Heat load to the cryogenic system in the 1000 m class superconducting DC power transmission system

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Abstract. Long-term circulation and load cycle tests of the cooling of the 1000 m class superconducting DC power transmission system in Ishikari, Japan were performed to measure the heat load delivered to and the power consumption of the cryogenic system. The average heat load and power consumption during these tests was about 2.5 and 120 kW, respectively. To increase the efficiency of superconducting power transmission systems, the selection and composition of constituent devices of the cooling system should be optimized.

1. Introduction

Superconducting power transmission presents an efficient way to send electricity long distances due to the zero resistance losses superconductivity offers. Unlike conventional power transmission systems, very little Joule heat losses are generated; however, transmission losses do occur due to the energy required to remove heat from the cryogenic system. The heat leak characteristics of cryogenic pipes at specific outer pipe temperatures have been investigated [1,2]. However, as the outer pipe temperature varies with the change of the environmental conditions such as the atmospheric temperature, weather, and direct sunlight hours, the incurred heat leak also vary. Losses occurring during circulation can also change with the change of the operation conditions of the system, such as the transmitted current, the flow rate and temperature of liquid nitrogen. Therefore, the heat load to the cryogenic system, which reflects the heat leak and losses during circulation, changes constantly during the actual operation of the superconducting power transmission system. The heat load to the cryogenic system, the cooling power of the cryocoolers, and the consumption power of the cooling system were therefore investigated using the 1000 m class superconducting DC power transmissions system in Ishikari, Japan to demonstrate the energy balance of the superconducting power transmission system [3,4,5]. The measurements were performed during long-term circulation and load cycle tests in the second cooling test of the 1000 m system [2,6]. The long-term circulation test was performed to test the stable circulation of the liquid nitrogen for about one month. This was then followed by a load cycle test, in which a current of 1 kA was turned on for 8 hours and off for 16 hours per day to simulate normal system operation for 22 days. The resulting energy balance of the 1000 m system could help improve the efficiency of superconducting power transmission systems.

2. Heat load and power consumption measurements
A piping and instrumentation diagram, including the cooling and cable systems, of the 1000 m system used here is shown in figure 1. The cooling system was situated at terminal A and consisted of two pumps (CP1 and CP2), two Turbo-Brayton cryocoolers (TB1 and TB2), two Stirling cryocoolers (ST1 and ST2), and auxiliary equipment. Two chillers (CH1 and CH2) supplied the coolant for the cryocoolers. An additional pump at terminal B (CP3) compensated for the pressure drop. The cable system consisted of the cryogenic pipe constituting a transmission line and containing two inner pipes within an outer pipe, and terminals at either end [1,2]. Of the two inner pipes, the cable pipe was used to install the cable and the return pipe was used to return the liquid nitrogen for circulation. The white and black valves shown in figure 1 represent opened and closed valves, respectively. The temperature, pressure, and liquid nitrogen level were monitored with temperature sensors “T,” pressure sensors “P,” and a level sensor “Lt1,” respectively.

During the long-term circulation test and load cycle test, only TB1 and TB2 were used; ST1, ST2, and CP2 were cut off by the valve settings. Liquid nitrogen, which was pressurized by CP1 and cooled by TB1 and TB2, passed from the reservoir to terminal A and through the cable pipe before reaching terminal B. At terminal B, the liquid nitrogen was re-pressurized by CP3 and then passed through the return pipe before returning to the reservoir. The temperature settings of TB1 and TB2 were 70 K. Accordingly, the temperature of liquid nitrogen at the outlet of TB2 was approximately 70 K. The flow rate of liquid nitrogen was set to 40 L/min.

The heat leak was estimated for each section of the cable system (the cable pipe, the return pipe, and the terminals) by measuring the increase in temperature between the inlet and outlet of each section, the flow rate, and the specific heat capacity of the liquid nitrogen. The cryogenic pipe was installed mostly outdoors; the outer pipe temperature was measured a few meters away from the building where terminal A was installed.

The consumed power was measured using electric power meters for TB1, TB2, CH1, and CH2 at their power inputs during the long-term circulation and load cycle tests. By a separate experiment, the consumption power of CP1, the hydraulic power, and the loss in CP1 were measured with respect to the flow rate and rotational speed of the impeller of CP1. The consumption power of CP1 was measured with an electric power meter at its power input. By referring this result with the flow rate and the rotational speeds during the long-term circulation and load cycle tests, the consumption powers of CP1 and CP3 were estimated.
3. Cooling power of the 1000 m system

The cryogenic system was cooled by TB1 and TB2 during the long-term circulation and load cycle tests. The nominal cooling powers of TB1 and TB2 are 2 kW at 66 K. The cooling and power consumption of TB1 and TB2 have been measured and reported previously [7], and are replicated in figure 2 for reference.

4. The heat load by the heat leak

Table 1. Heat leak of each component of the 1000 m system [2,7]. The numbers in the parentheses are the values of experimental uncertainties referred to the corresponding last digits of the results.

| 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)  |

The recovery of heat leak represents a main heat load to the cryogenic system. The heat leak characteristics of each component of the 1000 m system at specific outer pipe temperatures were previously reported and are summarized in table 1 [2,7]. The heat leaks of the cable and return pipes were shown to depend on the outer pipe temperature, which increase approximately 30%–40% with an outer pipe temperature increase of 20 °C.

5. The heat load by circulation

The discharge pressure, consumption power, hydraulic power, and pump loss of CP1 were measured with respect to the flow rate and the rotational speed of its impeller and are shown in figure 3. The consumption power at the zero rotational speed was subtracted from the measured values, as the subtracted value was unrelated to the pump work. The consumed power can thus be considered the input power of the pump. The hydraulic power, which was obtained from the discharge pressure and flow rate, increased with increasing discharge pressure and flow rate. The hydraulic power, which drives the circulation, was consumed by the fluid friction and converted to the heat load to the cryogenic system. The pump loss were measured as the internal energy increase of the liquid nitrogen. A large fraction of the loss was related to the rotation of the impeller, while approximately 40 W, as shown in figure 3, was unrelated to the rotational speed and was considered as the heat leak through the inner structure of the pump. The sum of the hydraulic power and pump loss represented the total circulation loss and was nearly equal to the consumption power. Therefore, the consumption power of the pump was added as the heat load of the circulation to the cryogenic system. Since the pressure drop increased with the second powers of the flow rate, the hydraulic power and, accordingly, the input power of the pump increases with the third powers of the flow rate. As the consumption power...
sharply increased with the flow rate, discharge pressure, and rotational speed, increasing the efficiency of the superconducting power transmission systems, which need pumps with a very large capacity, may be difficult.

![Figure 3](image.png)

**Figure 3.** (a) Discharge pressure, (b) consumption power, (c) hydraulic power, and (d) loss of CP1 with respect to the flow rate and rotational speed of the impeller.

### 6. Heat load and power consumption measurements of 1000 m system

The total power consumption of the cooling system, representing the sum of the power consumption of TB1, TB2, CH1, and CH2, is shown in figure 4(a). The consumption of CP1 and CP3 are not shown because they were small in comparison with the others. The total heat load of the cable system is shown in figure 4(b). The heat load of the cooling system including the heat leak of the cryogenic pipe in the cooling system and the loss in CP1, which was estimated to be about 0.4 kW, is not included in the figure. To obtain the heat leak of the cryogenic pipe in the cooling system, the heat leak from Tc1 to Tr1 was subtracted from that of Tp14 to Tp11. The loss in CP1 was estimated from the data in figure 3(d). Here, the spike appearing at 2016/10/20 was caused by a temporal stop of the circulation. The pattern of the transmitted current applied to the cable during the load cycle test and the outer pipe temperatures of the cryogenic pipe are shown in figure 4(c) and 4(d), respectively. The outer pipe temperature reflects the change of the environmental conditions.

The heat loads of the cable and return pipes fluctuated and gradually decreased in phase with the outer pipe temperatures, as a large part of the cryogenic pipe is installed outdoors, so the heat leak subject to changing outer pipe temperature are accordingly subject to changing environmental...
conditions. The environmental conditions should therefore be considered when designing the cooling capacity and power supply systems required to operate the cooling system. On the other hand, the heat loads of the terminals were not affected by the outer pipe temperature, because they were installed in the air-conditioned buildings. However, a small fluctuation of about 40 W was seen during the load cycle test in accordance with the pattern of the transmitted current. This fluctuation was considered to be the heat load originated in the current leads by the transmitted current.

The average total heat load of the cable system was about 2.2 kW; that of the cooling system was estimated at 0.4 kW. The total heat load was thus approximately 2.6 kW. The cooling power of TB1 at 70 K was about 2.1 kW and therefore could not meet the cooling requirements of the system. As a result, TB1, at the upper stream of TB2, was in a full-load operation. The residual heat load, which exceeded the cooling power of TB1, was cooled by TB2, resulting in a partial load operation of TB2. This affected the power consumption of TB1 and TB2 and the consumption power of TB2 is an almost half of TB1. Furthermore, the power consumption of the chillers was almost 2/5 of the total power consumption. The power required for the coolant of the cryocoolers should also be considered to estimate the total efficiency of the cooling system. Partial load operation of TB2 and the use of the chillers likely reduced the efficiency of the system. Therefore, the choice of cryocooler with appropriate cooling capacity and disuse of chillers could increase the system efficiency.

![Figure 4. (a) Power consumption, (b) heat load, (c) current, and (d) outer pipe temperature during the long-term circulation and load cycle tests.](image-url)
Table 2. Summary of the power consumption and heat loads for the four cases.

| Case | Consumption power (kW) | HL (kW) | HL/Total |
|------|------------------------|---------|----------|
|      | TB1 | TB2 | CH1 | CH2 | CP1 | CP3 | Total |       |       |
| 1    | 45.3 | 23.6 | 26.7 | 22.2 | 0.23 | 0.10 | 118.1 | 2.2(2.6) | 0.019(0.022) |
| 2    | 44.3 | 23.1 | 27.4 | 21.5 | 0.23 | 0.10 | 116.7 | 2.1(2.5) | 0.018(0.021) |
| 3    | 50.7 | 24.3 | 30.4 | 26.5 | 0.23 | 0.10 | 132.3 | 2.4(2.8) | 0.018(0.021) |
| 4    | 41.4 | 22.0 | 25.3 | 19.6 | 0.23 | 0.10 | 108.6 | 1.9(2.3) | 0.017(0.021) |

* HL represents the heat load of the cable system. Values in parentheses include the heat load of the cooling system.

The resulting power consumption and heat load of the cable system is summarized in Table 2. The heat load of the cable system includes the heat leak from Tc1 to Tr1 and the loss of CP3. The overall heat load of the system, shown in parentheses, was obtained by adding the heat load of the cooling system, 0.4 kW, to the heat load of the cable system. Case 1 and Case 2 are the averages during the long-term circulation and load cycle tests, respectively. Case 3 and Case 4 are the maximum (2016/9/16 15:05) and the minimum (2016/10/31 6:06) in the whole period, respectively. The average heat load to the cryogenic system was about 2.5 kW, while the power consumption was about 120 kW. The ratio of the total heat load to the total power consumption, which relates to the efficiency of the system, was determined to be about 0.02 in all cases.

7. Summary

The heat load to the cryogenic system and the power consumption of the cooling system were measured with the 1000 m class superconducting DC power transmission system in Ishikari, Japan. The measurements were performed during long-term circulation and load cycle tests in the second cooling test of the 1000 m system. The average heat load to the cryogenic system during these tests was about 2.5 kW, while the consumption power was about 120 kW. To increase the efficiency of superconducting power transmission systems, the efficiency of each component of the cooling system and its composition, such as the use of chillers, should be optimized.

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