A Cryogen Recondensing Cooling System for Scientific Experiment in the Pulsed High Magnetic Field

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Abstract. Traditional cryostat for scientific experiment in the pulsed high magnetic field uses liquid helium as the cooling source. To reduce the running cost and increase the operational efficiency, a cryogen recondensing cooling system based on a GM cryocooler has been developed for a 60 T measurement cell at Wuhan National High Magnetic Field Center. A helium cryostat with a recondensing system provides cooling power for sample holder insert. The bottom of the insert with a vacuum space is immersed in 4 K liquid helium bath, so that the helium gas inside the insert condenses to liquid phase at the neck tube on the top of the insert’s tail. The temperature of the sample can reach 1 K and stay stable at 1.2 K for 2 hours by pumping the helium bath in the insert. The gas evaporated from the helium cryostat is recondensed by a GM cryocooler liquefier, and is circulated in a closed-loop system.

1. Introduction

A measurement cryostat is one of the basic tools for scientific experiments in pulsed high magnetic fields [1]. In order to obtain temperatures of 4 K and below, traditional cryostats (e.g. helium bath cryostat and helium-gas-flow cryostat [2]) for scientific experiments in pulsed high magnetic fields use liquid helium as the cooling source. Because of the high price of liquid helium, a first generation cryogen-free cryostat based on a GM cryocooler has been developed for a 60 T pulsed magnetic field measurement cell at Wuhan National High Magnetic Field Center. In the first generation cryogen-free cryostat, the sample temperature can be kept at the lowest temperature 1.5 K for 9 minutes. In the sample region, stability of the temperature is obtained: ±0.1 K at 20 K - 300 K, ±0.2 K at 5 K - 20 K and ±0.02 K at 1.5 K - 5 K [3]. In 2014, Wuhan National High Magnetic Field Center has designed and fabricated a second generation cryogen-free cryostat based on a GM cryocooler with a temperature-control insert. The lowest temperature of the cryostat is 1.4 K and can hold for 12 minutes. Using the temperature-control insert, the stability of the sample temperature is obtained: ±0.01 K between 1.4 K and 20 K and ±0.05 K between 20 K and 300 K [4].

The first generation and second generation cryostats, although have got very good performance, but the lowest temperature holding time is short, which would affect the experiment efficiency. In order to develop a new cryostat with longer holding time of the lowest temperature, we design and fabricate cryostat with a cryogen recondensing cooling system and a sample insert for scientific experiment in the pulsed high magnetic field, based on a GM cryocooler (model RDK415D with compressor F-50H, 1.5 W @ 4.2 K). Experiment results show that, in the sample region, the cryostat with the cryogen
recondensing cooling system has a lower temperature than the first two generation cryogen-free cryostats and a longer holding time of the lowest temperature for scientific experiments in pulsed high magnetic fields.

2. Design and experimental setup

Figure 1 shows the sketch of the measurement setup with the cryostat. The outer diameter of the tail is 17 mm, which is 4 mm less than the inner diameter of the pulsed magnet (the magnet bore has a diameter of 21 mm). The distance from the top of the magnet to the center region of the coil is 124 mm. The length of the tail is 500 mm, which ensures that samples can be inserted into the homogenous field area of the magnet.

As shown in figure 1, the pulsed magnet, the LN$_2$ Dewar, the tail of the $^4$He bath cryostat and the sample insert are concentric. The pulsed magnet and the lower part of the cryostat are immersed in liquid nitrogen which is stored in the open LN$_2$ Dewar. The sample chamber in the insert is located at the center of the pulsed magnet.

In the cryogen recondensing cooling system and the $^4$He bath cryostat, the helium gas is supplied by a standard 40 liters helium gas cylinder-1 equipped with a pressure regulator. The helium gas inlet valve controls the rate of the helium flow. A pressure gauge, which is connected to the helium gas supply line with a thin tube, measures the pressure in the $^4$He bath cryostat and helium recondensing cooling system. Before the cryostat cooled down and filled with sufficient liquid helium, the warm helium gas is precooled successively by the heat exchanger mounted on the first stage cylinder, the first stage cold head and the heat exchanger mounted on the second stage cylinder. The cooled helium gas is liquefied in a helium condenser that is mounted on the end of the second stage cold head. Liquid helium flows to the $^4$He bath cryostat through the LHe inlet line which is a vacuum insulated flexible transfer line. When...
the liquid helium in the $^4$He bath cryostat can meet the needs of cooling the sample insert, the helium gas inlet valve is closed. The helium gas evaporated from the $^4$He bath cryostat is recondensed by the cooling system based on a GM cryocooler. The cryogen recondensing cooling system and the $^4$He bath cryostat work in closed cycle. The cryostat retains a constant liquid level, as a result there is no need to refill liquid helium or helium gas for long operating periods.

At the bottom of the insert, there is a vacuum space between the inner tube and outer tube for separating the liquid helium in sample chamber from the $^4$He bath. The helium gas in the insert, which is supplied by a standard 40 liters helium gas cylinder-2 equipped with a pressure regulator, is liquefied by bringing the helium gas in thermal contact with the $^4$He bath. The $^4$He bath also offers a thermal barrier and heat sink to minimize the conductive and radiative heat load on the sample space. To eliminate the eddy current heating during the pulse, the inner layer of the $^4$He pot is made of fiberglass tubes. The material of the other parts is stainless steel. The inner tube is coated with Stycast 1266TM epoxy, and bonded with the upper tube of the sample insert using epoxy. In order to obtain temperatures below 4.2 K, a vacuum pump is used to pump the helium gas in the insert through the pumping line.

In order to provide an adiabatic environment, there are two vacuum jackets, which is respectively mounted at outside of the cryogen recondensing cooling system and the $^4$He bath cryostat. The temperature is measured and controlled by a calibrated Cernox temperature sensor (Lake Shore, model CX-1010) and a cryogenic temperature controller (Lake Shore, model 331).

Figure 2 shows a photo of the measurement setup with the recondensing cooling system. The facility consists of the recondensing cooling system, $^4$He bath cryostat, the sample insert system, the pulsed magnet, the LN$_2$ Dewar, some measuring devices, the coaxial current lead and some supporting parts for the magnet.

![Figure 2. Photo of the measurement setup with the recondensing cooling system.](image)

3. Test results
After pumping for about 3 days on the vacuum-insulated chambers of the cryogen recondensing cooling system and the $^4$He bath cryostat, the vacuum was below $1.0 \times 10^{-3}$ Pa due to the large outgassing from the inner and outer surface of the chamber. The space insert, the cryogen recondensing cooling system and the $^4$He bath cryostat were flushed with helium gas three times through the helium gas inlet valves. The inlet gas pressure in the system was maintained at 0.5 bar by adjusting the pressure regulator.

Figure 3 shows the time dependence of the measured temperatures of cold heads in the cryogen recondensing cooling system during cool-down from room temperature to normal working temperature. The experimental procedure was as follows: inserting the $^4$He bath cryostat into an open liquid nitrogen Dewar, transferring liquid nitrogen to this Dewar until the level was above the bottom flange of the
cryostat, then opening the helium gas inlet valve and setting the pressure at 0.5 bar. The first stage cold head was cooled down to below 35 K after operating the GM cryocooler for about 2 hours. After about 20 hours, the second stage cold head became 4 K and liquid helium appeared in the condenser; the liquid helium flowed to the ⁴He bath cryostat through the vacuum insulated LHe inlet line. The volume of the ⁴He bath cryostat is about 12 liters. After another 20 hours, the cryostat was full of liquid helium. Then, closing the helium gas inlet valve, the cryogen recondensing cooling system and the ⁴He bath cryostat worked in closed cycle without helium input.

![Cooling curve of cold heads in the recondensing cooling system.](image1)

**Figure 3.** Cooling curve of cold heads in the recondensing cooling system.

Figure 4 shows the time dependence of the measured temperature of the sample chamber in the insert during cool-down to 1.2 K. After operating the recondensing cooling system for about 25 hours, the outside of the insert was surrounded with liquid helium, and the temperature was about 4 K. Then, the helium gas was inputted to the insert. About 10 minutes later, after closing the helium gas inlet valve and starting the vacuum pump, the sample temperature decreased quickly to 1.2 K.

![Cooling curve of sample chamber in the insert.](image2)

**Figure 4.** Cooling curve of sample chamber in the insert.

Figure 5 shows the temperature stability details at 1.2 K, which demonstrates that the sample temperature can be kept at 1.2 K for 2 hours. The cooling time between two 60 T pulses is about 30-40
minutes [5]. The time interval in which the temperature is stable is long enough for many times of scientific experiments in the pulsed high magnetic field.

![Temperature stability details at 1.2 K](image)

**Figure 5.** Temperature stability details at 1.2 K

### 4. Conclusions

A cryogen recondensing cooling system for use with a pulsed high magnetic field up to 60 T was designed and fabricated using a small GM cryocooler. The main results are as follows:

The outer diameter of the system’s tail is 17 mm, which can be used in a 60 T pulsed magnet. The temperature of sample chamber can be kept at 1.2 K for 2 hours. The experimental results show that the lowest temperature of this system, the length of time for maintaining the lowest temperature and the temperature stability of this system satisfy the scientific experiment requirements in the pulsed high magnetic field. This type of cryogen recondensing cooling system can be widely used in the cryogenic measurement of magnetization, electric transport behavior and Hall resistance experiments in a pulsed high magnetic field, without refilling liquid helium.

### References

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