Hybrid cooling system with cryocooler and liquid-nitrogen for HTS-SQUID system

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Abstract. We developed a hybrid cooling system consisting of a liquid-nitrogen Dewar and a cryocooler with the aim of cooling HTS-SQUIDs fast at operation sites, extending cooling period time, and avoiding noise increase caused by the cryocooler. Liquid nitrogen is evaporated mainly by thermal inflow into the Dewar. Thus, we tried reducing the thermal inflow into a glass Dewar by cooling its inner surface using a small Stirling cryocooler with a cooling capacity of 16 W at 77 K, and examined the cooling period and the operation procedure. We successfully kept 0.6 liter of liquid nitrogen for one week with 0.2 liter reduction. It was also indicated that long time and low noise operation of HTS-SQUIDs would be possible in the hybrid cooling system by temporarily stopping the cryocooler during measurements.

1. Introduction
We have been developing several monitoring systems utilizing HTS-SQUIDs for oil reservoir with water or CO₂ injection for enhanced oil recovery, and carbon dioxide capture and storage (CCS) [1]. In such application, we sometimes require a long period cooling technique without adding serious noises to SQUIDs. Although the cooling technique using liquid nitrogen is suitable for cooling HTS-SQUIDs fast at an operation site and operating them without additional noise, their operation period is limited by the holding time of liquid nitrogen. On the other hand, cooling techniques utilizing a cryocooler for SQUIDs have been reported by several researchers [2-6]. Cryocooler enables to keep a low-temperature for a long time. However, it often causes serious noises to SQUIDs. Moreover, in the time domain electromagnetic (TEM) measurements which we often use for exploration or monitoring of underground resources, metal parts should be located far from the SQUID sensor to avoid the influence of eddy current induced in the metal parts. Since the power consumption of SQUID is estimated to be only several nano-watts, it seems negligibly small comparing with the thermal inflow of a few watts, which is caused by thermal conduction and heat radiation [7]. It means that the holding time of liquid nitrogen can be extended by reducing the thermal inflow. Thus, we have tried developing a hybrid cooling system where the thermal inflow into liquid nitrogen in a glass Dewar is reduced by using a small Stirling cryocooler. Our final goal is development of a cooling technique for HTS-SQUIDs in a compact pressure-resistant vessel which enables their operation, for example, in the sea.

2. Structure of hybrid cooling systems
The schematic image and a photograph of the hybrid cooling system are shown in figure 1. A glass Dewar with a capacity of liquid nitrogen of 1.2 liter covered with radio frequency shield was installed in a plastic case, and a Stirling cryocooler (SUNPOWER GT) with a cooling capacity of 16 W at 77 K
and the current meantime to failure of 200,000 hours was connected at the top of the glass Dewar. Since heat removal from the cryocooler is essential to exert its cooling capacity, the cryocooler was covered with a meander-type water cooling pipe and cooled by water circulation. The total size and weight of the hybrid system were ø110 mm × 950 mm and 14 kg, respectively.

Figure 1. Schematic image and photograph of the hybrid cooling system.

The performance of the glass Dewar was examined by measuring the time dependence of the remaining liquid nitrogen, as shown in figure 2. The obtained result was compared with calculation considering thermal inflow into the glass Dewar with a diameter of 65 mm, a depth of 385 mm, and a capacity of 1.2 liter [7].

Figure 2. Time dependence of remaining amount of LN₂ and thermal inflow in a glass Dewar.

The remaining amount of liquid nitrogen was calculated considering the thermal inflow into the glass Dewar caused by the thermal conductance of the glass, silver coating of glass, and nitrogen gas, as well as the thermal radiation from the thermal insulator at the top of the glass Dewar. The measured
data was consistent with the calculated value assuming that the thermal conductance of the glass, the thickness of silver coating, and the heat radiation efficiency factor of the thermal insulator were 0.8 W/m·K, 0.8 µm, and 0.2, respectively. The total thermal inflow used for the calculation was 0.5-3.7 W. This is small enough to be removed by the small cryocooler, even though the efficiency of cooling is limited by thermal conduction at several thermal connections between the cold head and the glass Dewar.

Though the cryocooler was originally an air cooling system, it was modified to that employing water cooling to keep the cold head at a stable temperature and to release heat from the cryocooler to the sea through the vessel. Figure 3 shows the distribution of surface temperature of the cryocooler which was measured by using a thermography camera in the cases of air cooling and water cooling. In the case of air cooling, the surface temperature of the cryocooler body and the heat dissipation fin reached 100 °C and 77 °C, respectively. The cold head temperature is sensitive to the heat dissipation from the cryocooler body. In order to cool the cold head below 77.2 K, the fin must be cooled below 32 °C in our system. The cooler body was successfully cooled below 30 °C by dissipating the heat to the water in a bath through the ring-shaped radiator shown in figure 1.

The time dependence of the cold head temperature for the cases of various cold head positions is shown in figure 4. In this experiment, atomosphere in the Dewar was the air. The cooling efficiency depends on the position of the cold head thermally connected to the glass Dewar, because the thermal inflow into the glass Dewar depends on the depth from the top of the glass Dewar. Assuming the cold head temperature is 77 K, the thermal inflow from the upper side (except the thermal inflow through the cooler rod) into the cold head at 55 mm, 65mm, and 85 mm were estimated to be 1.6 W, 1.4 W, and 1.2 W, respectively. When the cold head position was lower than 65 mm, the air was liquefied at 83 K. According to the experimental results, we determined the position of the cold head from the top of the glass Dewar to be 85 mm.
We presupposed that the cryocooler is operated intermittently and measurement using a SQUID is carried out while the cryocooler is stopped. Thus, the cryocooler was not covered with a magnetic shield. Nonetheless, the noise spectra were measured to understand the performance of the hybrid cooling system. The noise measurements were carried out in a cylindrical magnetic shield made of permally, although the upper part of the cylinder was open. The influence of vibration and the magnetic noise caused by the water pump and the cryocooler was examined as shown in figure 5.

![Figure 5](image1.png)

**Figure 5.** Noise spectra measured by using a SQUID in the hybrid system.

The white noise level without operation of the cryocooler was approximately $10^{-13}$ T/√Hz. Operation of both the cryocooler and water pump increased the noise level to $10^{-12}$ T/√Hz. The main noise was magnetic noise because the noise spectrum was the same with that measured by using another magnetometer placed outside and near the hybrid system. Large noise peaks appeared at 60 Hz which was the cryocooler operation frequency and its harmonic frequencies. Though we could reduce the environmental magnetic noise by using a permalloy magnetic shield cover, the vibration noise is essential for the hybrid system. The vibration magnitude of the Dewar was examined by using a movement recorder and compared with the SQUID noise spectrum in figure 6.

![Figure 6](image2.png)

**Figure 6.** Comparison of vibration spectrum with the magnetic noise spectrum.
The vibration peaks are observed at 60 Hz and its harmonic frequencies which agree with the peaks in the noise spectrum. It was also found that the vibration at the bottom of the Dewar was reduced by 1.5 order of magnitude from the vibration of the cold head owing to the thermal connection cushion ring between the cold head and the glass Dewar.

3. Cooling performance of the hybrid system

The cold head temperature and the amount of remaining liquid nitrogen during one week operation were examined. Before start of the cryocooler, 0.6 liter of liquid nitrogen was injected into the Dewar. The cooler temperature was not controlled by artificial heating or input power control with temperature feedback. The variation of the cold head temperature during the initial three hours is shown in figure 7. Though the cryocooler temperature was not controlled, the cold head temperature converged at 77.2 K automatically after the phase transition at 1.5 hours. The convergent temperature depends on the atmosphere gas in the Dewar. Actually, in the case of the air shown in figure 4, it covered at 83 K.

![Figure 7](image7.png)

Figure 7. Transient of cold head temperature in a cooling process with liquid nitrogen in the Dewar.

The variation of cold head temperature and the of amount of remaining liquid nitrogen during one week operation is shown in figure 8. The cold head temperature was almost stable and kept in a range from 77.2 K to 77.4 K for a week. The amount of liquid nitrogen was reduced from 0.58 liter to 0.38 liter, implying that the decrease rate is about 0.028 liter/day. The transient of remaining liquid nitrogen without cryocooler operation is also shown in the figure. The expected holding time for 0.5 liter liquid nitrogen of about 40 hours was successfully extended to over 20 days by operating the cryocooler.

![Figure 8](image8.png)

Figure 8. Variation of cold head temperature and amount of remaining LN$_2$ during one week operation.
Assuming that the cryocooler is stopped during measurement using a SQUID, we measured the transient of the cold head temperature and amount of remaining liquid nitrogen through intermitted operation of the cryocooler, as shown in figure 9. The cryocooler was first operated for five hours to cool enough the glass Dewar. Then, it was stopped for 30 minutes and operated again for 1.5 hours. The run and stop repetition operation was carried out for several times, and then the interval was changed to one hour stop and 2 hours run. Though the amount of liquid nitrogen decreased to 0.32 liter by this intermittent operation, the reduction rate was less than half of the rate without cryocooler operation. After intermittent operation, the cryocooler was operated for fifty hours. The reduction rate of liquid nitrogen during the fifty hours’ operation was 0.01 liter/day, which was about 1/3 of that shown in Fig. 8. This is due to the improvement of the cooling efficiency by covering the cold head rod with superinsulations in this experiment. In real monitoring operation, we need one hour measurement for one day and the next measurement will be carried out after several weeks. Though further improvement of the cooling efficiency is required to realize such an operation, the hybrid cooling system seems promising for use in monitoring systems, for example, under the sea.

![Variation of the cold head temperature and amount of remaining liquid nitrogen during intermittent operation followed by long time operation of the cryocooler.](image)

**Figure 9.** Variation of the cold head temperature and amount of remaining liquid nitrogen during intermittent operation followed by long time operation of the cryocooler.

### 4. Summery

We developed a hybrid cooling system utilizing liquid nitrogen and a cryocooler for long-time monitoring systems with HTS-SQUIDs. We successfully extended the holding time of liquid nitrogen by cooling the upper part of a glass Dewar with a small cryocooler. Though we still have some issues to improve the efficiency of cooling, we demonstrated the possibility of preparing a monitoring tool for long-time low-noise measurement using HTS-SQUIDs.

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