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DEVELOPMENT OF ZERO BOIL-OFF COOLING SYSTEMS FOR SUPERCONDUCTING SELF-SHIELDED MEG

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ABSTRACT

A mobile Magneto encephalography (MEG) of Sumitomo Heavy Industries, Ltd. (SHI) uses a high temperature superconducting magnetic shield (HTSMS), Superconductor-Normal-metal-Superconductor (SNS) type Superconducting Quantum Interface Device (SQUID) sensors, and they are cooled by a zero boil-off cooling system. The zero boil-off cooling system consists of a circulating cooled helium gas system for cooling the HTSMS below temperature 90 K and a helium recovery system for cooling the SNS type SQUID sensors to liquid helium temperature. The zero boil-off cooling system are designed to allow measurement in an operating state, allowing arbitrarily long usage. We succeeded first measurement of neuron current in brain by using SHI's MEG with helium zero-boil off cooling system in 2018. This paper describes overview of SHI's MEG, the thermal design of the zero boil-off cooling system for our MEG and the results of cooling test.

1. Introduction

Sumitomo Heavy Industries, Ltd. (SHI) began development on a mobile Magneto encephalography (MEG) composed of a high temperature superconducting magnetic shield (HTSMS), Superconductor Normal-metal Superconductor (SNS) type Superconducting Quantum Interface Device (SQUID) sensors, and a zero boil-off cooling system in 2007.

Historically, the system began as a collaboration between SHI, Shimadzu, and Japan's National Institute of Information and Communications Technology [1].

SHI's MEG system is designed to allow measurement with the zero boil-off system in an operating state, allowing arbitrarily long usage. These results show that our system is capable of operating in a nearly worst case scenario. We believe these results show promise for our vision of a more mobile MEG – one not only free from a shielded room, but perhaps even capable of traveling to where it is needed.

Integration tests have been performed with all major components, and we have shown that the MEG system is capable of measuring brain activity. These results are particularly noteworthy because they demonstrate the ability of the superconducting magnetic shield to reject noise even in hostile environments, as no shielding measures were taken apart from the aforementioned superconducting self-shielding. Furthermore, this data was captured while the zero boil-off system was running.

2. System Overview

SHI-MEG shown in Figure 1 consists of a Dewar within a high temperature superconducting magnetic shield (HTSMS), SNS type SQUID sensors, a zero boil-off cooling system, Measurement system, and a control and GUI PC..

Key Features
1) High Temperature Superconducting Magnetic Self-Shielding
2) Zero-Boil Off Helium Recovery System
3) Robust SNS Type SQUID Sensors
4) Open Source Software Environment [2]

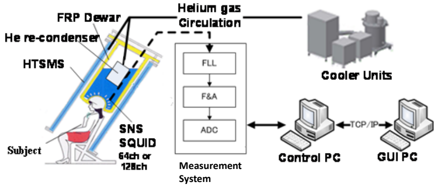
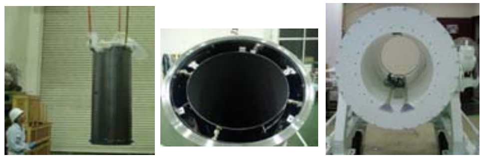


FIGURE 1. System Configuration of SHI-MEG

2.1 High temperature superconducting magnetic shield (HTSMS) [2]

1) The superconducting material used in HTSMS is $(Bi, Pb)_2Sr_2Ca_2Cu_3O_x$ (Bi2223).
2) Bi2223 is sprayed on the inner surface of a tube of non-ferrous material.
3) Our HTSMS is cooled by circulating cold helium gas below temperature 90K.
4) Its critical current density of the shield material is at least 100 A/cm2.
5) Its size is φ650mm × H1600mm and the shielding factor is more than 5000 at center.
6) The shielding performance is maintained even in the low-frequency region below 1 Hz.



HTSMS welded cooling pipe at 90 degree pitch in longitude direction

Set HTSMS in outer vacuum chamber

Vacuum chamber within HTSMS

FIGURE 2. High Temperature Superconducting Magnetic Shield（HTSMS）

2.2 SNS type SQUID sensor [2]

1) The sensors employed in SHI's MEG system are internally developed SNS-junction SQUIDs with intrinsic flux noise of less than 5fT/√Hz at 10Hz and less than 20fT/√Hz at 1Hz.
2) The array is composed of 64 radial gradiometers, upgradable to 128. Each gradiometer has a diameter of 30mm and baseline of 45mm.

SHI's SNS junction SQUIDs are robust to temperature cycling and electrical current.

3) After 40 thermal cycles between room temperature and liquid helium temperature, they show no deterioration in performance.
4) Similarly, no degradation is observed following applications of currents as high as 90 mA.

3. Thermal design of Zero boil-off cooling system

Figure 3 shows diagram of the zero boil-off cooling system that is comprised of a helium recovery system for cooling the SQUID sensors to liquid helium temperature and a circulating cooled helium gas system for cooling the HTSMS below temperature 90 K.

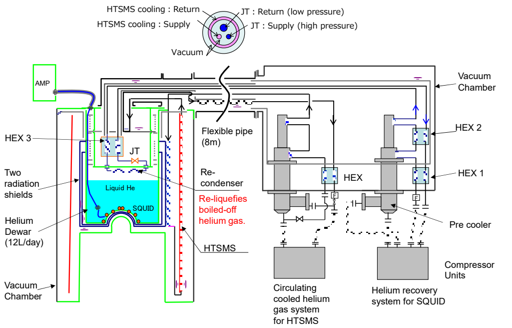
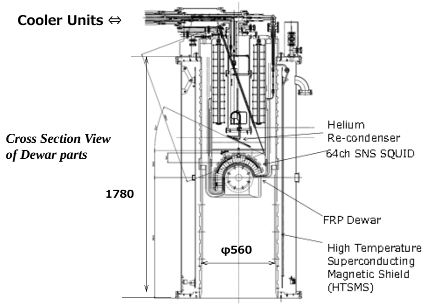


FIGURE 3. Diagram of the zero boil-off cooling system

Inner shell for containing liquid helium and outer shell for keeping vacuum of the Dewar are made of a kind of fiber reinforced plastic (FRP). Two-stage radiation shields of copper meshed type are installed between the inner shell and outer shell. Both radiation shields are attached to the inner shell (FRP) by bonding for mechanical and thermal functions. Multilayer insulation (MLI) of 10 layers is covered on the outside of outer radiation shield.

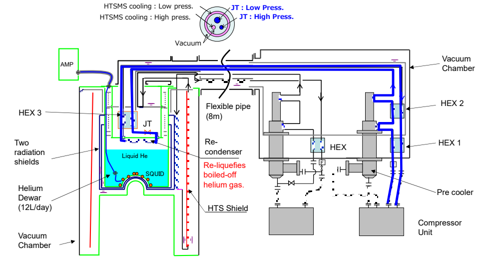
We modified the materials of JT piping, HEX3 and re-condenser inside Dewar are used non-ferrous metals such as copper, titanium and aluminium etc.



3.1 Helium recovery system for cooling SQUID

The helium recovery system for cooling SQUID is a 4K Joule-Thomson (JT) cooler (SHI Model: GC310SCR) paired with a two-stage GM cooler (SHI Model: RDK415D) for cooling the SQUID sensors below temperature 4.5 K.

We select the location of HEX3and JT valve are inside Dewar for SQUID, because of influence of heat leak by radiation through flexible pipe is less than in case of liquid helium transportation.



3.2 Optimization of 4K JT cooler for the helium recovery system

Optimization of the cooling capacity and the high pressure (supply pressure) for the 4K JT cooler was attempted on the basis of the thermal analysis [3]. We consider a system composed of the flexible connecting pipe, the third heat exchanger, the JT valve and the 4 K stage as in Figure 4. The cooling capacity at the 4 K stage (Q_3) is estimated from the equation.

$$Q_3/m=h_7-h_5-\eta_3\Delta h_{HEX3}$$

Here we have;
h_n : ^{4}He-gas enthalpy at temperature T_n
η_3 : efficiency of third heat exchanger
Δh_{HEX3} : heat exchanged in third heat exchanger when efficiency of 100%
m : mass flow rate of ^{4}He-gas

And, a heat leak (Q_a) into supply pressure line in flexible connecting pipe is expressed by the equation ($Q_a/m=h_a-h_5$).

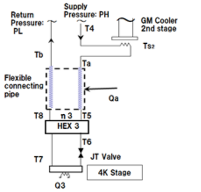


FIGURE 4. Flow diagram

For example, Figure 5 present analysis results of the cooling capacity (*Q3*) in the 4 K stage shown respectively against the supply pressure (*PH*) with the inlet temperature (*T5*) at the supply pressure side of the third heat exchanger as a parameter. The efficiency of third heat exchanger (η_3), mass flow rate (*m*), suction pressure (*PL*), and temperature of final stage are fixed, respectively, as 0.97, 1 Nm³/hr, 1.3 Mpa, and 4.5 K.

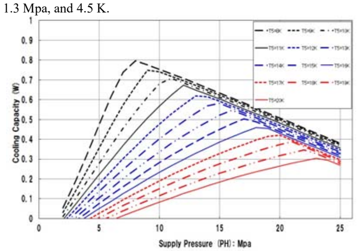
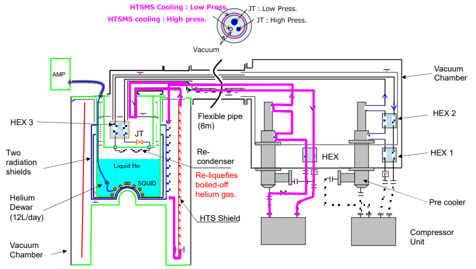


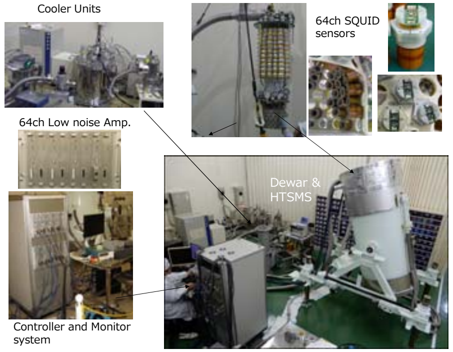
FIGURE 5. Analysis result: *Q3* in the 4 K stage plotted against *PH* with *T5*

3.3 Circulating cooled helium gas system for HTSMS

The second cooling system is a circulation loop, a heat exchanger and a two-stage GM cooler (SHI Model: RDK-408R) for cooling the radiation shield of Dewar and HTSMS below temperature 90 K.



4. Cooling performance test results



Test configuration of SHI-MEG in SHI Niihama Factory

4.1 Cooldown performance of Zero boil-off cooling system

Figure 6 shows cooldown of zero boil-off cooling system. The temperature of HTSMS becomes to below 90 K after about 22 hours from cooler operation started. The cooler for SQUID cooling started after 17 hours, then liquid helium started to transfer into Dewar after 42 hours. Total liquid helium volume of 100 L was used in this operation. Finally, zero boil-off state reached with liquid helium volume of 43 L after 53 hours from operation start.

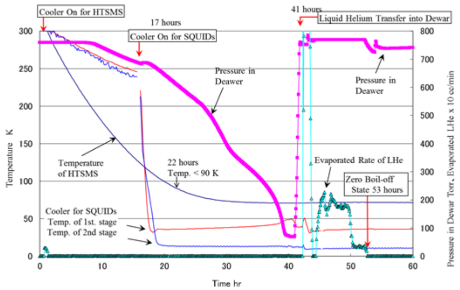


FIGURE 6. Cool down profile of the zero-boil off cooling system

4.2 Cooling performance of Zero boil-off cooling system

Figure 7 shows a steady state operation status under zero boil-off condition.

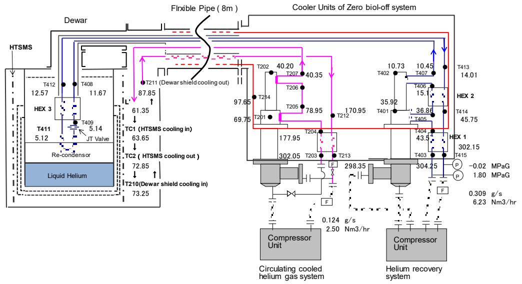


FIGURE 7. A steady state operation status under zero boil-off condition

Table 1 shows estimation of heat loads at main parts from temperature, pressure and mass flow in Figure 7. Cooling power at re-condenser for recovery of evaporated helium is estimates about 3.31 W from Figure 7, when the supply pressure (PH) is 1.7 MPa in case of the temperature (T5) of 11.67K.

TABLE 1. Estimation of heat loads from test results in Figure 7

Main parts	Heat Loads (W)
Circulating cooled helium gas system	
First stage of GM cooler	63.84
Second stage of GM cooler	24.89
Supply line in flexible connecting pipe	13.64
Outer radiation shield of Dewar	1.48
HTSMS	7.42
Radiation shield at upper part of HEX3	9.41
Return line in flexible connecting pipe	53.59
Helium recovery system	
First stage of GM cooler	10.78
Second stage of GM cooler	7.50
JT Supply line in flexible connecting pipe	1.96
JT Return line in flexible connecting pipe	2.30
Cooling power at re-condenser	3.31

4.3 Noise level and brain activity measurement

Measurements of the noise-level have been performed under zero boil-off operation. The noise level is realized less than 10 fT/√Hz at 10 Hz. The noise level at several frequency region was low enough to MEG measurement compared to the noise level of the conventional magnetic shield room (MSR). What makes these results noteworthy is that they were performed outside of a magnetically shielded room, with the zero boil-off cooling system continuously running. In addition, the shielding efficiency of our HTSMS is no degradation during over 20 years after production, this is a worthy of mention. We also succeeded in measurement of neuron current in brain to tactile stimulation and auditory stimulation with helium zero boil-off cooling system [4]. Despite this, the MEG's robust SNS sensors, low noise cooling system, and superconducting magnetic shield worked in tandem to produce reasonable results.

5. Conclusions

We have designed, fabricated and tested the zero boil-off coolingsystem for cooling SHI-MEG. The verification test results showed the cooler has a satisfactory performance with respect to the specifications required for SHI-MEG.

We believe these results show promise for the future of our system and support the feasibility of measuring biomagnetic signals outside of a magnetic shield room (MSR).

An agreement has been reached for lending out the first unit to an institution in Japan. The next steps will be to implement feedback received from our development partners and to place the second and third units.

6. References

[1] Ohta H, et al. (2007) A Whole-Head SQUID System in a Superconducting Magnetic Shield, IEEE Trans. On Applied Superconductivity Vol.17, 730-733
[2] Hornberger E, et al, "Development of a Superconducting Self-Shielded Zero Boil-Off MEG", The Journal of Japan Biomagnetism and Bioelectronics Society, vol. 30, no. 1, p.130-131, 2017
[3] Narasaki K, "Analysis of two-stage Joule–Thomson expansion", Cryogenics **74** (2016) 59-65
[4] Tanaka K, et al, "Measurements of MEG with a Superconducting Self-shield and Zero Boil-Off System", Manuscript 3214 submitted to 2019 41st Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC). Received April 17, 2019

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