Heat leak of cryogenic pipe for superconducting dc power transmission line (SCDC)

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Abstract. Main loss of the superconducting DC power transmission line (SCDC) comes from the heat leak of the cryogenic pipe because of no internal heat generation in the dc cable. It should be minimized to realize the high performance of SCDC. The heat leak of the cryogenic pipe depends on the ambient temperature, and when it is high, the heat leak is also high. Therefore, we estimated the sensitivity of the heat leak for the ambient temperature at first, and estimated the effect of this for the distance between the cryogenic stations. The major process of the heat leak is the heat transfer through the multi-layer insulation (MLI) and the second process is the thermal conduction of the support leg of the inner pipe in our design. The MLI is made from the multi-layers of the aluminium-coated thin film (ACTF) with the spacer, and the support leg is made of the glass fiber reinforced plastic (GFRP). The aluminium layer reflects the infrared light highly to reduce the heat transfer by radiation, and the spacer can prevent the direct contact with the ACTF. Therefore, the weight of the MLI should be light to minimize the thermal transfer of the spacer. We tested various types of MLI to find the optimum MLI structure experimentally. Usually, the measurement of the heat leak is not easy in an actual cryogenic pipe and we need the long experiment time and a relatively large instrument to evaluate the heat leak. However, since we need to evaluate many MLIs, we developed the different way to estimate the heat leak through the MLI by a small experimental device. To find the optimum MLI, we started to test three samples of the MLI supplied from Kaneka Corp., and measured the temperature of the MLI. Since the heat capacity of MLI is low, we used the 50-micron meters thermocouple (TC) and attached it to measure the temperature of the MLI carefully. The result of the experiment shows that we found that the net type of the spacer is better than the spacer used in Ishikari project, and the heat leak would be half of the Ishikari project. We also measured the thermal conductivity of two test samples of GFRP to reduce the heat conduction of the support leg. The thermal conduction of these two GFRPs are almost 1/2 to 1/4 of the recommended values of the NIST. Because of these efforts to reduce the heat leak of the cryogenic pipe, we can expect the target values of the heat leak is a half of the Ishikari project in the next project, and if we can reach this value, we can extend the distance of the cryogenic stations to ~100km actually on the earth. The values of this distance is important to transfer the electricity for all over the world like the gas and oil pipeline in the present time.

1. Introduction
Superconducting dc power transmission line (SCDC) will be one of the most important energy transmission line in this century because the renewable energy (RE) will be a major energy source in this century and RE can produce only electricity and not oil and natural gas. Moreover, the share of the electricity for energy is increasing continuously. Therefore, the major energy transport will be electric...
power transmission line from the gas and oil pipe lines as the major energy transmission line. The loss of the SCDC comes from the heat leak of the cryogenic pipe mainly, and the reduction of the heat leak of the cryogenic pipe is one of the major subjects to develop the SCDC. Ishikari project was started in 2013, and the 500-meter and 1000-meter SCDC were designed and constructed [1], the heat leak of the cable pipe is very low [2] because of the radiation shield structure. The low heat leak can extend the length of the transmission line to 10 km to 20 km by the same design of the Ishikari system, but its length is limited by the heat leak of the return pipe, and the design study for 100 km transmission line was performed [3] because the pump station of the gas and oil pump station is connected to the pipe line for each 100 km in the present world. In this meaning, if we can construct the 100 km SCDC, the technology of SCDC will be completed as the first phase. However, an ambient temperature dependence of the heat leak should be considered, and when the ambient temperature is high, the heat leak is high [4]. Therefore, we analyze the experimental data of Ishikari project to find the relation of the heat leaks and the temperature of the outer pipe and performed the thermo-hydrodynamic analysis for the 100 km transmission line in the section 2. In order to reduce the heat leak of the cryogenic pipe, we study the heat leak processes of the multi-layer insulation (MLI) and the support leg as the basic researches in the small test benches, and these are discussed in section 3.

2. Ambient temperature dependence of heat leak of cryogenic pipe

The heat leak of the cryogenic pipe is affected by the ambient temperature, and since the cryogenic pipe is set on the ground in Line 2, Ishikari project [2]. Actually, the heat leaks of the cryogenic pipe were reported for two different temperatures [4]. Fortunately, we measured the inlet and outlet temperatures of the cryogenic system and also measured the temperatures of the outer pipe for a long time. In spite of the change of the operation conditions of the cryogenic system, such as flow rate, the liquid nitrogen temperature from the refrigerator and the pressure, but the temperature and the flow rate were almost constant for long time as the standard operation. Therefore, we try to estimate the temperature dependence of the heat leak of the cryogenic pipe.

2.1. Experimental data from Ishikari project

In order to measure the outer pipe temperatures, we set four thermocouples (TCs) on the outer surface of the outer pipe of the cryogenic pipe at each one minutes, shown in figure 1.

![Diagram of TC settings on the outer pipe](image)

**Figure 1.** Setting of four TCs on the outer pipe, and the time history of their temperatures.
The measurement had been done from September 16\textsuperscript{th} to November 16\textsuperscript{th}, 2016. The peak temperature appeared around noon, and the lowest temperature appeared in early morning usually, but the temperatures decreased gradually from September to November by the change of the seasons. Four linear fitting lines are also plotted in the same graph.

The heat leak of the cryogenic system could be estimated by the temperature difference of the inlet and outlet temperature of the liquid nitrogen for individual cryogenic components, and the linear functions are fitted to the temperature differences of return and the cable pipes. Therefore, if two linear fitting functions of the temperatures and the heat leaks are coupled, we can get the sensitivity of the heat leak for the ambient temperature, and it is given by

\[
\text{Heat leak/temperature} = 1.31 \times 10^{-2} \sim 1.46 \times 10^{-2} [W/m/K] \tag{1}
\]

This result is consisted with the ref. [4] including the error estimation, and therefore we can estimate the heat leak at any ambient temperatures.

2.2. \textit{Thermo-hydrodynamic analysis for long transmission line}

Since the main aim of the SCDC is to realize a low loss and low voltage system, the longer transmission line is better for practical use, and the 100km SCDC was designed as the feasibility study not only for the technologies but also the economy of the system [3, 5]. Gas and oil pipe lines are the major energy transport system to connect the countries in the present time, and its length is sometimes longer than 3000 km. These system needs to use the pump station for each \~100km because of the viscosity of the oil and gas. In this meaning, if the distance of the cryogenic stations that includes the refrigerator, the pump, the measurement and control system, should be same as \~100km, we can build the intercontinental SCDC like the present gas and oil pipe line. Therefore, we recalculate the distance between two cryogenic stations to use the heat leak estimated from equation (1) at higher temperature, and the thermo-hydrodynamic estimation is shown in figure 2.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Thermo-hydrodynamic analysis for long SCDC, depending on the Ishikari’s data [2, 4].}
\end{figure}

When the heat leak is 0.85 [W/m] of the return pipe at -2.0 degree Celsius, the distance between two cryogenic station is 100 km, but when the outer pipe temperature is high as 28.0 degree Celsius, the heat leak is also high as 1.25 [W/m] for the return pipe, the distance between two cryogenic stations is short as 68 km from 100 km.
The average underground temperature is $\sim 17.0 \pm 5.0$ degree Celsius at $\sim 2.0$ meter below from the surface in Nagoya area of Japan, and we can expect the distance of $\sim 83$ km. Therefore, in order to establish the 100 km system, we should reduce the heat leak much more from the Ishikari data, and our target value is lower than the half of the present heat leak.

3. **Heat leak through multi-layer insulation**

The multi-layer insulation (MLI) is the key components to reduce the heat leak by the radiation to the cryogenic pipe. It is composed of the aluminum coated thin film (ACTF) and the spacer, and the role of the spacer is to avoid the direct touch of the ACTF because the thermal conductivity of the aluminum is high. The lamination structure is adopted, and the materials of the thin film and the spacer are polyester (PET) usually.

3.1. **Analytical model for MLI and its calculation results**

The physical process of the MLI is to reflect the infrared light many times at aluminum surfaces between two different temperature ACTFs, therefore the reflection ratio should be high, and usually we discuss the concept of emissivity instead of reflection ratio. The heat flux $Q_{F12}$ between two flat surfaces and the heat flux $Q_{C12}$ between the co-axial two pipes are given by [6]

\[
Q_{F12} = \frac{A\sigma(T_1^4 - T_2^4)}{\left(\frac{1}{e_1} + \frac{1}{e_2} - 1\right)}
\]

\[
Q_{C12} = \frac{\sigma(T_1^4 - T_2^4)}{\left(\frac{A}{A_1e_1} + \frac{A}{A_2e_2} - 1\right)}
\]

where $\sigma$ is Stefan-Boltzmann constant, $A$ is the area of flat plane, $A_1$ and $A_2$ are the area of two pipe surfaces of co-axial structure, $T_1$ and $T_2$ are the temperatures of two surfaces and $e_1$ and $e_2$ are emissivity of two surfaces.

![Figure 3](image.png)

**Figure 3.** The heat leaks and the temperatures of the ACTF’s layers from one layer to ten layers.

Equation (2) is applied the structure of outer and inner pipes and its MLIs for the configuration of the cryogenic pipe in Ishikari project [1], and we can calculate the temperatures of each ACTF of the MLI and the heat leak for one layer to 10 layers, and they are shown in figure 3. The calculation results
are obtained to solve the biquadratic equations for each layer temperature as unknown parameter, and we do not consider the effect of the spacer. This means that the heat flux can be transferred only by the radiation. Here, the temperature of the outer pipe is assumed to 300 K, and the inner pipe temperature is 77 K, the emissivity of the outer and inner pipes is 0.06 and 0.03, respectively. These emissivity of the ACTF is 0.015. These values are measured by the optical ways individually.

The calculated heat leak is only 0.1 [W/m] for 10 layers of MLI in the configuration of the Ishikari Line2 part 1, however the experimental heat leak is 0.83 [W/m] at 270.8 K ~ 1.20 [W/m] at 290.6 K for the return pipe in spite of 21 layers experimentally. Therefore, the experimental heat leak is almost 40 times higher than the calculated heat leak. Therefore, we may think that we have a potential to reduce the heat leak experimentally by the improvement of the device.

3.2. Temperature measurement of MLI

At first, we consider the reason of the discrepancy of the experiment and the calculation, and the cause might be the presence of the spacer, and we should include the effect of the spacer of the MLI. However, an analysis of the spacer of the MLI is difficult, and we started to find the optimum spacer experimentally. In order to find the optimum spacer, many experiments are needed and the previous way of the experiment to estimate the heat leak is not effective because the experimental device is large relatively, and we spent four weeks to get one data of the heat leak at least. Therefore, instead of the direct measurement of the heat leak in previous work [7], we measured the temperature of the ACTF of the MLI by the 50 µm thermocouples (TC) in the desktop device. It is effective to shorten the experimental time and to save the experimental cost, and we can get one experimental data by one day [8]. The schematic structure of the desktop device is shown in figure 4.

Figure 4. The desktop device to measure the temperature of ACTF with the spacer, and they are set on the cryo-head of the refrigerator.

The small GM cryo-cooler system is used, and the temperature of the cryo-head is controlled at 77.0±0.1 K. The vacuum chamber is made from the stainless steel. The stainless-steel and aluminum plates are used to change the weight of the ACTF and its spacer, and these surfaces including the cryo-head is covered by the ACTF to control their emissivity. Three different types of the spacers are prepared, and set into the device and the temperature of the ACTF was measured by the TCs. The master equation of the experiment is given by

$$q_1 = q_2 + q_3$$  \hspace{1cm} (4)

where $q_1$ is the heat flux from the stainless-steel vacuum pipe to the plate by radiation, and it is given by equation (2), and $q_2$ is also the radiation heat flux from the plates of the stainless-steel or the
aluminum to the cryo-head given by equation (2), and equation (3) is the conduction heat flux from the stainless-steel or the aluminum plate to the cryo-head through the spacer. We can calculate the values of $q_1$ and $q_2$ because we measured the temperature of the plate, therefore we can estimate the thermal conductivity of the spacer from equation (4). Many experiments for three types of the spacers have been done in various conditions, and the heat flux of the thermal conduction is minimized for the Net of the spacer finally. In addition, when the weight of the plate is heavy, the heat leak is enhanced even in light weight for unit area (~ 50 [g/m] gram per square meter). Therefore, if we put the stainless-steel pipe and/or the superconducting cable on the MLI, the heat leak should be quite high.

We also performed the different type of the experiment to use the same small device. MLI is five layers, but the spacer is different from each other. We measured the temperatures of each ACTF and the stainless-steel vacuum vessel, and the experimental data of the temperatures are shown in figure 5.

![Figure 5. Temperature measurements for three different types of the spacer of MLI in the small device.](image)

Here, 9B05, 9B12, Net are the names of the spacer, and the temperature of the outermost ACTF is highest for the Net, and the temperature difference between the outermost ACTF and the innermost ACTF is largest for the Net. Therefore, we concluded that the net type spacer is the best spacer for the MLI. Unfortunately, the spacer of the 9B12 was used in Ishikari project, and we expect that we could reduce the heat leak through the MLI in the next project.

4. Heat leak through support leg

The support leg is made from the glass-fiber reinforced plastics (GFRP), and it is composed of glass fiber and the resin. The thermal conductivity of GFRP depends on the direction of the fiber, and we made two test samples carefully to reduce the thermal conductivity. They are shown in figure 6.

![Figure 6. Fiber structures inside GFRP of two test samples.](image)

Thermal conductivities of two samples were measured along z-direction by stationary method from 40 K to 250 K. The experimental data are plotted and the analytical functions are fitted in figure 7 [8]. Since the integration value of thermal conductivity by temperature is proportional to the heat flux between two different temperature surfaces of the rectangle-shaped cubic, the integrated values are proportional the heat leak of the GFRP, and shown in Table 1. The integration had been done from 77...
K to 300 K for two samples, and two recommended values for GFRP from NIST [9] are also listed in the table. The integration values from the NIST is larger than those of the test samples.

The shape of the GFRP in the table is similar to the bottom GFRP leg to support the all inner structures with the radiation shield in Ishikari project. Its length is 30 mm to insulate the temperature difference between ~77 K to the ambient temperature, the width is 5 mm and the depth is 18 mm. These parameters are fixed by the tensile stress of the GFRP mainly in design, and the support leg is thought to be one of the major heat leaks of the cryogenic pipe.

Figure 7. Measured thermal conductivities of two test samples.

The integration values in the Table 1 is almost the same as the results of FEM calculation [10]. Since the heat leak from the support leg will be reduced ~1/4 to ~1/2 if we use the sample A from the recommended values of NIST. Unfortunately, we do not have data of GFRP used in Ishikari project, and also do not know the fiber direction in detail but we suspect that the recommended values of the NIST is one of good estimations for the Ishikari project [1].

Table 1. Temperature integration values of thermal conductivities from 77K to 300K for the support leg of the Ishikari project.

|                  | sample A | sample B | NIST Warp | NIST Normal |
|------------------|----------|----------|-----------|-------------|
| Integration value [W] | 0.11     | 0.23     | 0.43      | 0.29        |

5. Summary and present conclusion
The heat leak of the cryogenic pipe is the major cause of the loss of the SCDC, and in order to establish the ultra-long transmission line to connect the continents in the world, one of the target values of the heat leak is almost half of the Ishikari experimental data, such as ~ 0.5 [W/m] at 25.0 degree Celsius because the distance between the cryogenic stations is longer than 100 km. This temperature was measured at the 2.0 meter below the surface of the ground in Saida, Algeria [11], it is located in Sahara Desert, and it was the maximum temperature for whole year.

Major heat leak of the cryogenic pipe depends on the heat flux through the MLI and the GFRP support, and therefore it is reasonable that they would be able to be reduced to half in both processes as mentioned in the previous sections. We will use a new GFRP for the support, and also use a better spacer for the MLI. We did not mention the covering method of the MLI, but it is also important, too. Since the values of the heat leak is quite low, it is not easy to confirm the heat leaks in the short cryogenic pipe. Therefore, we will test various ideas during the construction of the cryogenic pipe in the next stage, and we believe that the next project will be 10 km to 20 km transmission line.
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