Cooling test of the 500 m class superconducting DC power transmission system

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Abstract. Recently, 500 m and 1000 m class superconducting DC power transmission systems were constructed in the Ishikari area in Japan and the cooling test of the 500 m system was performed. The heat leak of the cryogenic pipe and the total heat load of the system were estimated in the cooling test. The cryogenic pipe of the system has two inner pipes in one outer pipe for circulation. The heat leak was 0.98 W/m and 0.44 W/m for each inner pipe. The total heat load of the system was 1.37 kW except for the heat load by the current feeding and the circulation pumps, while the total cooling power of the system was approximately 3 kW. The pressure drop of the circulation was measured to be 19.5 kPa at the rated flow rate of 30 L/min for the 1000 m circulation both ways in the 500 m transmission line. By the cooling test, it was confirmed that the system can be operated stably.

1. Introduction
Superconducting direct current (DC) power transmission has been developed and connected to the actual power grids around the world [1, 2, 3, 4, 5, 6]. The superconducting DC power transmission, which uses characteristics of the superconductivity of zero electric resistance, is an efficient way to transmit electricity generated by renewable energies for long distances, because the loss caused by the electric resistance of the cable is not arisen. Moreover, since the output of renewable energies, such as the photovoltaic power generation and the wind power generation, are DC or once converted to DC before sent out to the grid, it is advantageous to send electricity by DC from the beginning in terms of the efficiency of conversions and transmission, though the electricity from renewable energies is generally converted to alternative current (AC) presently. If consumer sides also use the electricity by DC is Internet data centers (iDCs). They consume electricity a lot for servers which work by DC power.
Recently, 500 m and 1000 m class superconducting DC power transmission systems had been constructed in the Ishikari area in Japan and the construction of the 500 m system was completed in the spring of 2015 [7, 8]. We call the constructions and the operations of these systems “Ishikari project”. The 500 m class line connects a photovoltaic power plant of 204 kW and DC380 V to an iDC operated with DC power to demonstrate the efficient use of the superconducting DC power transmission systems for the transmission of the electricity generated by renewable energies to the consumers using DC power directly. The cooling test of the 500 m class superconducting DC power transmission system was performed in the summer of 2015 to estimate the performance of the system. We will report the results of the test related to the cooling and the circulation of the system, together with those for the cooling system including cryocoolers and circulation pumps.

2. 500 m class superconducting DC power transmission system

The details of the system was explained in the previous paper [9]. Here, the system related to the cooling and the circulation will be explained. Fig.1 shows a system diagram of the 500 m system. In the figure, the valves indicated by white are opened in a normal operation mode of the system and those indicated by black are closed. The cooling system consists of two circulation pumps of centrifugal types, two cryocoolers, two flowmeters of Coriolis types, a reservoir with a capacity of 1 m$^3$ and a heater. Two different types of cryocoolers are used; one is a Turbo-Brayton type, whose rated cooling power is over 2 kW at 66 K, and another is a Stirling type, whose rated cooling power is over 1 kW at 77 K. The measurement of actual cooling powers of the cryocoolers are one of the aims of the test. As seen in the figure, there are two flow lines in the cooling system. The flow from the reservoir to the Turbo-Brayton cryocooler goes to the cable system and returns to the reservoir. The flow cooled by the Stirling cryocooler returns directly to the reservoir and circulates independently from the Turbo-Brayton line. The circulation pump in the Stirling line can be used for the circulation of the Turbo-Brayton line by switching the valves, in the case that the circulation pump in the Turbo-Brayton line cannot be used. The cooling system has a heater, whose capacity is 4 kW. The heater is used to simulate the heat load of the cable system during the test of the cooling system.

The circulation line in the cable system consists of a cryogenic pipe of 500 m, in which the cable core is installed, and two terminals at both the ends of the cryogenic pipe. The cryogenic pipe was newly developed for the project, which has two inner pipes in one outer pipe for circulation. The schematic drawing of the cryogenic pipe is shown in Fig.2. Smooth pipes are used for the outer pipe and for the inner pipes. At the intervals of approximately 12 m along the inner pipes, there are bellows sections to compensate the thermal shrinkage of the pipes. The diameter of the outer pipe is 267.4 mm, that of the inner pipe in which the cable core is installed (cable pipe) is 76.3 mm and that of the inner pipe to return the liquid nitrogen (return pipe) is 60.5 mm. A bundle of multi-layer insulation are wrapped around each inner pipe. The cryogenic pipe is laid in the ground. Before construction of the system, the cryogenic pipe was tested with test pipes. The details of the cryogenic pipe used in the 500 m system and the test experiment were explained previously [9]. The cryogenic pipe has a joint section, in which cable cores with the lengths of approximately 300 m and 200 m are connected. The flow of liquid nitrogen from the Turbo-Brayton cryocooler firstly enters the terminal A, travels 500 m in the cable pipe, and reaches the terminal B. The flow reached the terminal B enters the return pipe and travels back 500 m to the reservoir. Therefore, the actual circulation distance is approximately 1000 m.

The system equips temperature sensors and pressure gauges to monitor the condition of the system. The labels starting with “T” in Fig.1 denote temperature sensors and those starting with “P” denote pressure gauges. Pr1 and Ph1 are differential pressure gauges, which measure the difference of pressures of two positions accurately, and the other gauges measure the pressures with respect to the atmospheric pressure. Because these pressure gauges are set at different
In the normal operation of the 500 m system, the temperature of liquid nitrogen was controlled to be 70 K at the outlet of the Turbo-Bryton cryocooler. The cooling power of the Turbo-Bryton cryocooler is controlled based on the outlet temperature, while the Stirling cryocooler is operated by the maximum cooling power. Therefore, the total cooling power of the cooling system is controlled by the Turbo-Bryton cryocooler. The flow rate of the Turbo-Brayton line is controlled to be 30 L/min and that of the Stirling line is to be 20 L/min, in the normal operation.
3. The test of the cooling system
In advance of the cooling test of the cable system, the cooling system was tested independently. The line connected to the cable system was switched to the heater by changing valve settings. The heat load by the heater was changed from 1.67 kW, an expected heat load of the cable system, to 2.70 kW. During this time the variations of temperatures of liquid nitrogen were measured. The temperatures of the inlet and the outlet of the Turbo-Brayton cryocooler are shown in Fig. 3. In this measurement, the cooling power of the Turbo-Bryton cryocooler was controlled so that the temperature of the liquid nitrogen at the outlet of the Turbo-Brayton cryocooler was 70 K. As seen in the figure the temperature of the outlet returns to 70 K soon after the change of the heater power, which means that the cooling power of the system follows the change of the heat load well. Therefore, it is expected that the cooling system can be operated stably after it is connected to the cable system, whose heat load will vary depending on the operation mode of the cable system and the environment.

4. Characteristics measurements of the cooling system
The cooling powers of the cryocoolers were measured from the temperature rises of the liquid nitrogen between the inlet and the outlet of the cryocoolers and the flow rates. The cooling power of the Turbo-Brayton cryocooler was estimated to be 2.2 kW at 71 K and that of the Stirling cryocooler was estimated to be 0.81 kW at 72 K. The power consumptions of the cryocoolers were measured at the same time. From these results the COPs were 0.042 and 0.062 for the Turbo-Brayton cryocooler and the Stirling cryocooler, respectively.

The circulation pumps were developed for this project. The Q-H curve, that is the relationship between volume flow rates and discharge pressures of the circulation pump, and the input power of the circulation pump were measured with respect to the rotational speed of the circulation pump. These results are shown in Fig. 4. Since both the circulation pumps used in the Turbo-Brayton and Stirling lines are the same design, the result for the circulation pump in the Turbo-Brayton line is shown. The head curve of the cooling system is also shown in the figure. The pressure difference between the Q-H curve and the head curve of the cooling system can be used for the circulation in the cable system.

The heater power which balanced with the total cooling power of both the cryocooler was
Figure 4. The Q-H curve and the input power of the circulation pump for the different rotational speeds of the circulation pump. The head curve of the cooling system is also shown.

Figure 5. The temperature variation of liquid nitrogen between the inlet and the outlet of the cable system during current feeding. The mode of the current feeding is shown in the figure.

measured. From this result and the input power of the circulation pump, the amount of heat leak in the cooling system was estimated, which was 0.13 kW. Therefore the cooling power of 2.88 kW is available, at the maximum, for the cable system.

5. Circulation test during current feeding
After connecting the cooling system to the cable system, the stability of circulation during current feeding was tested. 600 A was applied for 8 hours a day for 8 days from a power supply, which simulated the current feeding from the PV plant connected to the cable system. The
temperature of liquid nitrogen was controlled to be 70 K at the outlet of the Turbo-Brayton cryocooler and the flow rate was set at 30 L/min. The temperatures of the liquid nitrogen were measured at the inlet (Tc1) and the outlet (Tr1) of the cable system. The result is shown in Fig.5. The figure to show the mode of the current feeding is composed from the time record of the current feeding, for reference. As seen in the figure, the variation of the temperature correlating with the current feeding was not observed, which indicated that the system could be operated stably during current feeding.

6. The heat leak of the cable system
The result of the heat leak measurement of the cable system is summarized in Table 1. The values in the parentheses are uncertainties of the measurement. The heat leak of the cable system was estimated with the temperature rises of liquid nitrogen between the measurement points shown schematically in Fig.1, mass flow rates and specific heat capacity of liquid nitrogen. The flow rate dependences of the temperature rises were measured to check the measurement [10]. The temperature rises at the rated flow rate of 30 L/min are shown for reference, which were estimated from the flow rate dependences of the temperature rises. At the rated flow rate, the sum of the temperature rise in the terminals and the cable pipe, in which the cable core is installed, is 1.01 K. Therefore, the temperature rise along the cable core of 500 m is approximately 1 K at the flow rates of 30 L/min. Because the temperature of the inlet of the cable system is controlled to be 70 K, the cable core is kept approximately below 71 K. This is enough lower than the temperature required from the specification of the cable core.

| Component              | Terminal A | Cable pipe | Terminal B | Return pipe | System     |
|------------------------|------------|------------|------------|-------------|------------|
| Measurement points     | Tc4-Tc1    | Tc7-Tc4    | Tc10-Tc7   | Tr2-Tr5     | Tr1-Tc1    |
| dT (K) @ 30 L/min      | 0.23(3)    | 0.58(3)    | 0.20(3)    | 0.26(3)     | 1.46(3)    |
| Heat leak (kW)         | 0.20(2)    | 0.49(2)    | 0.17(2)    | 0.22(3)     | 1.24(2)    |
| Heat leak per meter (W/m) | 0.98(4)    | 0.44(5)    |            |             |            |

The heat leak of the cable system is estimated to be 1.24 kW as shown in Table 1. This value is larger than the sum of the heat leaks of the terminals and the cable and return pipes, which would be due to the heat leak of the additional pipings between these components. Since the heat leak of the cooling system was estimated to be 0.13 kW as already explained, the total heat load of the system was 1.37 kW except for the heat load by the current feeding and the circulation pumps. Since the total cooling power of the cryocoolers is approximately 3 kW, it is confirmed the cooling system has enough margin for operation. The results of the heat leak for the cable pipe and the return pipe were 0.98 W/m and 0.44 W/m, respectively. These values agree well with the results obtained with a test pipe reported previously [9].

7. The pressure drop measurement
The pressure drop is caused by the friction between the liquid nitrogen and the surface in the cryogenic pipe, which could limit the circulation distance. Therefore the estimation of the pressure drop is important for designs of long superconducting power transmission lines. The pressure drop measurement was performed with the pressure gauges of Pc1, Pc3, Pr3 and with the differential pressure gauge of Pr1 in Fig.1. The values of the pressure drop were the deferences of the pressures at the measurement points, Pc1-Pc3 for the cable pipe and Pr1-(Pc1-Pr3) for the return pipe and Pr1 for the cable system. The differences of the heights of the pressure gauges were considered in the estimation.
The pressure drops of the cable pipe and the return pipe, together with the head curves of the cooling and cable system sides, are shown. Total system head curve of the 500 m system and that of the 1000 m system which estimated from the 500 m result are shown with the Q-H curves of the circulation pump.

The result of the pressure drop for the cable system was 19.5(4) kPa for the 1000 m circulation both ways in the 500 m transmission line and those for the cable and return pipes were 9(2) kPa and 9(2) kPa, respectively, for the 500 m circulation at the rated flow rate of 30 L/min. The values in the parentheses are the uncertainties of the measurement. The uncertainty of the cable system is smaller than the others for the use of the differential pressure gauge with high accuracy. The result is summarized in Fig.6. In the figure, the pressure drops of the cable system, the cooling system, the cable pipe and the return pipe are plotted on the Q-H curve of the circulation pump. The total system head curve of the 500 m system is also shown in the figure. From this figure, the operation points of the circulation can be inferred.

The pressure drop is proportional to the circulation distance. The total system head curve for the 1000 m system in our project is calculated by doubling the pressure drop of the cable system in the 500 m system. The result is also shown in Fig.6. In the 1000 m system, it is planned that circulation pumps of the same design will be used, though the maximum rotational speed will be limited up to 6000 rpm. From this estimation, it is confirmed that the circulation at the flow rate of 30 L/min which is the rated flow rate of the 1000 m system will be possible. However, the circulation at the flow rate of 40 L/min, which has been sometimes performed in the 500 m system, would be difficult and would demand an additional circulation pump in series.

8. Conclusion
The cooling test of the 500 m class superconducting DC transmission system was performed and its stable operation was confirmed. The cryogenic pipe adopted in the project has two inner pipes in one outer pipe for circulation. The heat leak for each inner pipe of the cryogenic pipe was measured. The heat leak to the cable pipe was 0.98 W/m and that to the return pipe was 0.44 W/m. The total heat load of the system was 1.37 kW except for the heat load by the current feeding and the circulation pumps. This value is almost half of the total cooling power of the cryocoolers. The pressure drop of the circulation was measured. The pressure drop of the cable system was 19.5 kPa at the rated flow rate of 30 L/min for the 1000 m circulation both ways in the 500 m transmission line. These results can be used for the designs of future longer transmission lines.
Acknowledgments
This work was supported in part by the Japanese Ministry of Economy, Trade and Industry (METI).

References
[1] Stemmele M, Merschel F, Noe M and Hobl A 2013 Proc. IEEE Int. Conf. on ASEMD 323
[2] Tomita M, Muralidhar M, Fukumoto Y, Ishihara A, Suzuki K, Kobayashi Y and Akasaka T 2013 IEEE Trans. Appl. Supercond. 23 3601504
[3] Sytnikov V E et al. 2013 IEEE Trans. Appl. Supercond. 23 5401904
[4] Dai S et al. 2014 IEEE Trans. Appl. Supercond. 24 540014
[5] Lim J H, Yang H S, Sohn S H, Yim S W, Jung S Y, Han S C, Kim H W, Kim Y H and Hwang S D 2015 IEEE Trans. Appl. Supercond. 25 5402804
[6] Watanabe H, Ivanov Y V, Hamabe M, Chikumoto N, Kawahara T, Takano H and Yamaguchi S 2016 IEEE Trans. Appl. Supercond. 26 5400504
[7] Yamaguchi S, Koshizuka H, Hayashi K and Sawamura T 2015 IEEE Trans. Appl. Supercond. 25 5402504
[8] Chikumoto N, Watanabe H, Ivanov Y V, Takano H, Yamaguchi S, Koshizuka H, Hayashi K and Sawamura T IEEE Trans. Appl. Supercond. in press.
[9] Watanabe H, Ivanov Y V, Hamabe M, Chikumoto N, Takano H and Yamaguchi S 2015 Physics Procedia 67 239
[10] Watanabe H, Sugino M, Sun J, Ivanov Y, Hamabe M, Kawahara T and Yamaguchi S 2011 Physica C 471 1304