliblation heater.

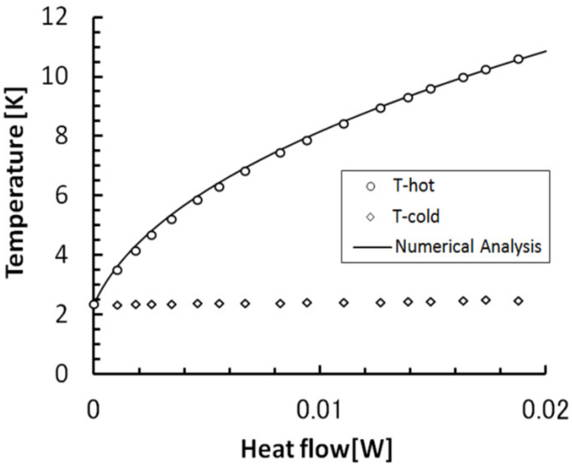


Fig. 7. Calibration results for the 4 K heat-flow meter.

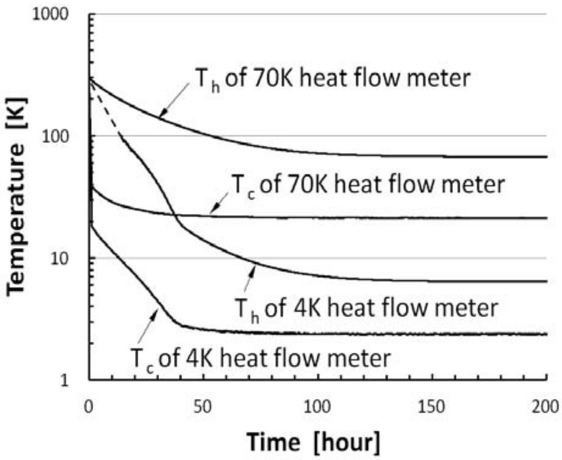


Fig. 8. Temperature variation of heat flow-meters with time during calorimeter cooling for the MLI thermal performance test.

around the 70 K drum, it was sewn with thread in two places 180° from the overlap seam. The MLI sample wound onto the 4 K drum was secured by sewing the side opposite the overlap seam in a single line parallel to the drum axis. The top and bottom bases of each drum were covered with a cup-shaped MLI blanket.

With the heat flow through the MLI on the 70 K drum denoted **as** $\dot{Q}_1$, and the heat flows measured by the 70 K and 4 K heat-flow meters denoted as $\dot{Q}_2$ and $\dot{Q}_3$, respectively, we then have

$$\dot{Q}_1 = \dot{Q}_2 + \dot{Q}_3 . \tag{1}$$

Thermal performance of MLI on the 70 K drum is defined using the surface area of the drum S_H (=0.425 m^2) as,

$$\dot{q}_H = \dot{Q}_1 / S_H . \tag{2}$$

Similarly, the thermal performance of the MLI on the 4 K drum with a surface area S_L (=0.170 m^2) is

$$\dot{q}_L = \dot{Q}_3 / S_L . \tag{3}$$

On this basis, the MLI thermal performance as measured by the calorimeter in this study is given in Table 1. Here, N/H is the layer density, i.e., the number of MLI layers N divided by the MLI thickness H (calculated from the circumference of the outermost MLI layer).

Table 1. Thermal performance of MLI sample KFP-9B08.

MLI sample	N [layers]	N/H [layers/mm]	T_h [K]	T_c [K]	$\dot{q}$ [W/m^2]
around the 70 K drum	50	15.2	298	64	1.5
		18.1	298	68	1.6
around the 4 K drum	20	11.5	64	5.5	0.025
		15.3	68	6.4	0.034

5. Summary

Measurements were carried out on the thermal performance of MLI using a prototype calorimeter, which was cooled by a two-stage GM cryocooler. The results show that the heat flow through the MLI can be determined from the hot-end temperature of the thermal resistance parts of the 70 K and 4 K heat-flow meters. Reference data was thereby obtained on the thermal performance of the lightweight MLI.

Acknowledgements

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