Heat leak measurement of the cryogenic pipe for the superconducting power transmission at different surface temperatures

Hirofumi Watanabe, Toru Takeuchi, Katsuya Miyake and Satarou Yamaguchi
Chubu University, Kasugai, Aichi 487-8501, Japan

h_watanabe@isc.chubu.ac.jp

Abstract. The heat leak of the cryogenic pipe constituting a transmission line of the superconducting power transmission depends on the surface temperature of the cryogenic pipe, because the heat leak is mainly caused by the radiative and conductive heat transfers. The heat leak of the cryogenic pipe for the superconducting power transmission has been measured with respect to its surface temperature ranging from -3 to 53 °C to investigate the effect of the surface temperature variation and to obtain data for the installation of cables in different places with different environmental conditions. The cryogenic pipe used for the measurements has two inner pipes, called cable pipe and return pipe, in a single outer pipe. For the cable pipe the heat leak of 0.82 W/m at -3 °C increases to 1.27 W/m at 51°C, while for the return pipe the heat leak of 0.46 W/m at -3 °C increases to 0.94 W/m at 51°C. The heat leak increases smoothly with the surface temperature, which can be well reproduced by a formula based on the temperature dependences of the radiative and conductive heat transfers. The heat leak by the conductive heat transfer is discussed based on the experiments and the calculations.

1. Introduction
Heat leak characteristics of a cryogenic pipe constituting a transmission line of the superconducting power transmission are important, because they affect the efficiency of the transmission line. Since the heat leak is mainly caused by the radiative and conductive heat transfers, it depends on the temperatures of low and high temperature sides of the cryogenic pipe. The temperature of the low temperature side is practically constant at the liquid nitrogen temperature, which rises slightly along the flow channel due to the heat leak. On the other hand, the temperature of the high temperature side depends on the surface temperature of the cryogenic pipe, which can vary largely with the change of the atmospheric temperature, the weather, and the direct sunlight hours, where the transmission line is installed. Thus, the heat leak can depend on the environmental conditions, where the transmission line is installed.

We have tested the cryogenic pipes developed for the 500 m and 1000 m superconducting DC power transmission lines constructed in Ishikari, Japan [1, 2, 3] and measured the heat leak of the cryogenic pipe with these actual lines and 12 m test pipes, which have been reported previously in the surface temperature range from -3 to 17.4 °C [4, 5, 6, 7]. In addition to these, the heat leaks were measured up to 53 °C in this study with the use of one of the 12 m test pipes. This study is to investigate the effect of the surface temperature variation and to obtain data to install the cables in different places with different environmental conditions. Once the heat leak with respect to the surface...
temperature has been obtained, annual heat load variation to the cryogenic system can be estimated with the information of the atmospheric temperature variation where the transmission line will be installed. The information of the actual heat load variation makes the determination of the specification of the cooling system, such as the cooling power of the cryocoolers and the capacity of the circulation pumps possible.

2. Experiment

The schematic drawing of the cryogenic pipe used for the measurements is shown in figure 1. This pipe was developed for the Ishikari project and details of this pipe can be seen in the previous papers [4, 5, 6]. This pipe has two inner pipes in a single outer pipe. The space between the inner and outer pipes is evacuated for the vacuum insulation. One of the inner pipes is to install the superconducting power cable, the other is to return the liquid nitrogen for circulation. We call the former ‘cable pipe’ and latter ‘return pipe’. The corrugated pipes have been commonly used for the cryogenic pipe for the superconducting power transmission. However, the cryogenic pipe used in this study uses smooth pipes for both the inner and outer pipes. One layer of the blanket composed of 21 sheets of the multilayer insulation (MLI), denoted by 21×1, in this paper, is wrapped around each of the inner pipe. The cryogenic pipes with MLI of 7×3 and 3×3 have been tested previously and the results are also presented in this paper. The inner pipes are fixed against the outer pipe at the room temperature by the supports made of the fiber reinforced plastic (FRP) whose thermal conductivity is small and strength is high. The unit length of this cryogenic pipe is 12 m. The 12 m cryogenic pipes are connected at the place where the transmission line will be installed to make a longer cryogenic pipe.

![Figure 1. The schematic cross section of the cryogenic pipe used in the experiments [4, 5, 6].](image)

The experimental method was the same as that used in the previous study [4]. In this study, the 12 m test pipe was used. The liquid nitrogen was filled in the inner pipes. After then, the rate of the evaporated nitrogen gas, which was proportional to the heat leak, was measured with flowmeters connected to the cable and return pipes. The flow rate was converted to the heat leak by multiplying a conversion factor obtained with the latent heat per a unit weight of the liquid nitrogen and the density of the nitrogen gas at 20 °C at which the flowmeters were calibrated. The conversion factor was 3.857 W/(L/min). The heat leak measurements were performed with respect to the surface temperature of the cryogenic pipe. In the measurements below 30 °C, the surface temperature was not controlled, which was the room temperature at the time the measurements were performed. Since the variation of the room temperature was very slow during the acquisition time of the data used for analysis, the uncertainty introduced into the results was considered to be small. The uncertainty caused by this temperature variation was considered in the uncertainty of the heat leak. On the other hand, the surface temperature over 30 °C was set by the heaters which were controlled by the temperature controllers based on the surface temperatures measured by the thermocouples. Therefore, the temperature variation was very small during the measurements and the uncertainty of the small temperature variation was also included in the uncertainty of the heat leak. The uncertainties which came from the
flowmeters and the data logger were also considered together with those coming from the dispersion of the data acquired. These procedures were verified by the heater experiments, in which the heat was applied to the inner pipes by heaters attached to the inner pipes and the flow rates of the resultant nitrogen gas were measured. The difference of the applied and measured values was at most 7% below 30 °C, which mainly originated from the surface temperature variation during the heater experiments, and this was considered in the uncertainty of the heat leak.

3. The results and discussions
The results are shown in figure 2. The abscissa is the surface temperature of the cryogenic pipe and the ordinate is the heat leak per 1 m of the cryogenic pipe. The solid symbols are the data of the cable pipe and the open ones are those of the return pipe. The circles and the diamonds are the present and previous measurements [4] with the 12 m test pipe, respectively, while the squares and triangles are the data measured at the 500 m and 1000 m lines in Ishikari [5, 6, 7]. Except for the triangles, the wrapping of MLI is 21×1. For the triangles, they are either 3×3 or 7×3 as indicated on the figure. The uncertainties discussed in the previous section are shown in the figure. The estimated uncertainties are not too large in comparison with the measured values. The uncertainties below 30 °C are larger than those over 30 °C. This mainly originates from the heater experiments.

![Figure 2. The heat leak per 1 m of the cryogenic pipe with respect to the surface temperature. The ● □ ■ ▲ ◆ and ○ △ □ ◇ are for the cable pipe and for the return pipe, respectively. The ● ○ are present result and ◆ ◇ are previous results with the 12 m test pipe [4]. ■ □ and ▲ △ are measured at the 500 m and 1000 m lines in Ishikari [5, 6, 7]. 21×1, 3×3 and 7×3 indicate numbers and layers of MLI.](image)

For the cable pipe, the heat leak of 0.82 W/m at -3 °C became 1.27 W/m at 51°C. The heat leak rose 0.45 W/m by the surface temperature rise of 54 °C. On the other hand, for the return pipe, the heat leak at -3 °C was 0.46 W/m, which became 0.94 W/m at 51°C. The heat leak rose 0.48 W/m by the surface temperature rise of 54 °C. The heat leak of the cable pipe was about 1.5 times larger than that of the return pipe, though the rises of the heat leak were almost the same. It is considered that this was due to the difference of the support structures for the inner pipes.

The heat leak of 7×3, 0.28±0.12 W/m, was much smaller than that of 21×1 for the return pipe. In these cases, the numbers of the MLI layers were the same, that is, 21 layers. Therefore, the heat leak through the MLI should be the same for both the cases. However, in the case of 7×3, there were three seams and the inner seams were hidden by the outer blankets of MLI. This reduced the heat leak through the seams significantly in the case of 7×3. On the other hand, the heat leak of 3×3,
1.108±0.088 W/m, was much larger than that of 21×1 for the cable pipe. In these cases, this difference may originate from the numbers of the MLI layers.

The experimental method with the 500 m and 1000 m lines was different from that of the experiments with the 12 m test pipes. In the case of the experiments with the 500 m and 1000 m lines, the temperature rises of the liquid nitrogen circulating in the inner pipes due to the heat leak were measured, which were converted to the heat leak with the specific heat capacity and the flow rate of the liquid nitrogen. All of the data, including the data obtained with the 12 m test pipes and with the 500 m and 1000 m lines, sit on the same smooth curves. The data taken with the different experimental methods were consistent with each other and the values obtained in these experiments were verified. From these experiments the heat leak of actual transmission systems can be safely estimated from that obtained with short test pipes.

The curves on figure 1 are

\[
y = m1 \times (T + 273.15)^4 - 77.3^4 + m2 \times (T + 273.15) - 77.3
\]  

(1)

where \(m1\) and \(m2\) are the fitting parameters in the units of W/(m K^4) and W/(m K), respectively, \(T\) is the surface temperature in units of °C. The first term of equation (1) represents the temperature dependence of the radiative heat transfer and the second term that of the conductive heat transfer. As shown in figure 1, this function is well fitted to the experimental data. The results of the fitting parameters are shown in table 1. Though these fitting parameters reveal the contributions of the radiative and conductive heat transfers to the heat leak, their interpretation may be difficult. Therefore, the contributions of the radiative heat transfer \(m1 \times \{300^4 - 77.3^4\}\) and the conductive heat transfer \(m2 \times \{300 - 77.3\}\) at 300 K were calculated and shown in table 2. As seen in the table, the radiative contributions were almost the same for both the inner pipes, though the difference of the conductive contributions was large. This means that the difference of the heat leak observed in the experimental results mainly originated from the conductive heat transfer. It is recognized that the conductive contributions were not small unexpectedly in comparison with the radiative contributions. The present procedure obtaining the surface temperature dependence of the heat leak and fitting equation (1) gives the way to extract the contributions of the radiative and conductive heat transfers from the total heat leak.

| Table 1. Fitting parameters. | \(m1 \times 10^{-11}\) W/(m K^4) | \(m2 \times 10^{-3}\) W/(m K) |
|-------------------------------|-------------------------------|-------------------------------|
| Cable pipe                    | 6.26±0.50                    | 2.33±0.21                    |
| Return pipe                   | 6.67±0.54                    | 0.67±0.22                    |

| Table 2. Calculated heat leak from the formula at 300 K. | Radiative (W/m) | Conductive (W/m) | Total (W/m) |
|---------------------------------------------------------|-----------------|------------------|-------------|
| Cable pipe                                              | 0.505±0.040     | 0.518±0.046      | 1.023±0.061 |
| Return pipe                                             | 0.538±0.043     | 0.149±0.048      | 0.687±0.065 |
| Total                                                   | 1.043±0.059     | 0.667±0.067      | 1.710±0.090 |

The finite element method calculations were performed to evaluate the heat leak by the conductive heat transfer through the supports. There are three types of supports, which are axial force supports, transverse force supports and vertical force supports. These supports are made of FRP and fixed to the parts made of the stainless steel at the low and high temperature sides. The thermal conductivities recommended by NIST [8] were used. The thermal contact resistance between the parts was not considered and the boundary conditions were fixed at 77 K and 300 K for the low and high temperature sides, respectively. The calculated results are shown in figure 3 and table 3. The results in table 3 were converted to the values per 1 m of the cryogenic pipe. The calculated heat leak to the
cable pipe was 0.315 W/m and that to the return pipe was 0.074 W/m. These values were a bit smaller than those obtained from the experiments shown in table 2. This might be due to the conductive heat leak through MLI not considered in the calculations. The calculated heat leak to the cable pipe was larger than that to the return pipe. This tendency agreed with the results shown in table 2. The heat leak through the vertical force supports, which were pressed down to the outer pipe by the weight of the inner pipes, had a large impact on the overall heat leak. The reduction of the conductive heat transfer by the optimization of the support structures could further reduce the heat leak of the present cryogenic pipe.

![Figure 3](image.png)

Figure 3. The results of (a) the axial force support (2 supports/12 m), (b) the transverse force support (8 supports/12 m), and (c) the vertical force support (7 supports/12 m).

### Table 3. The heat leak through the supports per 1 m of the cryogenic pipe.

| Support   | Cable pipe (W/m) | Return pipe (W/m) | Total (W/m) |
|-----------|------------------|-------------------|-------------|
| Axial     | 0.035            | 0.014             | 0.049       |
| Transverse| 0.040            | 0.060             | 0.100       |
| Vertical  | 0.240            | -                 | 0.240       |
| Total     | 0.315            | 0.074             | 0.389       |

### 4. Summary

The heat leak of the cryogenic pipe for the superconducting power transmission has been investigated with respect to its surface temperature ranging from -3 to 53 °C. The cryogenic pipe used in this study was developed and used in Ishikari project, which had two inner pipes in a single outer pipe.

For the cable pipe, the heat leak was 0.82 W/m at -3 °C and 1.27 W/m at 51°C. The heat leak rose 0.45 W/m smoothly by the surface temperature rise of 54 °C. For the return pipe, the heat leak was 0.46 W/m at -3 °C and 0.94 W/m at 51°C. The heat leak rose 0.48 W/m smoothly by the surface temperature rise of 54 °C.

The heat leak variations were well reproduced by the formula based on the temperature dependences of the radiative and conductive heat transfers. Based on the formula, the contributions of the radiative and conductive heat transfers were extracted from the experimental data. Together with the calculations of the conductive heat transfer through the supports for the inner pipes, it turned out that the heat leak by the conductive heat transfer was rather large. The optimization of the supports may further reduce the heat leak of the cryogenic pipe.

From the consistency between the data obtained with the 12 m test pipe and the 500 m and 1000 m lines, the heat leak of actual transmission systems can be safely estimated from that obtained with short test pipes.

### Acknowledgement

This work was supported by Chubu University Grant (A).

### References

[1] Yamaguchi S, Koshizuka H, Hayashi K and Sawamura T 2015 *IEEE Trans. Appl. Supercond.*
[2] Yamaguchi S, Ivanov Y, Watanabe H, Chikumoto N, Koshiduka H, Hayashi K and Sawamura T 2016 *Physics Procedia* **81** 182-6

[3] Chikumoto N, Watanabe H, Ivanov V Y, Takano H, Yamaguchi S, Koshizuka H, Hayashi K and Sawamura T 2016 *IEEE Trans. Appl. Supercond.* **26** 5402204

[4] Watanabe H, Ivanov V Y, Hamabe M, Chikumoto N, Takano H and Yamaguchi S 2015 *Physics Procedia* **67** 239-44

[5] Watanabe H *et al.* 2017 *IOP Conf. Series: Materials Science and Engineering* **171** 012116

[6] Watanabe H *et al.* 2017 *IEEE Trans. Appl. Supercond.* **27** 5400205

[7] Watanabe H, Ivanov V Y, Chikumoto N, Yamaguchi S, Ishiyama K, Oishi Z, Watanabe M and Masuda T 2018 *J. Phys. Conf. Ser.* **1054** 012076

[8] https://trc.nist.gov/cryogenics/materials/materialproperties.htm