Test Apparatus utilizing Gifford–McMahon cryocooler to measure the thermal performance of multilayer insulation

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Background

The cryostats for Large-scale Cryogenic Gravity-wave Telescope (KAGRA) need multilayer insulation (MLI) whose outgas rate into vacuum space must be very low in order to avoid water condensation on the surface of laser mirrors. For a candidate MLI to KAGRA cryostats, Kaneka Corporation is developing new light weight MLI utilizing very thin non-woven polyester spacer laminated on one side of aluminized Mylar. As the MLI is fabricated on the low temperature thermal shield operated at around 10K, a new calorimeter is developed to evaluate the insulation performance of MLI utilizing Gifford-McMahon cryocooler.

Objectives

- Design and construct a prototype of calorimeter cooled by GM refrigerator to measure insulation performance of MLI
- Development of two heat-flow meters operated at around 4K and 77K and method of their calibration
- To measure the thermal performance of MLI (KFP-9B08) which is developed by KANEKA Corporation as a candidate MLI for KAGRA cryostats.

Conclusion

- A prototype calorimeter cooled by Gifford-McMahon refrigerator has been developed to measure the insulation performance of MLI.
- Two heat-flow meters have been developed to measure the heat-flow at around 4K and 70K.
- The heat-flow through the heat-flow meter can be obtained by the hot side temperature of the thermal resistance part of the meter.
- The thermal insulation performance of the light weight MLI developed by KANEKA was measured by the calorimeter at 6K and 65K.

Acknowledgement : Mr. Noboru Kudo of KEK succeeded in the assembly of cold drums and heat-flow meters of the calorimeter by gold brazing using the hydrogen furnace. The students of Teikyo University, Mr. Satoshi Takada, Mr. Akira Matsuyama, Mr. Kazuki Nojiri, and Mr. Ryo Hagiwara constructed the test apparatus and drew lots of illustrations of calorimeter by CAD. The authors would like to express our gratitude to them for their valuable contributions to this project.

Test Apparatus

Test Apparatus Cooled by GM-cryocooler

MLI sample is wound on the surface of OHFC drum which is vertically supported. The drum is connected to the hot end flange of heat-flow meter, and the cold end flange is connected to the cold head of refrigerator. There are two drums which are different in diameter and coaxial each other. The inner drum is cooled by the 2nd stage of the refrigerator at around 6.5K, and the outer drum is cooled by the 1st stage at around 65K.

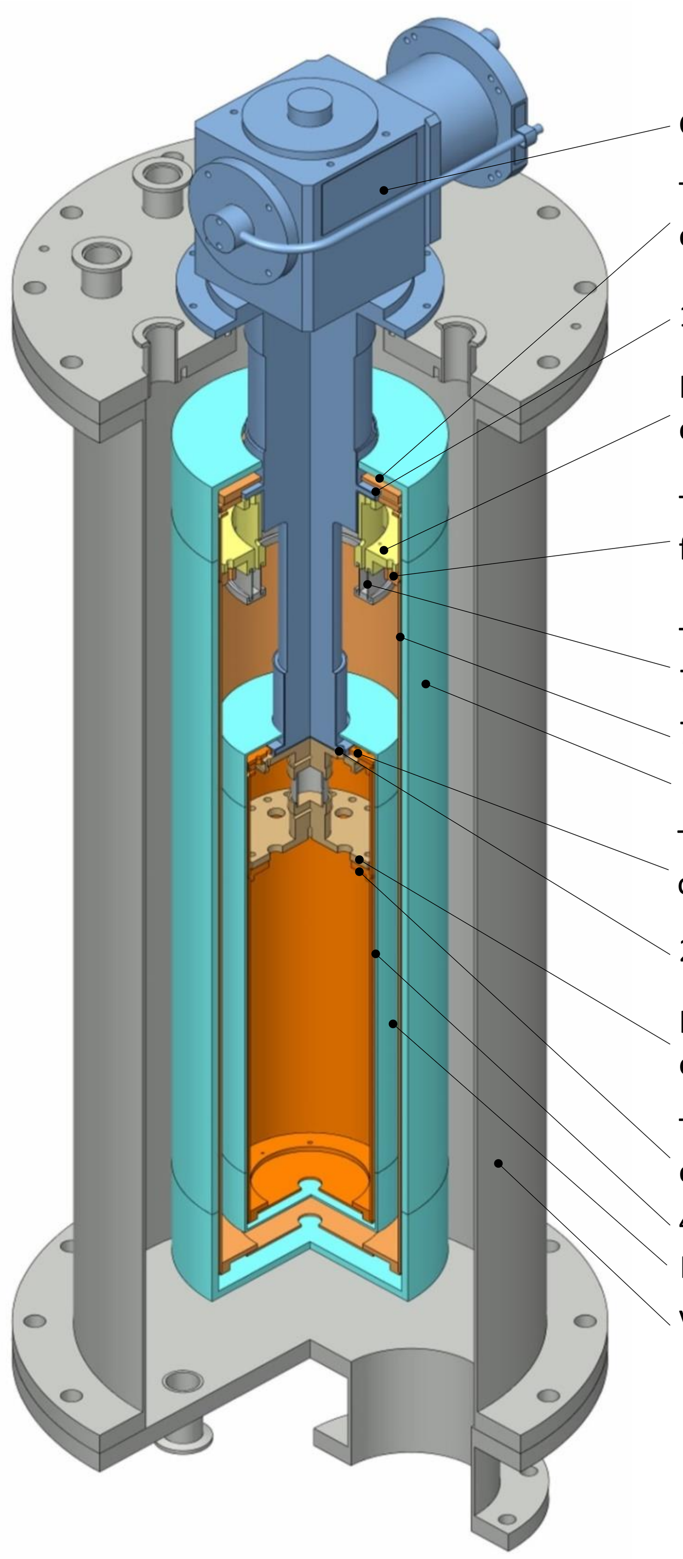

Figure 1. Test apparatus utilizing GM refrigerator for measuring thermal performance of MLI

Heat-Flow Meters

Heat-Flow Rate is measured by the temperature difference across the thermal resistance part which is made of very thin stainless steel (SUS304) pipe. The cold end and the hot end of the resistance are gold brazed to OFHC flanges. The temperatures of both sides of the thermal resistance are measured by Si-diode thermometers for 70K Heat-Flow Meter and by Germanium resistance thermometers.

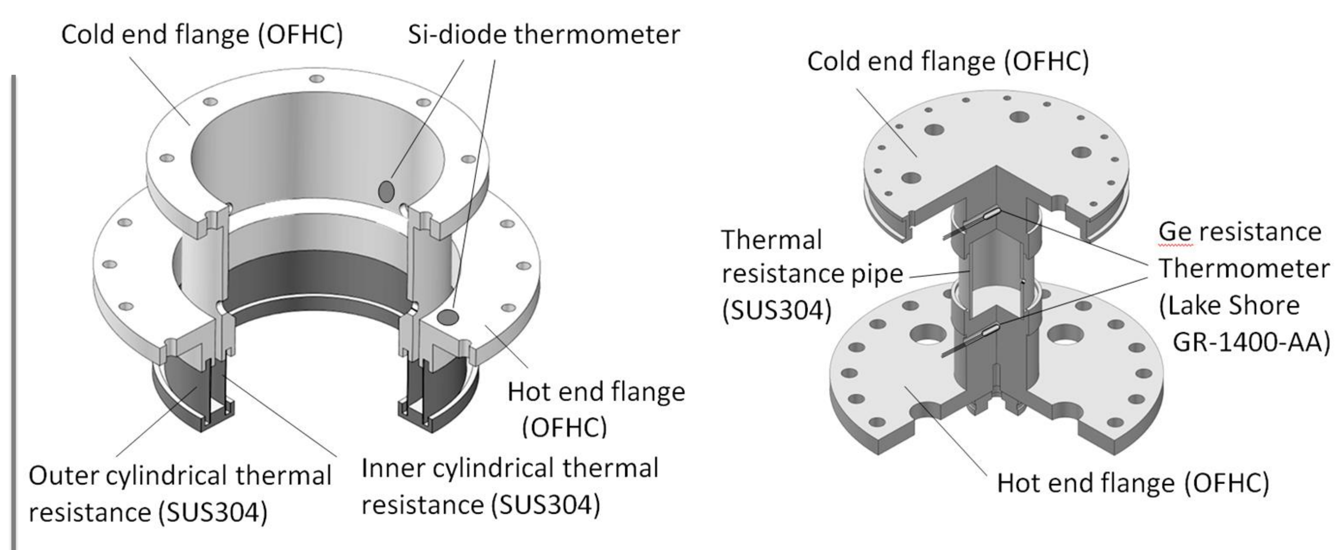

Figure 2. Schematic diagrams of heat-flow meter

Heat-Flow Meter and Cold Drum Assembly

The drums can move vertically about 5mm. When the heat-flow meter is calibrated, cold end flange of the heat-flow meter is disconnected from the thermal link flange of the drum, and the thermal link flange of the drum for calibration is connected to the cold head of refrigerator. Then the calibration heater is electrically heated, and the hotter side temperature of thermal resistance of the meter is raised up.

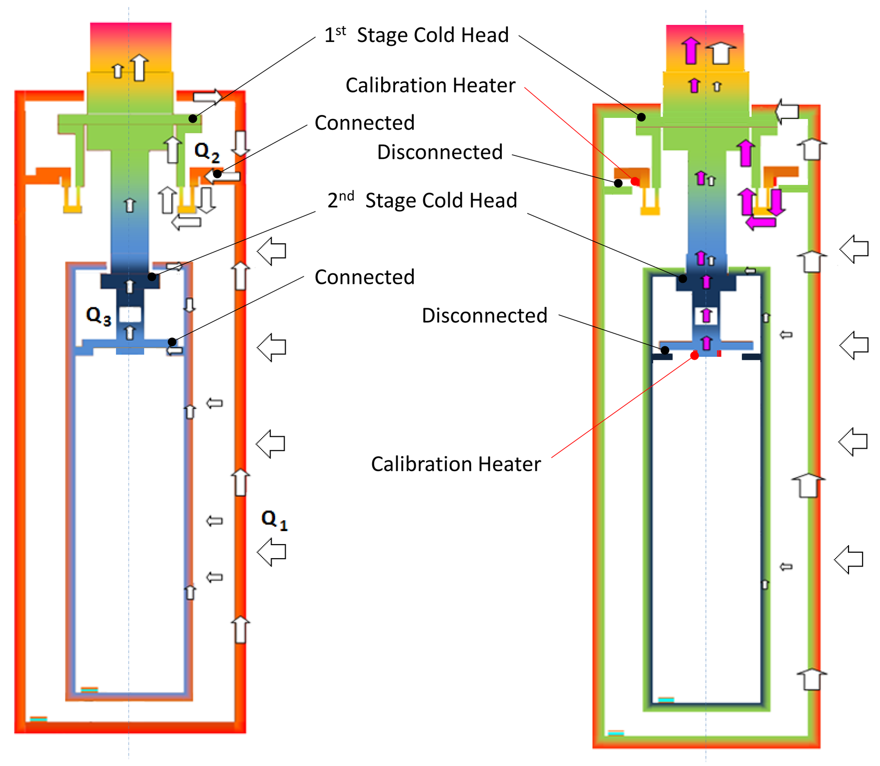

Figure 3. Assembly of calorimeter and heat-flow

70K and 4K heat-flow meters measure the heat-flow $\dot{Q}_2$ and $\dot{Q}_3$, respectively.

$$\dot{Q}_1 = \dot{Q}_2 + \dot{Q}_3 \qquad (1)$$

Heat flux through the MLI around 70K drum is given by,

$$\dot{q}_H = \frac{\dot{Q}_1}{S_H} \qquad (2)$$

where S_H is the surface area of 70K drum.

Heat flux through the MLI around 4K drum is given by,

$$\dot{q}_L = \frac{\dot{Q}_3}{S_L} \qquad (3)$$

where S_L is the surface area of 4K drum.

MLI Sample

The MLI sample shown in Figure 4 is measured its thermal insulation performance by the calorimeter developed in this study. This MLI is made from 9μm thick DAM which is aluminum coated polyester film on both side by vapor deposition process. And very light nonwoven polyester fabric is fused to one side of the DAM. The mass of a single film of the MLI is 19.6 g/m².

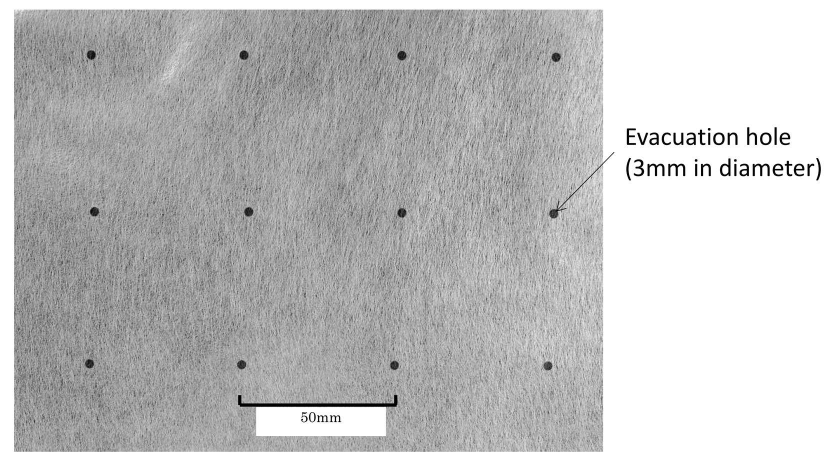

Figure 4. Light weight MLI (KFP-9B08) developed by Kaneka Corporation (This figure shows the nonwoven polyester fabric laminated side .)

Set-up of Calorimeter

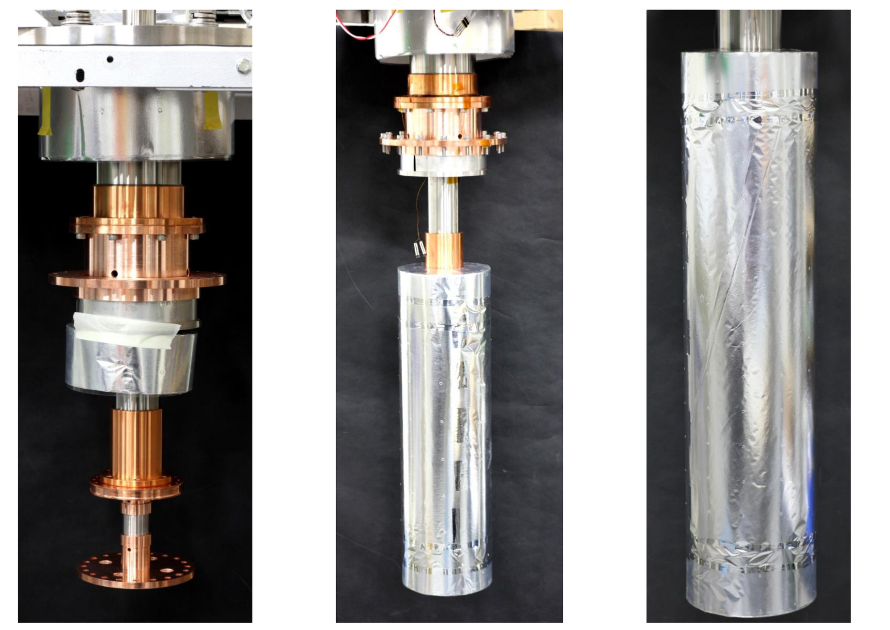

Figure 5. 70K & 4K Heat-Flow Meters are assembled to the 1st stage and 2nd stage of the refrigerator (Left), 4K drum with MLI (KFP-9B08 : 20 layers) is assembled (Middle), 70K drum with MLI (KFP-9B08 : 50 layers) is assembled (Right)

Cool-down of the Test Apparatus

After vacuum chamber was evacuated for 100 hours by turbo-molecular pump, the cool-down of calorimeter by G-M refrigerator started. As the cold drum is disconnected from the hot end flange of heat-flow meter, both sides of the meter were cooled to the same temperature. The bottom of the OFHC drum was almost at the same temperature as the hot end of the heat-flow meter.

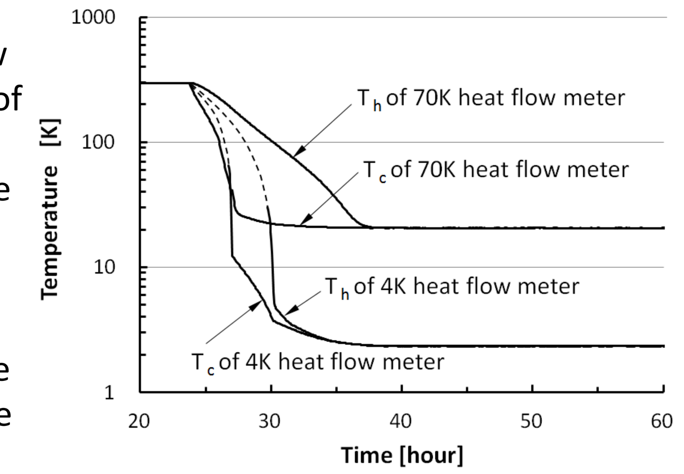

Figure 3. Temperature variation of heat-flow meters with time during calibration (Electric power to two calibration heaters is off.)

Results

Calibration of Heat-Flow Meter

Figure 4 shows the change over time of the hot-end temperature T_h and the cold-end temperature T_c of the thermal-resistance component in 70 K heat-flow meter while varying the electrical input to the calibration heater. It can be seen that T_c was almost constant at 20.4~21.5 K, because is far lower than the cooling capacity of the cryocooler. In contrast, T_h increased monotonically from 20.4 to 103.9 K. Figure 7 shows the variations in the hot- and cold-end temperatures of this heat-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. 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 components of the heat-flow meters.

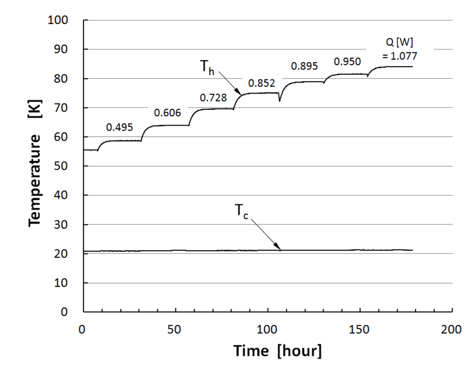

Figure 4. Dependence of temperature of 70K heat-flow meter on input power to calibration heater

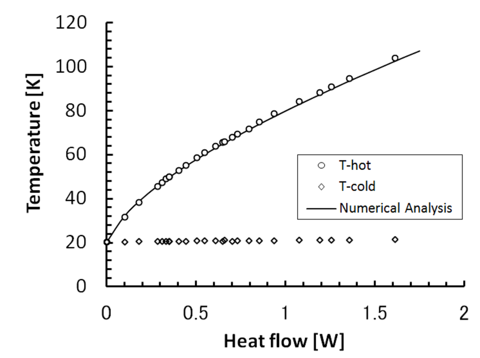

Figure 5. Calibration results for 70K heat-flow meter

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 components of the heat-flow meters. In the numerical analysis, the thermal conductivity used for the SUS 304 was based on data published by Touloukian Y.S. et al.

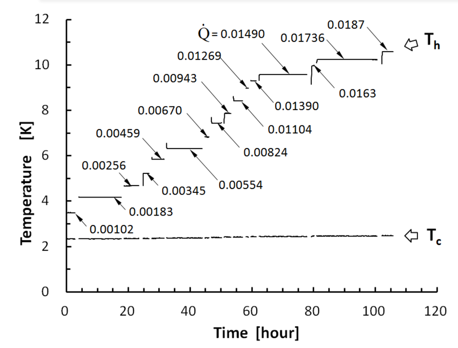

Figure 6. Dependence of temperature of 4K heat-flow meter on input power to calibration heater

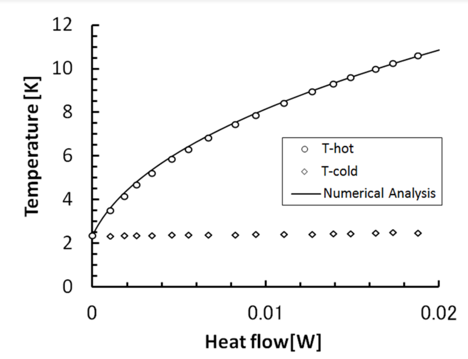

Figure 7. Calibration results for 4K heat-flow meter

Thermal Performance of MLI(KFP-9B08)

The calorimeter assembled for test mode was cooled down. The cold-end temperature of heat-flow meter came down to the same value as that obtained at calibration mode. But the temperature of hot-end showed higher value than that of cold-end temperature.

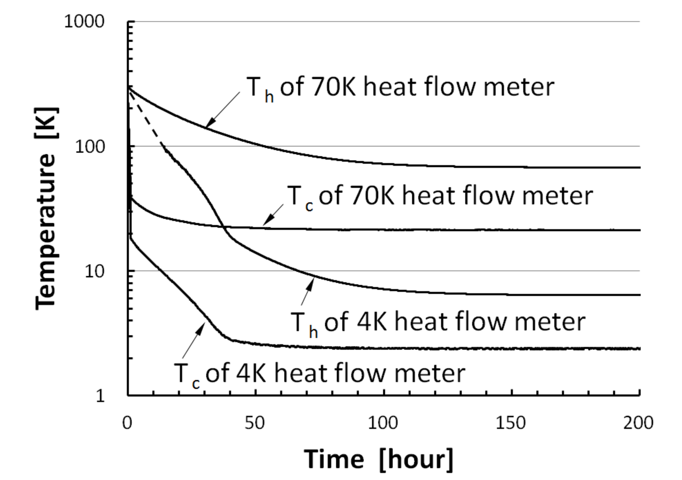

Figure 8. Temperature variation of heat-flow meters during calorimeter cooling for the MLI thermal performance test

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/m²]
around 70K drum	50	15.2	298	64	1.5
		18.1	298	68	1.6
around 4K drum	20	11.5	64	5.5	0.025
		15.3	68	6.4	0.034

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