Heat leak and pressure drop measurements of the 1000 m class superconducting DC power transmission system in Ishikari

**Hirofumi Watanabe**, Yury V Ivanov, Noriko Chikumoto, Satarou Yamaguchi, Kotaro Ishiyama, Zenji Oishi, Michihiko Watanabe and Takato Masuda

1Chubu University, Kasugai, Aichi 487-8501, Japan
2Chiyoda Corporation, Yokohama, Kanagawa, 220-8765, Japan
3Sumitomo Electric Industries, Ltd., Osaka, Osaka, 554-0024, Japan

E-mail: h_watanabe@isc.chubu.ac.jp

**Abstract.** The second cooling test of the 1000 m class superconducting DC power transmission system constructed in Ishikari, Japan, was performed in 2016. In this cooling test, the heat leaks to the low temperature parts and the pressure drops of the liquid nitrogen circulation were measured for each section of the 1000 m system. The heat leaks were measured at different outer pipe temperatures of the cryogenic pipe constituting the transmission line. The total heat leaks of the cable system, composed by the cryogenic pipe and the terminals, were 1.746 and 2.091 kW at the outer pipe temperatures of -2.4 and 17.4 °C, respectively, which were consistent with those measured in the first cooling test. The heat leak of the cryogenic pipe increased by 30-40 % by the increase of the outer pipe temperature from -2.4 and 17.4 °C. The pressure drop of the cable system was 42.80 kPa and that of all the system, including the cooling system, was 98.4 kPa at the flow rate of 36.03 L/min. The degradation of the heat leak and pressure drop characteristics were not observed between the first and second cooling tests. Based on the present results, the heat leak, the temperature rise and the pressure drop of 10 km systems were estimated. From this estimation it can be said that the cooling and the circulation of 10 km systems are possible by the present level of technology.

1. Introduction
500 m class and 1000 m class superconducting DC power transmission systems were constructed in Ishikari, Japan [1, 2, 3]. This project, we call, Ishikari project. The 500 m system connects a photovoltaic power plant to an internet data center and the transmission of electricity was successfully performed in 2015. The 1000 m system was constructed to obtain data for future longer transmission systems. In the winter of 2015, the first cooling test was performed and the tests about the cooling and the circulation, such as a heat leak measurement and a pressure drop measurement, were mainly performed. The results of these measurements were reported in the previous paper [4]. The second cooling test was performed from July to December in 2016. In this test, the heat leak and the pressure drop were measured again to test changes in these properties between these periods.

The heat leak of the cryogenic pipe constituting a transmission line affects the heat load to the cooling system, in particular, in long distance transmission lines. The heat leak data at the different
outer pipe temperatures, that is, the different environmental conditions, are required to design superconducting transmission systems. In the first cooling test, the heat leak in each section of the 1000 m system was measured at the outer pipe temperature of -3.0 °C [4]. In the second cooling test the heat leak was measured at -2.4 °C together with at 17.4 °C to see the difference of the heat leak at different outer pipe temperatures.

For a section of the transmission line of the 1000 m system in Ishikari project, the cryogenic pipe with a radiation shield was adopted [5]. The heat leak to the inner pipe which surrounded by the radiation shield was measured to be 0.034±0.033 W/m in the first cooling test [4]. This was quite small, though the relative uncertainty of the measurement was nearly 100 % and the accuracy is not enough to design longer transmission lines over several tens of km. This result was estimated from the temperature rise of the circulating liquid nitrogen and the accuracy of the measurement was almost limited by the uncertainties of the temperature sensors due to the small temperature rise of the liquid nitrogen. To obtain higher accuracy, a low flow rate experiment was performed to increase the temperature rise along the flow channel.

The estimation of the pressure drop property of the liquid nitrogen circulation is quite important to design cooling and circulation systems in superconducting power transmission systems, because higher discharge pressure of the pump will be required as the increase of the pressure drop, which makes the capacity of the pump lager. In addition to this, because the output power of the pump can be a heat load to the cryocooler through the friction loss of the liquid nitrogen, that is, the pressure drop and the loss of the pump itself, it can be larger than the heat leak of the cryogenic pipe in the case of long transmission lines. Therefore, data about the pressure drop are required for the design of future longer transmission systems. From this point of view, the pressure drop of each section of the 1000 m system was measured again in the second cooling test.

2. 1000 m system in Ishikari project

The details of the 1000 m system in Ishikari project have already been explained elsewhere [3, 4]. Only the details connecting to the present paper will be explained. The cryogenic pipe constituting a transmission line is extended into outdoors in a U-shaped configuration from the buildings where terminals and a cooling system are installed. The length of the transmission line is approximately 1000 m. The cable has two joins, at which the cryogenic pipe is sectioned. The section 1 is a straight part with a length of 475 m, the section 2 has a curved part whose radius is 7 m with a length of 137 m and the section 3 is a straight part with a length of 379 m. Different types of cryogenic pipes are used for each section. In the section 1, a cryogenic pipe with a radiation shield is used, while in the section 2 and 3 a cryogenic pipe without a radiation shield is used. In both the designs, two inner pipes are installed in a single outer pipe for the circulation. Smooth pipes are used for the inner pipes to reduce a pressure drop. The inner pipe in which the cable core is installed is called a “cable pipe” and the other pipe to return back the liquid nitrogen for circulation is called a “return pipe”. Therefore, the distance of the circulation is approximately 2000 m, though the length of the transmission line is approximately 1000 m. In the cryogenic pipe with a radiation shield, the cable pipe is surrounded by a radiation shield to shield the heat from the outer pipe at the room temperature. The radiation shield is thermally attached to the return pipe. Therefore, almost all the incident heat on the radiation shield will be removed by the liquid nitrogen flowed in the return pipe. It is expected that the heat leak to the cable pipe and the temperature rise along it will be significantly reduced, provided the cryogenic pipe with a radiation shield is used.

Figure 1 shows a piping and instrumentation diagram of the 1000 m system. In this figure the ranges of the cooling system and the cable system termed in this paper are shown. The 1000 m system equips two Turbo-Brayton cryocoolers (TB1 and TB2) with a nominal cooling power over 2 kW at 66 K and two Stirling cryocoolers (ST1 and ST2) with a nominal cooling power over 1 kW at 77 K. Centrifugal pumps (CP1 and CP3) and a positive displacement pump (CP2) are installed. CP1 and CP2 are in the cooling system and situated at the terminal A side and CP3 is situated at the terminal B side, which is 1000 m away from the terminal A. To measure the flow rate of liquid nitrogen, two
Coriolis type flowmeters are equipped. The reservoir has a volume of 2 m$^3$, which has a function to regulate the base pressure of the system. Temperature sensors (labelled with T) and pressure gauges (labelled with P) are equipped to monitor and to estimate the conditions of the 1000 m system. The flow channel of the liquid nitrogen can be switched by valve settings. In the second cooling test, ST1 and ST2 were not used and only one or two Turbo-Brayton cryocoolers were used depending on the types of experiments. During the heat leak and pressure drop experiments only CP1 was used, while CP2 and CP3 were cut off from the flow channel by the valve setting. On the other hand, during a low flow rate experiment, only CP2 was used.

3. Heat leak measurements

Figure 2 shows an example of the liquid nitrogen temperatures during the heat leak measurement together with the flow rate of the liquid nitrogen and the outer pipe temperatures of the cryogenic pipe. The legend in the top figure is explained in figure 1. Tu1-Tu4 in the bottom figure were the outer pipe temperatures measured in the outdoors at a few meters away from the building where Terminal A is installed. The temperature of the liquid nitrogen rises as it flows from Tc1 to Tr1 for the heat leak of each section. Tc1 is just downstream of the cryocoolers and nearly constant due to the controlled outlet temperature of the Turbo-Bryton cryocoolers. The others vary depending on the flow rate and the outer pipe temperatures.

The heat leak was calculated with the temperature rise, the flow rate and the specific heat capacity of the liquid nitrogen. The temperature rise was estimated from the temperature difference in each section measured with respect to the flow rate [6]. The time required for the travel of the liquid nitrogen in each section was considered. The temperature at the outlet of a section was compared with that at the inlet measured at the time before required for the travel. The data which stayed for an enough long period of time in the range of the outer pipe temperature of -2.4±2.7 °C were used for the estimation in the case of the example in figure 2. The regions used for the estimation are shown in figure 2 with the red circles. The results of the heat leaks of the cryogenic pipe in this study are summarized in table 1 for the outer pipe temperatures of -2.4±2.7 and 17.4±2.6 °C. The temperature ranges of liquid nitrogen were 76.4±2.1 and 71.7±2.5 K for the outer pipe temperatures of -2.4±2.7 and 17.4±2.6 °C, respectively. The vacuum degree between the inner and outer pipes during these measurements was less than 0.005 Pa. The results obtained in the first cooling test at the outer pipe
temperatures of -3.0±3.5 °C and at the liquid nitrogen temperature of 76.8±2.0 K [4] are summarized in table 2 for a reference. The results for the different sections of the 1000 m system are summarized in table 3. The numbers in the parentheses are the values of experimental uncertainties referred to the corresponding last digits of the results.

![Figure 2. Liquid nitrogen temperatures during the heat leak measurement together with the flow rate and the outer pipe temperatures.](image)

Table 1. Heat leaks per unit length of each section at different outer pipe temperatures. The numbers in the parentheses are the values of experimental uncertainties referred to the corresponding last digits of the results.

| Section | Cable (W/m) | Return (W/m) | Total (W/m) | Cable (W/m) | Return (W/m) | Total (W/m) |
|---------|-------------|--------------|-------------|-------------|--------------|-------------|
| 1       | 0.033(35)   | 0.832(36)    | 0.865(50)   | 0.024(34)   | 1.204(38)    | 1.228(51)   |
| 2       | 0.92(13)    | 0.51(14)     | 1.43(18)    | 1.34(13)    | 0.63(17)     | 1.96(21)    |
| 3       | 0.792(45)   | 0.431(46)    | 1.222(52)   | 1.021(45)   | 0.535(63)    | 1.556(77)   |

Table 2. Heat leaks per unit length measured in the first cooling test [4]. The numbers in the parentheses are the values of experimental uncertainties referred to the corresponding last digits of the results.

| Outer pipe -3.0±3.5 °C |
|-------------------------|
| Section | Cable (W/m) | Return (W/m) | Total (W/m) |
|---------|-------------|--------------|-------------|
| 1       | 0.034(33)   | 0.851(33)    | 0.886(47)   |
| 2       | 0.95(12)    | 0.52(13)     | 1.47(17)    |
| 3       | 0.818(42)   | 0.462(42)    | 1.280(59)   |
At the outer pipe temperature of -2.4 °C the heat leak is down to 0.865±0.050 W/m per two inner pipes in section 1. At this temperature the heat leak to the cable pipe was measured to be 0.033±0.035 W/m and quite small in comparison with the other sections. This is because almost all the heat leak to the cable pipe was received with the radiation shield and removed with the liquid nitrogen in the return pipe. Between the first and second cooling tests, the heat leaks were measured at the similar outer pipe temperature of -3.0 and -2.4 °C. The results of these measurements agree well with each other within the range of the uncertainties. In the second cooling test, heat leaks were measured at different outer pipe temperatures. As expected, the heat leak was increased in all the sections of the cryogenic pipe. The heat leak increases approximately 30-40 % by the increase of the outer pipe temperature of 20 °C.

The heat leaks of the terminals are approximately 230 W as shown in table 3. These values were obtained during no load condition, though they contain a portion of the conductive heat through current leads. Because the temperature in the buildings where the terminals were installed was air conditioned, the heat leaks of the terminals are almost independent on the outer pipe temperatures. The total heat leaks of the cable system not including the cooling system were from 1.690±0.023 to 2.091±0.022 kW depending on the range of the outer pipe temperatures. The results of the present study were consistent with those obtained in the first cooling test. The heat leak property was not changed between the two cooling tests.

| Outer pipe (°C) | Terminal A (kW) | Terminal B (kW) | Cable pipe (kW) | Return pipe (kW) | Total (kW) |
|----------------|----------------|----------------|----------------|-----------------|------------|
| -3.0           | 0.199(17)      | 0.233(16)      | 0.461(16)      | 0.676(16)       | 1.690(23)  |
| -2.4           | 0.225(18)      | 0.248(17)      | 0.459(17)      | 0.658(18)       | 1.746(20)  |
| 17.4           | 0.226(18)      | 0.249(17)      | 0.600(17)      | 0.901(20)       | 2.091(22)  |

4. Pressure drop measurements

Pressure drop was measured with pressure gauges and a differential pressure gauge installed along the flow channel shown in figure 1. The total pressure drop of the 1000 m system is the difference of the pressures as Pp12-Pp11. The pressure drop of the cable system was measured with a differential pressure gauge of Pr1. The pressure drops of the cable and the return pipes are Pc1-Pc4 and Pp32-(Pc1-Pr1), respectively. Since these gauges are installed at different heights, the obtained values were corrected by them.

![Figure 3. The pressure drop of the 1000 m system measured in the first [4] and second cooling test.](image)
Figure 3 shows the results of the pressure drop measurements in the second cooling test together with those measured in the first cooling test [4]. The measurements were performed during the temperature measurement shown in figure 2. The average temperature measured at Tc1 was 74.3 K, while those at Tr1 were ranged from 76.1 to 78.4 K depending on the flow rate. Since the average temperature measured at Tc1 in the first cooling test was 74.9 K, the experiments were performed in the similar temperature ranges between the first and second cooling tests. The pressure drop increases as the increase of the flow rate almost proportional to the second power of the flow rate. The pressure drops of the cable pipe and the return pipe were 13.3 and 23.4 kPa, respectively, at the flow rate of 36.03 L/min. The pressure drop of the cable system itself was 42.80 kPa at this flow rate, which contained the pressure drop in the adjunctive piping and the terminals. For the additional pressure drop of 55.6 kPa by the cooling system, the total pressure drop of the 1000 m system was 98.4 kPa at 36.03 L/min. These results agree well with those obtained in the first cooling test as shown in the figure. The degradation of the pressure drop characteristics was not observed between the first and second cooling tests.

5. Low flow rate experiment
A low flow rate experiment was performed at the flow rate around 4 L/min with the 1000 m system to simulate a temperature variation of the liquid nitrogen at 40 L/min in 10 km systems. The result is shown in figure 4. The positive displacement pump (CP2) was used to reduce the flow rate and the actual flow rate during the measurement was 3.9 L/min. The spikes before 16/11/21, in particular, in Tr7 originated from the thermal oscillations near CP3 for forgetting to close a valve near it. After the valve was closed, the spikes disappeared. Two days after the flow rate was reduced to 3.9 L/min, the temperature variation reached a steady state. At this state the temperature variation varied with the outer pipe temperature. Stable circulation was confirmed even in this low flow rate condition at 3.9 L/min.

The heat leaks of the cable pipe surrounded with a radiation shield were 0.034±0.033, 0.033±0.035 and 0.024±0.034 W/m for the outer pipe temperatures of -3.0, -2.4 and 17.4 °C, respectively, as shown in table 1 and table 2. These values are in the range of uncertainties and, thus, consistent with each other. The relative uncertainties are around 100 % and the accuracies of the results are not enough for further estimations to design longer transmission lines. As already mentioned in Section 1, this is mainly attributed to the uncertainties of the temperature sensors used in the measurements. To overcome this problem, the flow rate was reduced to expand the temperature rise along the cable pipe. The temperature differences were measured between Tc8 and Tc9 with the flow rates from 9.9 to 3.9 L/min in addition to the flow rates over 15 L/min. The temperature rise was estimated with the same method explained in Section 3 [6]. The vacuum degree between the inner and outer pipes was less than 0.01 Pa. The obtained heat leak was 0.0634±0.0059 W/m. The relative uncertainty is reduced to less
than 10%. This result is also consistent with the other results if the ranges of the uncertainties are considered.

6. Estimation for longer transmission lines
The heat leak, the temperature rise, and the pressure drop of 10 km transmission lines are calculated with the present results. The results are shown in table 4. The use of the cryogenic pipe with a radiation shield in Ishikari project and the flow rate of 20 L/min are supposed. In the calculation, the heat leak at the outer pipe temperature of 17.4°C shown in table 1, 1.204 W/m, is used for the return pipe and that obtained by the low flow rate experiment, 0.0634 W/m, is used for the cable pipe. The heat leak of the terminals is the sum of the heat leaks of the terminals at the outer pipe temperature of 17.4°C in the table 3. The specific volume and the specific heat capacity of the liquid nitrogen at 77 K are used for convenience. The pressure drop of the terminals is calculated by subtracting the pressure drops of the cable pipe and the return pipe from that of the cable system shown in figure 3.

The heat leak to the cable pipe is calculated to be 0.634 kW. Consequently, the temperature rise along the cable pipe, which affects the current characteristics of the cable core, is 1.14 K. This value is quite small, if the transmission distance is considered. The pressure drop of the cable pipe is calculated to be 40.5 kPa and that of the return pipe is 78.5 kPa. The total pressure drop of the cable system is 120.2 kPa. If the pumps with a similar capacity with those used in Ishikari project are installed at each side of the terminals, the circulation will be possible. Therefore, it can be said that the cooling and the circulation of 10 km systems are possible by the present level of technology.

Table 4. Extrapolated values for 10 km systems with the present results at the flow rate of 20 L/min.

|                      | Heat leak (kW) | Temperature rise (K) | Pressure drop (kPa) |
|----------------------|----------------|----------------------|---------------------|
| Cable pipe           | 0.634          | 1.14                 | 40.5                |
| Return pipe          | 12.04          | 21.61                | 78.5                |
| Terminals            | 0.475          | 0.852                | 1.2                 |
| Total                | 13.15          | 23.60                | 120.2               |

7. Conclusion
The second cooling test of the 1000 m system in Ishikari project was performed. The heat leaks were measured at the different outer pipe temperatures of the cryogenic pipe. The total heat leaks of the cable system were 1.746 and 2.091 kW at the outer pipe temperatures of -2.4 and 17.4°C, respectively. The heat leaks measured in this study were consistent with those measured in the first cooling test. The heat leak of the cryogenic pipe increased by 30-40% by the increase of the outer pipe temperature from -2.4 and 17.4°C. The pressure drop of the cable system was 42.80 kPa and that of all the system, including the cooling system, was 98.4 kPa at the flow rate of 36.03 L/min. The degradation of the heat leak and pressure drop characteristics were not observed between the first and second cooling tests. Based on the present measurements, the heat leak, the temperature rise and the pressure drop of 10 km systems were estimated. From the estimation it can be said that the cooling and the circulation of 10 km systems are possible by the present level of technology.

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