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An Ultra-low Vibration Helium Reliquefier for Dual-Helmet Magnetoencephalography (MEG)

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Abstract. An ultra-low vibration helium reliquefier has been developed that can be integrated into an innovative magnetoencephalography (MEG) system with dual helmets for adult and pediatric use. The compact reliquefier establishes a closed-cycle helium loop for the MEG dewar allowing for uninterrupted, maintenance-free operation. The reliquefier, employing a Cryomech 4 K pulse tube cryocooler (model PT420), provides a liquefaction rate of 21 L/day from room temperature helium gas. Several vibration reduction measures have been applied to the system. The reliquefier incorporates a ~1.5 m long, horizontal, flexible liquid return line allowing it to be mounted outside of the magnetically shielded room (MSR). This arrangement greatly reduces vibrational, acoustic, and magnetic interference. In the prototype tests, this setup reached noise levels of ~18 fT/ $\sqrt{\text{Hz}}$ without the use of noise cancellation software. The spontaneous brain activity signal showed nearly identical signal quality with the reliquefier turned on and off.

1. Introduction

Magnetoencephalography (MEG) is a functional neuroimaging technique for mapping brain activity by recording magnetic fields produced by naturally occurring electrical currents in the brain. MEG systems utilize SQUIDS operating at liquid helium temperatures to measure brain activity which varies between 10^{-11} and 10^{-14} Tesla. In many MEG facilities, the evaporated helium gas is released from the MEG cryostat into the atmosphere. Regular manual transfer of liquid helium is required. The high cost of helium maintenance has limited wide-spread use of this technology for measuring human brain functions.

A commercial MEG helium recycling system has been developed by Elekta-Neuromag, in which a GM cryocooler cold head is installed in the cryostat of the MEG system. However, this cryocooler must be turned off during MEG measurements because of its high noise level. Large storage tanks, a compressor and a control system are used to collect the helium boil off gas to be liquefied later [1]. Adachi et al have developed a closed-cycle liquefaction system, incorporating a pump and storage tank, for an MEG with partial SQUID coverage of only 16 channels [2]. Using a principal component analysis (PCA)-based noise cancellation algorithm, the recycler noise was reduced to below 50 fT/ $\sqrt{\text{Hz}}$.

More recently, a simpler configuration of the reliquefier system for a pediatric MEG was introduced by Wang et al [3]. This “babyMEG” consisted of 375 magnetometers and utilized direct liquefaction. The system recondensed the evaporating gas using a thermosiphon loop and eliminated the need for helium storage tanks and recovery compressors. A 1.5 W pulse tube cryocooler, utilizing a remote motor configuration, was used for the reliquefier. This compact reliquefier has been in successful operation with the MEG for more than 18 months [4]. The system introduces a 1.4-Hz vibration of ~400 fT/ $\sqrt{\text{Hz}}$



as measured by magnetometers. After using external active shielding with fluxgate magnetometers and compensation coils, and applying the signal space projection and synthetic gradiometer, the low-frequency vibration noise peaks were reduced to nearly white noise levels of ~ 10 fT/ $\sqrt{\text{Hz}}$.

Korea Research Institute of Standards and Science (KRISS) and Compumedics Neuroscan are co-developing a dual-helmet MEG (model Orion LifeSpan) which can be used for both adult and pediatric patients. The adult helmet contains 192 gradiometers and the pediatric helmet houses 144 gradiometers. Cryomech was contracted to develop a helium reliquefier to maintain zero boil off for this MEG. This paper presents the design, performance and noise level of this compact helium reliquefier.

2. System design

2.1. Reliquefier design

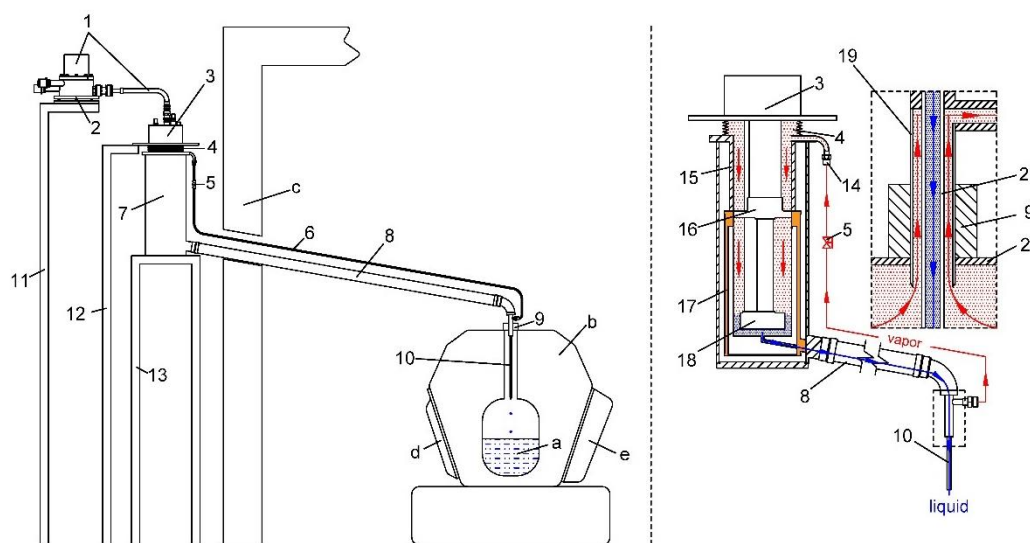


Figure 1. System integration of the MEG with the reliquefier (Left) and the reliquefier schematic (Right). (a) dewar of the MEG; (b) dual-helmet MEG; (c) MSR wall; (d) pediatric helmet; (e) adult helmet. (1) remote motor assembly; (2) sliding carriage; (3) cryocooler cold head; (4) bellows; (5) needle valve; (6) vapor return line; (7) reliquefier assembly; (8) flexible part of liquid return line; (9) rotating seal assembly; (10) insertion tube of liquid return line; (11) stand for remote motor assembly; (12) cold head stand; (13) reliquefier stand; (14) gas inlet port; (15) vacuum insulated sleeve; (16) 1st stage of the cold head; (17) radiation shield; (18) 2nd stage of the cold head; (19) co-axial vapor return tube; (20) vacuum jacketing on liquid return line; (21) top flange of MEG dewar.

Figure 1 shows the integration of the reliquefier into the MEG. Unlike the reliquefier in reference [3], this reliquefier utilizes a 1.5 m long, horizontal liquid return line (8). The reliquefier assembly can be mounted outside of the MSR and the liquid return line goes through the MSR wall (c). The vertical insertion tube (10) of the liquid return line is inserted into the neck of the MEG liquid dewar (a). The vapor return line (6) directs boil off vapor from the MEG dewar to the reliquefier assembly.

A 2W-class 4 K pulse tube cryocooler, Cryomech model PT420-RM, is mounted in the reliquefier. This cryocooler cold head uses a remote motor assembly (1) which is mounted on a sliding carriage (2). The remote motor assembly connects to the cold head (3) via a $\frac{1}{2}$ " ID flexible line. A bellows (4) is inserted between the cold head and the reliquefier assembly to reduce vibration transmission. A support structure (12) firmly holds the cold head in place.

The cold head and reliquefier assembly are shown in greater detail on the right of figure 1. The reliquefier contains two cooling stages (16,18) encased in a vacuum insulated sleeve (15). The reliquefied helium drips down through the horizontal flexible transfer tube (8) and an insertion tube (10) into the dewar belly (a) of the MEG cryostat. The evaporating vapor returns to the top of the reliquefier through a vapor line (6), made of SS flexible line. This vapor is precooled and then liquefied by the cold head. In this manner, the reliquefier establishes a closed helium loop and maintains zero boil off in the MEG system.

The new dual-helmet MEG requires the entire MEG assembly (b) to rotate 180° horizontally to switch between adult and pediatric helmets. A co-axial, vacuum-insulated vapor return tube (19) is installed on the top of the liquid insertion tube. It incorporates a rotating seal (9) that allows the MEG to rotate axially about the insertion tube. The vapor and liquid flows are indicated on the right side of figure 1. This rotating seal, developed specifically for this project, creates a helium-tight enclosure for both stationary and dynamic conditions.

2.2. *Vibration reduction*

Vibration was significantly reduced through several measures. The remote motor assembly is detached from the pulse tube cold head and vibration transmission from the motor to the cold head is minimized with the use of a flexible line. The remote motor assembly was installed on a sliding carriage (2) to reduce the vibration force generated from pulsing flexible lines. Flexible isolation bellows (4) were employed between the coldhead and reliquefier assembly to further decouple the two. Most importantly, the 1.5 m horizontal flexible liquid return is used to offer increased isolation of the reliquefier chamber from the MEG.

3. **Reliquefier performance**

Before being installed into the reliquefier assembly, the performance of PT420RM pulse tube cryocooler was tested and shown in figure 2. The PT420RM produced cooling capacities of 2.0 W @ 4.2 K and 64 W @ 45 K, simultaneously, with an electrical input of 12.5 kW.

After installing the cryocooler into the assembly, the reliquefier was qualified at Cryomech's facility. A testing setup was used that replicated its operation in the field. The reliquefier was mounted to a stand and the flexible liquid line (8) was positioned at a ~10° tilt. The testing pot consisted of a ~2.8 L liquid volume that was housed in a vacuum. Two calibrated silicon diodes were used to measure the temperature of the volume as well as an additional shield. A heater was placed at the bottom of the liquid volume to provide a heat load into the liquid helium. The testing procedures are similar to those in reference [5]. High pressure helium from cylinders is regulated down to absolute pressure of 120 kPa and supplied to the reliquefier during cool-down and liquefaction.

Figure 3 shows a cool-down of the system. This MEG-specific reliquefier had a slower cool-down than a standard reliquefier due to the extra mass that needed to be cooled. Despite this, the reliquefier began to liquefy helium for cooling the liquid volume at around 2.5 hours, indicating that the pulse tube cryocooler had cooled the reliquefier assembly and the 1.5 m extension from room temperature to liquid helium temperatures.

Once steady conditions at liquid helium temperatures have been achieved, liquefaction testing is conducted by using a Teledyne Hastings HFM-200 flow meter (calibrated to 20 SLPM, accuracy of $\pm 1\%$ F.S.) to measure the gas flow rate into the reliquefier, shown in figure 4. The reliquefier produces liquid helium from room temperature gas at a rate of 21.0 L/day. In order to test reliquefaction/recondensing capacity, a heat load is applied to the liquid helium volume and the reliquefier becomes part of a thermosiphon loop that recondenses and reliquefies helium [5]. The results are shown in figure 5. This system could sustain a heat load of 0.97 Watts, which corresponds to a liquid helium boil off rate of 32.4 L/day.

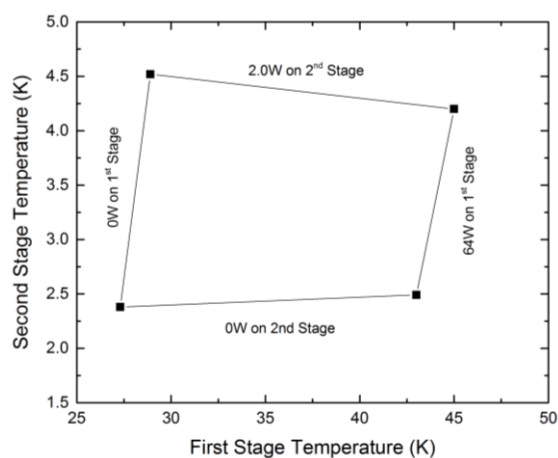


Figure 2. Measured cooling load map of PT420RM

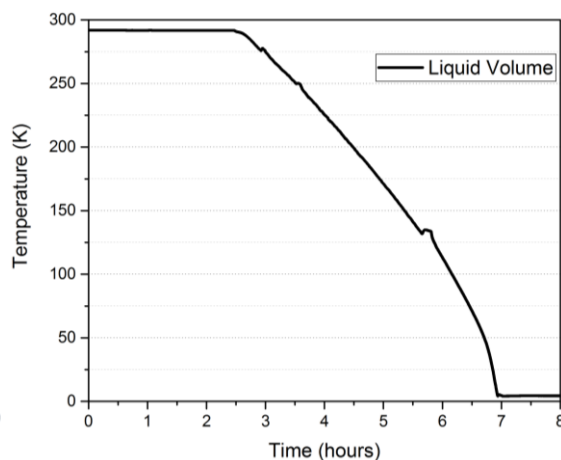


Figure 3. Cool-down time of liquid volume with the reliquefier

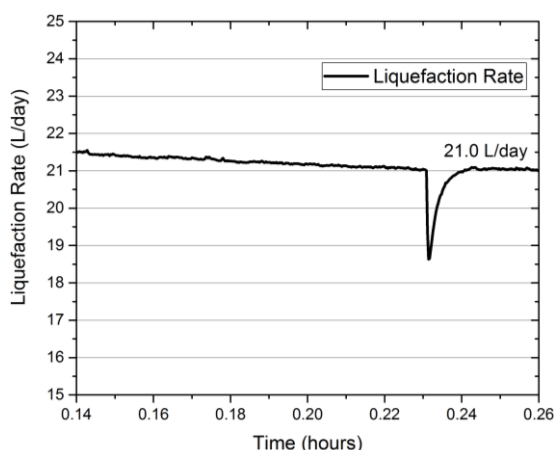


Figure 4. Liquefaction capacity of the reliquefier.

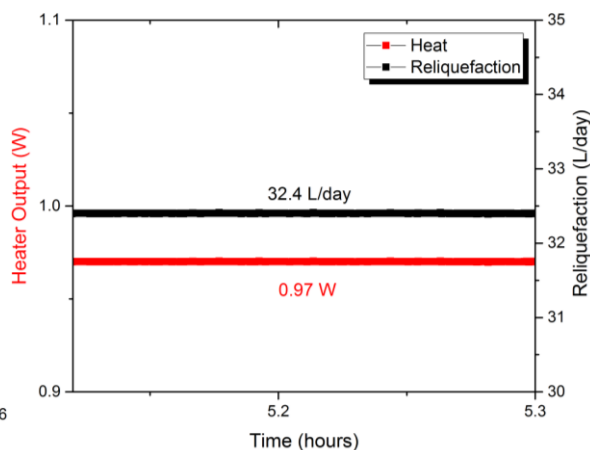


Figure 5. Reliquefaction/recondensing capacity of reliquefier

4. Zero boil off MEG with reliquefier

This reliquefier was first integrated into a single helmet MEG system at KRISS, as shown in figure 6. The system has been in operation since April 2018 (4 months) without any helium loss. An additional heat load of 0.25 W is applied to the reliquefier condenser to maintain a positive pressure (102.8 kPa absolute) in the MEG dewar. The dual helmet MEG is currently being developed and isn't ready for testing.

Figure 7 shows the magnetic noise (from the MEG, reliquefier and subject) with eyes closed and open. The noise data is the average of all the channels. Except for the vibration-induced peaks, the noise levels are nearly at white noise levels (3.5 fTrms/ $\sqrt{\text{Hz}}$). The average amplitude of the 1.4 Hz peak is 18 fTrms/ $\sqrt{\text{Hz}}$. It is introduced by the cryocooler which operates at a frequency of 1.4 Hz. The noise level in the current system is much lower than that in reference [2]. Compared to the spontaneous brain signal, which is considered brain noise, the noise level of the reliquefier MEG system is about 10 times lower. That is, the spontaneous brain signal has a signal-to-noise ratio of about 10 at most frequencies up to about 20 Hz, which corresponds to the main frequency range of spontaneous brain activity. At 1.4 Hz, the brain noise level is about 3 times larger than the MEG system noise. The measured MEG brain activity shows nearly identical quality of alpha rhythm signals with the reliquefier on and off.

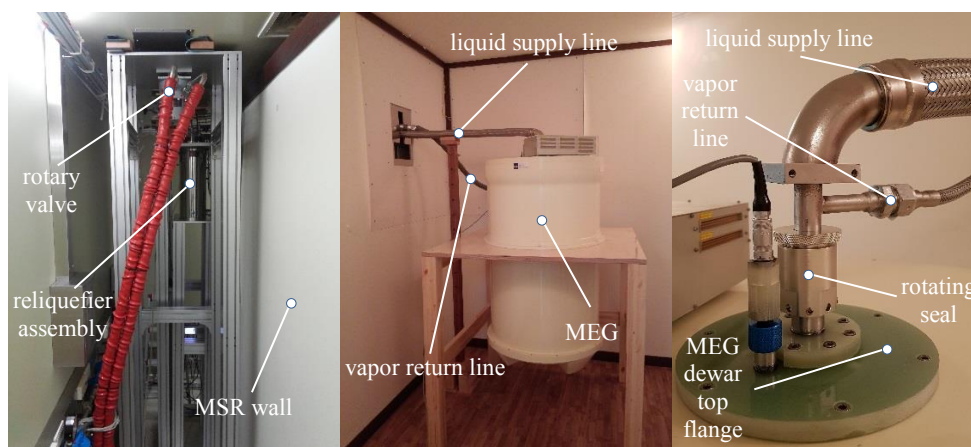


Figure 6. Photos of the installation. (a) Rotary valve and reliquefier chamber installed next to the left wall of the MSR. (b) Helmet dewar inside the MSR. (c) Rotating seal and coaxial vapor return line

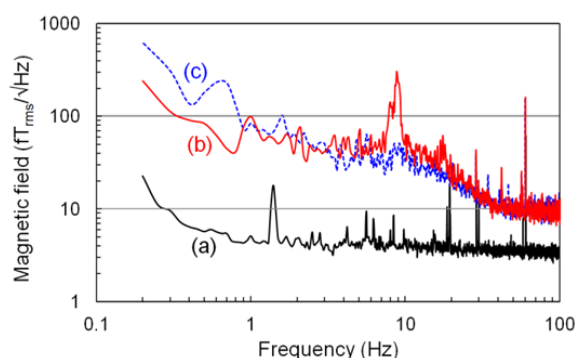


Figure 7. Comparison of magnetic field noise of the reliquefier MEG system with brain activity noises. (a) Without subject, (b) with subject and eyes closed, and (c) with subject and eyes open. All the noise spectra were averaged over all the channels.

5. Conclusion

We have developed a helium reliquefier for a dual-helmet MEG with multi-stage vibration isolation. The reliquefier, using a 4 K pulse tube cryocooler, provides a liquefaction rate of 21 L/day from room temperature gas. The reliquefier and MEG system generate a noise level of <18 fT_{rms}/√Hz without using software noise cancellation, which is much lower than brain activity signals.

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