**Investigation of thermal insulation for HTS cable systems**

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It is well known that the capability of HTS cable system in electric power transmission is increased as the temperature of the cable conductor is decreased. $LN_2$ is used to cool down the cable conductor. Vacuum and MLI(Multi-Layer Insulation) is employed to minimize heat leak and keep low temperature. In this study, heat leaks into $LN_2$ vessel are measured using boil-off calorimetry and performances of MLI related to the number of layers, patterns and layer density are studied.

## HEAT LOADS ON THE HTS CABLE SYSTEM

The HTS cable system is a highly feasible technology among the applications of high temperature superconductivity and a number of studies have been undergoing for a practical use. A HTS cable system is divided into two parts : conductor and refrigeration systems. Bi-2223 is widely used as a conductor and is refrigerated by sub-cooled $LN_2$. Subsequently the cable system is operated around 77K and the heat leak from the environment takes place. Multilayer insulation(MLI) is extensively used as insulation material at low temperature and it is well known that the performance of MLI is depend on the number of layers, material and layer density.[1] In this experiment, the heat leaks into the model cable cryostat are measured using boil-off calorimetry and compared to the result of calculation. Then the relations between heat leak and features of MLI which are the number of layers, patterns and layer density is investigated .

## EXPERIMENTAL SETUP

The model cable cryostat is shown in Figure 1. The upper and lower show plane and side view of the cryostat, respectively. The $LN_2$ and vacuum vessel are made of stainless steel. The length, outer diameter and thickness of $LN_2$ vessel are 1m, 63.5mm and 1.5mm respectively and are 1.3m, 127mm and 2mm for the vacuum vessel. The $LN_2$ vessel has a surface area of $0.2m^2$ and has a volume of 2.9 litres. $LN_2$ vessel is also provided with fill and vent lines which are open to atmosphere. MLI is wound over the surface of $LN_2$ vessel and the cross section is shown in Figure 2. It is shown from the figure that MLI is overlapped in circumferential direction and the length overlapped is 5cm. In order to fix MLI on $LN_2$ vessel it is tied at 4 points in longitudinal direction using cotton thread. Two piece of the supports made by Bakelite are employed to support the $LN_2$ vessel in the vacuum vessel. The pressure in the vacuum vessel is measured using a cold cathode vacuum gauge and maintained less than $8.0\times10^{-4}$ Pa while a measurement was going on. The flow rate of nitrogen gas evaporated in $LN_2$ vessel is measured using wet type flow meter.(WS-

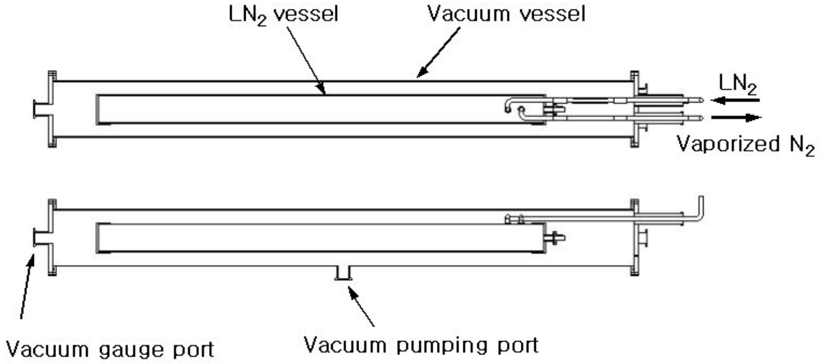


Figure 1 Physical configuration of the model cryostat

1A, Shinagawa) Because the level of liquid nitrogen is lowered as time goes on, 3 units of platinum temperature sensors(PT-111, Lakeshore) are used to examine the temperature of surface of $LN_2$ vessel. Figure 3 shows the locations where the sensors are set up. Data acquisition system using LabVIEW program is used to record all of the measured data into personal computer. Figure 4 shows schematic of the measuring system used in the experiment.

Figure 2 Cross section of MLI wound on $LN_2$ vessel

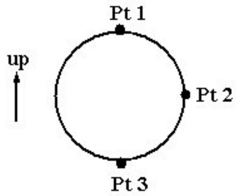


Figure 3 The locations of the temperature sensors

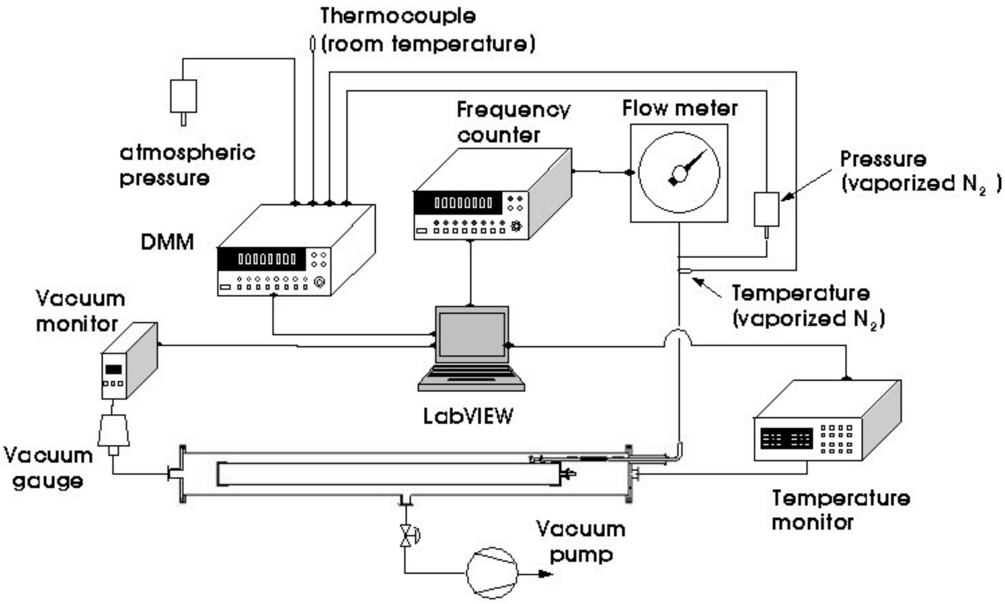


Figure 4 Schematic of the measuring system

Installation of MLI

In the experiment, two type of MLI are tested. The specification of the materials is shown in Table 1. MLI is installed as shown in Figure 2 and heat leaks on 1, 5, 10, 20 and 30 layers of NRC-2 are measured. To examine the effect of spacer to the performance of MLI, another measurements are carried out for 10 and 20 layers of IR-305.

Table 1 Specifications of the MLI

| Product name | Manufacturer | Specification |
|---|---|---|
| NRC-2 | MPI(USA) | Crinkled single side aluminized polyester film<br>Thickness 6µm(thickness of aluminum coating : 250Å) |
| Insulray IR-305 | Jehier(France) | Double aluminized polyester film with polyester tulle<br>Thickness 6µm(thickness of aluminum coating : 400Å) |

## CALCULATION OF RADIATION THROUGH MLI

If MLI is ideally established without contact between adjacent layers and emissivities of all layers are equal and constant, the radiation heat transfer through MLI of the heat transfer is expressed as follows[2] :

$$\dot{Q} = \frac{\sigma\left(T_H^4 - T_L^4\right)}{\frac{1-\varepsilon_H}{\varepsilon_H A_H} + \frac{1}{A}\left(\frac{1}{\varepsilon_L} + \frac{2N}{\varepsilon_s} - N\right)} \tag{1}$$

where, σ : Stefan-Boltzman constant, N : the number of layers, A : area, $\varepsilon_H$ , $\varepsilon_L$ , $\varepsilon_s$ : emissivity of surfaces of room temperature(300K), low temperature(77K) and layer of MLI, respectively. Since equation (1) is derived from the ideal condition, the results calculated from the equation are able to use as a reference to estimate the heat leaks measured from the experiment.

## RESULTS AND DISCUSSION

In all the experiment, surfaces of $LN_2$ and vacuum vessel are the cold and warm boundary, respectively. In the case without MLI, it takes about 7 hours until $LN_2$ vessel becomes empty. The evaporating times for the cases with MLI are twice or more than without MLI. The flow rates are stabilized after 1~5 hours after filling $LN_2$ vessel. In the case without MLI, difference in temperatures between Pt1 and Pt3(see Figure 3) exists. It is about 6K and hold on during the experiment. In the cases with MLI, the difference does not exist so that the temperature of surface is considered to be uniform and to have no concern with the level of $LN_2$. The difference of pressure between the inside of $LN_2$ vessel and atmosphere is less than 200Pa which is averaged for experiment.

### Determination of conduction heat through support

Radiation and conduction due to the supports made of Bakelite are constitute the total heat leak. Because the temperatures of $LN_2$ and vacuum vessel do not changed during the experiment, the heat leak by means of conduction is equal in all the experiments and measured to classify the radiation heat leak. The heat leak through supports is 1.1W.

### Heat leak for the number of MLI(NRC-2)

Figure 5 shows heat flux with respect to the number of layers. It is known from the figure that heat flux is exponentially decreased as the number of layers is increased. Especially, although 1 layer is applied, the heat leak is sharply decreased. It is less than 50% of the results without MLI. On the other hand, difference between the calculation and the measurement is observed and the difference converged as the number of layers is increased. In the experiment, there is a contact between layers so that this causes an additional heat leak through MLI.[3] Therefore the difference between the results of NRC-2 and the calculation exists.

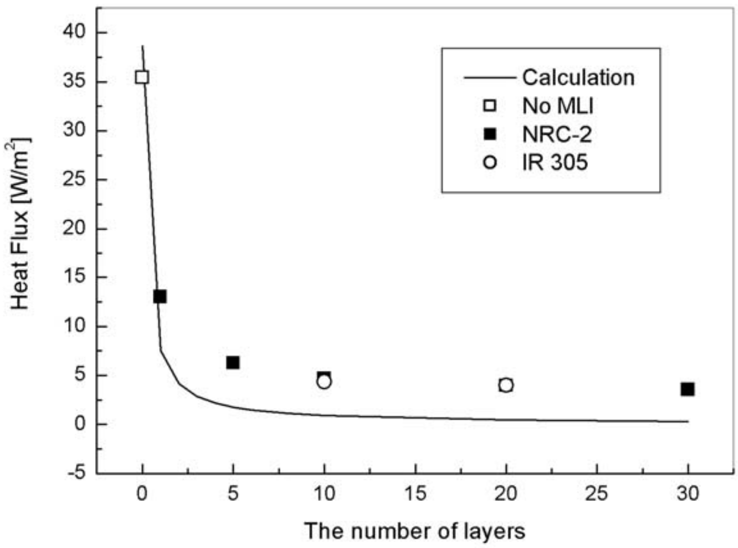


Figure 5 Heat flux with respect to the number of layers

Heat leaks for different patterns of MLI

As noted in Table 1, IR-305 has a polyester tulle(net) as a spacer. In order to examine the effect of spacer, the experiments are performed for 10 and 20 layers of IR-305 and compared to the result of NRC-2. From Figure 5, it is shown that there is no difference between the two for each layers. This result is expected due to the crinkled surface of NRC-2 which reduces contact heat transfer between layers. Consequently, it is considered that the crinkle surface plays the role of spacer.

Influence of layer density on heat leak

Heat leak for 10 layers of NRC-2 is measured at two different layer density. The heat leaks for 33 and 67 layers/cm are 4.7 and 9.8 W/ $m^2$, respectively. Heat leak is proportional to layer density. Because increased layer density results in increasing a contact area between layers, conduction heat transfer in MLI is increased. It is deduced from the experiment that layer density is more important factor in thermal insulation of $LN_2$ vessel than patterns of MLI.

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