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Compact, ultra-low vibration, closed-cycle helium recycler for uninterrupted operation of MEG with SQUID magnetometers

Chao Wang [a,*], Limin Sun [b], Ben Lichtenwalter [a], Brent Zerkle [a], Yoshio Okada [b]

[a] Cryomech, Inc., 113 Falso Drive, Syracuse, NY 13211, USA
[b] Boston Children's Hospital and Harvard Medical School, 300 Longwood Ave., Boston, MA 02115, USA

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ABSTRACT

A closed-cycle helium recycler was developed for continuous uninterrupted operation for magnetometer-based whole-head magnetoencephalography (MEG) systems. The recycler consists of a two stage 4 K pulse-tube cryocooler and is mounted on the roof of a magnetically shielded room (MSR). A flexible liquid helium (LHe) return line on the recycler is inserted into the fill port of the MEG system in the MSR through a slotted opening in the ceiling. The helium vapor is captured through a line that returns the gas to the top of the recycler assembly. A high-purity helium gas cylinder connected to the recycler assembly supplies the gas, which, after it is liquefied, increases the level of LHe in the MEG system during the start-up phase. No storage tank for evaporated helium gas nor a helium gas purifier is used. The recycler is capable of liquefying helium with a rate of ~17 L/d after precooling the MEG system. It has provided a fully maintenance-free operation under computer control for 7 months without refill of helium. Although the recycler is used for single-orientation operation at this initial testing site, it is designed to operate at ±20° orientations, allowing the MEG system to be tilted for supine and reclining positions. Vibration of the recycler is dampened to an ultra-low level by using several vibration isolation methods, which enables uninterrupted operation during MEG measurements. Recyclers similar to this system may be quite useful even for MEG systems with 100% magnetometers.

1. Introduction

Magnetoencephalography (MEG) is a functional neuroimaging technique for mapping brain activity by recording magnetic fields produced by electrical currents occurring naturally in the brain. All of the commercial MEG systems (i.e. Elekta-Neuromag VectorView and Triux; CTF MEG; Tristan MagView) presently use superconducting detection coils inductively coupled to superconducting quantum interference devices (SQUIDs) to measure MEG signals. SQUIDs are extremely sensitive detectors of magnetic flux. They utilize the Josephson junction to detect MEG signals from the human brain varying between 10^{-11} and 10^{-14} T.

All of these MEG systems operate at the temperature of liquid helium (LHe) (4 K), requiring LHe as the coolant. In many MEG facilities, the evaporating helium gas is released from the cryostat of the MEG system into the atmosphere, requiring regular manual transfer of the cryogen into the MEG system. This mode of operation is quite costly since the supply of LHe is scarce, expensive and sometimes unreliable, and the regular helium transfer consumes a significant amount of labor of a trained technician or technicians. Since helium is a precious natural resource that cannot be manufactured, some facilities use a method to capture the evaporating vapor and recondensing the gas. Although this second mode of operation saves helium, it limits the use of MEG to only large universities or research facilities which consume a significant amount of helium to justify the operation of a sophisticated and expensive reliquefaction facility. The large expense of helium maintenance has limited a wide-spread use of this technology for measuring human brain functions.

On-site helium recovery has recently become recognized as necessary in the field of MEG technology as helium becomes more expensive and an off-site recovery system may be difficult to establish in many cases. In response, some manufacturers have developed an open-cycle recovery system that collects the gas and reliquefies and stores LHe in a tank onsite. The stored LHe is

Abbreviations: MEG, magnetoencephalography; SQUID, superconducting quantum interference device; MSR, magnetically shielded room; BCH, Boston Children's Hospital; PPMS, physical property management system; MPMS, magnetic property measurement system; GM, Gifford–McMahon cryocooler; JT, Joule–Thomson cryocooler; MRI, magnetic resonance imaging; LHe, liquid helium.

* Corresponding author.
E-mail address: cwang@cryomech.com (C. Wang).

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then transferred back into the MEG cryostat in a conventional manner. Although this method recovers most (>80–90%) of helium, it still requires manual transfer of LHe by a skilled technician or technicians.

In order to eliminate the manual transfer altogether, closed-cycle recyclers are beginning to be developed for MEG facilities. In one approach, the recycler is placed above MEG sensors within a single cryostat in order to reduce the heat loss from the recycler to the MEG cryostat. Sata et al. [1,2] have shown that the recycler noise produced by a GM/JT recycler can be reduced to 15 pT, sensed by axial gradiometers with a detection coil diameter of 20 mm and a baseline of 50 mm. Using a template matching noise rejection algorithm, the noise of the recycler (2 Hz with harmonics) could be reduced to below the system noise level (white noise level 12–18 fT/$\sqrt{}$Hz) to measure evoked averaged MEG signals from human volunteers. Yu et al. [3] have used a similar design with the cold-head of the cryocooler inside the MEG cryostat. A superconducting plate was successfully used 25 mm above the MEG magnetometer array to reduce the noise from the cryocooler to as little as 1.7 pT/$\sqrt{}$Hz at the center of the superconductor plate. The superconductor plate produces an image of each magnetometer on the opposite side of the plate to provide an effective noise cancellation using this image [4]. More recently, a closed-cycle recycler has been developed by Elekta-Neuromag in Helsinki, Finland. In their system, a GT cold head is installed in the cryostat of the whole-head MEG system so that it can be tilted for measurements with the subject on a reclined seat or on a bed. The recycler, however, must be turned off during MEG measurements.

In the second approach, the recycler is placed outside the MEG cryostat to reduce its noise seen by the MEG sensors. One challenge for this approach is reduction of LHe loss in the transfer tube from the recycler to the MEG cryostat. Takeda et al. [5,6] have developed a closed-cycle recycler using two 1.5 W@4.2 K GM cryocoolers with a multi-concentric transfer tube. This recycler uses dual helium streams, one to collect evaporated helium vapor and to return it as liquefied helium to the MEG cryostat, and the second to use higher temperature helium gas (~40 K) to cool the radiation shield. Their recycler can liquefy at ~35.5 L/d. Although MEG measurements can be carried out while the recycler is operating, the noise from the GM pump causes a large amount of interference that requires an elaborate vibration damping method to reduce the noise. More recently, Adachi et al. [7] have developed a closed-cycle recycler using a pulse tube that produces an order of magnitude less vibration noise than the GM recyclers. Using a principal component analysis (PCA)-based noise cancellation algorithm, the recycler noise was reduced to below 50 fT/$\sqrt{}$Hz.

We have developed an efficient, closed-cycle helium recycler for MEG that is compact and simple in design without requiring a storage gas tank and a gas purifier as in other systems, with a very low vibration noise for uninterrupted operation of the recycler during MEG measurements. Unlike all previous attempts, we have successfully developed a system that can be used for MEG systems consisting entirely of magnetometers. This recycler uses a single, two-stage pulse tube cryocooler that has been developed at Cryomech [8,9]. The recycler has been used for some open cryostats, such PPMS and MPMS, wet dilution refrigerators and superconducting magnets. Below, we describe the design of this system and its basic performance characteristics using a small test reservoir. Then, we describe the performance of this system installed at a whole-head MEG facility of Boston Children's Hospital (BCH) recently established for basic and clinical human brain development research. We show that the recycler noise is sufficiently small so that the residual noise can be eliminated with well-established, simple noise cancellation algorithms and spontaneous brain activity measured by a magnetometer array can be monitored online in real time while the recycler is operating continuously uninterrupted. The performance of our recycler is overall superior to all previous closed-cycle systems.

2. System design

The recycler developed in this project is an extension of our previous recyclers based on a two-stage 4 K pulse tube cryocooler – Cryomech model PT415RM (1.5 W at 4.2 K) [8,9]. The development of a recycler specifically for MEG systems called for a modification of the basic system to significantly reduce vibration noise and to eventually allow for use with two different orientations of the MEG cryostat with the subject in the supine and reclined seated positions. The vibration was significantly reduced through two major steps. First, the motor/rotary valve assembly is detached from the pulse tube cold head. The vibration transmission from the motor to the cold head is minimized using a flexible tube. Second, the transmission of vibration from the cryocooler to the MEG system was reduced by using a flexible transfer tube connecting the recycler to the fill port of the MEG cryostat.

Fig. 1 shows the design of the recycler. The high-pressure helium gas from the compressor is delivered to the rotary valve-motor assembly (4) via a pair of long flexible tubes (3). The motor assembly is detached from the cold head (5) to reduce vibration of the recycler assembly (7). It is mounted on a sliding carriage (2). The sliding carriage allows free movement of the remote motor to reduce the force which could exert on the recycler assembly. A similar design has been used in a dry dilution refrigerator [10]. The rotary valve feeds compressed gas to the cold head (5) via a flexible line (4). A bellows (6) is inserted between the cold head and the recycler assembly to reduce vibration transmission. A support structure (12) mounted on the ceiling (d) holds the cold head firmly.

The cold head and recycler assembly are shown in some detail on the right. The recycler contains a 2-stage pulse tube (15, 16) encased in a vacuum insulated sleeve (17). A thermal shield (18) is used to reduce infrared radiation penetrating the vacuum container. The reliquefied LHe drips down through the flexible transfer tube (8) (444 mm long and 47 mm OD) and an insertion tube (9) (660 mm long and 12.7 mm OD) into the inner belly (a) of the MEG cryostat (b). The flexible part of the liquid return tube accommodates the MEG rotation up to 20° and also reduces the vibrations transferred from the recycler assembly to the MEG (b). The evaporating helium vapor returns to the recycler via two paths: (1) through the transfer tube which allows for LHe to drip down and helium gas to rise up to the recycler chamber through a single tube without vapor trap; and (2) through a vapor line (11), made of stainless steel flexible line, with a needle valve (10) to the gas inlet at the top of the recycler. In the recycler assembly (7), the pulse tube cold head resides in the vacuum insulated sleeve (17). Via path 1, LHe drains back to the belly of the MEG reservoir (a) through the liquid return line (8, 9). The helium vapor/gas via path 2 is pre-cooled by the first stage, the tubes of regenerators and pulse tubes, and finally condensed on the 2nd stage/condenser. A ultra high purity helium gas cylinder (14) is attached to the same gas inlet with a flow valve (13) to allow for building up the LHe level during the start-up phase. The recycler assembly is firmly mounted on the roof of the magnetically shielded room (MSR) for damping most vibrations from the recycler assembly.

3. Experimental results and analysis

3.1. Recycler performance test

The recycler performance was first evaluated at Cryomech prior to installing the recycler at the MEG facility at BCH. The recycler