Temperature oscillation suppression of GM cryocooler

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Abstract. GM cryocooler is a convenient refrigerator to achieve low temperatures about 4 K, while it is not suitable for precise measurements because of the large temperature oscillation of typically about 0.3 K. To resolve this problem, we have developed an adapter (He-pot) with a simple structure as possible. From the thermodynamic consideration, both heat capacity and thermal conductance should be large in order to reduce the temperature oscillation without compromising cooling power. Optimal structure of the He-pot is a copper cylinder filled with high pressure He-gas at room temperature. This can reduce the temperature oscillation to less than 10 mK below a certain temperature \( T_H \) without compromising cooling power. \( T_H \) are 3.8 and 4.5 for filled He-gas pressures of 90 and 60 atm, respectively. By using this He-pot, GM cryocooler can be applied to such as precise physical property measurements and THz detection.

1. Introduction

Cryogenic environment at around 1 K is required in the various fields such as low temperature physics, THz industry and radio astronomy. Liquid He is usually used to obtain such cryogenic environment. However, since He is a scarce resource, it is desirable to achieve such a low temperature by He-free method. Although GM (Gifford-McMahon) cryocooler is a hopeful candidate, there are two problems that the minimum temperature is limited to about 3 K, and large temperature oscillation \( T_{OSC} \) exists [1]. For the former problem, we have successfully developed a method of lowering temperature down to 0.3 K by a simple way in our preceding paper [2]. The purpose of this study is to reduce \( T_{OSC} \) of GM cryocooler by the simplest method as possible. In order to achieve this, we have attempted to attach an adapter (He-pot) to the bottom of the cooling head.

If a material with poor thermal conductivity is mounted on the cooling head, \( T_{OSC} \) can be reduced, but it weakens the cooling power. Consider the optimal conditions for reducing \( T_{OSC} \) without compromising cooling power. Fig. 1 shows a schematic diagram of an adapter attached to the cooling head. Let the cooling head and adapter temperature be \( T \) and \( T_0 \), respectively. If heat is not applied to the adapter, heat flow \( \dot{Q} \) is proportional to the temperature difference \( T - T_0 \), i.e.,

\[
\dot{Q} = K(T - T_0),
\]
where proportional constant $K$ is expressed by using thermal conductivity $\kappa$:

$$K = \frac{A}{L(T - T_0)} \int_{T_0}^{T} \kappa(T) dT.$$  

where $A$ and $L$ are the cross section and length of the adapter, respectively.

If heat $W$ per second is applied to the adapter, from (1) we obtain

$$W - \dot{Q} = W - K(T - T_0) = \frac{dQ}{dt} = C \frac{dT}{dt}.$$ (2)

Since $dT/dt = 0$ in the steady state, $T - T_0$ is proportional to $1/K$. In addition, $dT/dt$ is proportional to $1/C$ from (2). Therefore, in order to reduce $T_{OSC}$ without compromising cooling power, the material has to possess large $K$ and $C$. In order to achieve this, we have developed a He-pot, that is, copper container with large thermal conductivity into which high pressure He-gas with large heat capacity is compressed at room temperature.

2. Experimental procedure

Figure 2 shows an entire drawing of the He-pot attached to a GM cryocooler, which has two-stage. The 1st stage has a cooling power of 40 W at 50 K. The 2nd stage that cools the sample (cooling head) has a cooling power of 0.5 W at 4 K. The minimum temperature of the cooling head attains $\sim$3 K under the no-heat-load condition. The He-pot was made of copper filled with high pressure He-gas at room temperature. The He-pot was filled up with He-gas through a copper tube outer diameter of $\phi$3 from high pressure He-cylinder. Then, the thin copper pipe was beaten to be thinned and cut with nippers, and finally the cutting face was silver soldered. Silver solder can withstand a pressure of about 100 atm. Some He-pots were made to examine the pressure effect. A resistance thermometer was glued to the bottom of the He-pot.

3. Results and Discussion

We first examine how much pressure a copper cylindrical container can stand. The inset in Fig. 3 shows a longitudinal section of a He-pot. Strength of the cylinder is almost determined by the

Figure 1. Schematic diagram of the adapter mounted on the bottom of the cooling head of GM cryocooler. $T_0$ is the cooling head temperature, $T$ the the adapter temperature, $\dot{Q}$ heat flow from the adapter to the head, $W$ the heat applied to the adapter per unit time, $K$ the thermal conductivity of the adapter, and $C$ the heat capacity of the adapter.

Figure 2. The entire drawing of the present system (right) and enlarged around the He-pot (left).
ratio of inner- to outer-diameter $w=q/p$. Fig. 3 shows the pressure dependence of the strain $\epsilon$ of the container for $w=1.078$ ($p=51$, $q=55$) and $w=1.429$ and ($p=21$, $q=30$). At $w = 1.078$, the container begins to be distorted at about 10 atm, and $\epsilon$ attains 2.5% at 60 atm, and the container does not return to the original shape even though the pressure returns to ambient pressure again. At $w=1.429$, the container is not distorted at 90 atm within the experimental error. This result consists with the strength calculation. Therefore, at $w=1.4$, the container can stand up to about 100 atm which is the limit of durability of silver solder.

![Figure 3](image1.png)

**Figure 3.** He-gas pressure dependence of the strain $\epsilon$ for two different He-pots at room temperature. The inset shows a longitudinal section of the He-pot. He-pot is a cylindrical shape made of copper, where $p$ is the inner diameter, $q$ the outer diameter, and $w (=q/p)$ the ratio of the inner- to outer-diameter.

Figure 4 shows the temperature dependence of $T_{OSC}$ for various He-pots filled with He-gas pressure $P_{RT}$ at room temperature, together with that of $T_{OSC}$ for the cooling head. The $T_{OSC}$ of the cooling head is about 0.3 K at 3.5 K, while that at $P_{RT}=0$ atm comes to about 2/3. $T_{OSC}$ at $P_{RT}=30$ atm is about half of that at $P_{RT}=0$ atm. $T_{OSC}$ at $P_{RT}=60$ and 90 atm is almost identical to that at $P_{RT}=30$ atm above $T_H=3.8$ and 4.5 K, respectively. $T_{OSC}$ decreases abruptly below $T_H$. As an example of $T_{OSC}$ below $T_H$, Fig. 5 shows the time variation of $T_{OSC}$ of the He-pot and the cooling head of GM cryocooler at 3.5 K and at $P_{RT}=90$ atm. We can easily see that the He-pot reduces $T_{OSC}$ from ~0.3 K to ~10 mK. $T_{OSC}$ below $T_H$ is nearly independent of the He-gas pressure at room temperature, though there may be some pressure dependence because of experimental resolution of 10 mK. Similar temperature dependence was also observed at $P_{RT}=80$ atm, where the He-pot at $P_{RT}=80$ atm is half as high as those at $P_{RT}=60$ and 90 atm.

![Figure 4](image2.png)

**Figure 4.** Temperature dependence of $T_{OSC}$ of He-pot, for the He-pot pressure at $P_{RT}=0$, 30, 60, 80, and 90 atm. The height of the pot in the case of $P_{RT}=80$ atm is half of the others. The temperature dependence of the $T_{OSC}$ of the cooling head is also shown.
Figure 6. Temperature dependence of the He-pot pressure calculated from the van-der-Waals equation for the case of $P_{RT}=30$, 60 and 90 atm. The curve line indicates the temperature dependence of He vapor pressure.

The characteristic temperature $T_H$ is considered to be a temperature at which He-gas liquefies. We consider this assumption thermodynamically. The equation of state for the real gas is given by the van-der-Waals equation,

$$P = \frac{RT}{V_m} - a \frac{b}{V_m^2},$$

where $P$ is the pressure, $R$ the gas constant and $V_m$ the mol volume. $a$ and $b$ are van-der-Waals coefficients, which are $a=0.0341$ atm·dm$^6$·mol$^{-2}$, $b=0.0238$ dm$^3$·mol$^{-1}$ for He-gas [3]. Figure 6 shows the calculated temperature dependence of the pressure for the He-pot filled with He-gas pressures of 30, 60 and 90 atm at 300 K. The curve in Fig. 6 shows the vapor pressure of He. When the pressure in the He-pot is greater than the vapor pressure, He-gas is considered to liquefy. The temperatures derived from the intersection at $P_{RT}=30$, 60 and 90 atm are 3.16, 3.78 and 4.2 K, respectively, which are nearly the same as $T_H$. Therefore, $T_H$ corresponds to the liquefied temperature. Thus, it is found that liquid He reduces $T_{OSC}$ strongly. Since $T_{OSC}$ below $T_H$ does not depend on both the volume of He and that of He-pot, the principle contribution to reduce the oscillation is only very thin liquid He on the surface of the He-pot, so that the required condition of the He-pot is to have adequate surface area to reduce $T_{OSC}$.

4. Summary

In order to reduce $T_{OSC}$ of GM cryocooler, we have made a He-pot filled with high pressure He-gas at room temperature. The He-pot is a cylindrical container made of copper, and the ratio of inner- to outer-diameter is $\sim 1.4$. When the He-pot is filled with He-gas at $P_{RT}=90$ atm, it can reduce $T_{OSC}$ to at least 10 mK below $T_H=4.5$ K. The $T_{OSC}$ is nearly independent of the He-pot volume. Thus, the pot size may be smaller. Only using the He-pot attached to the cooling head, we have succeeded in reducing the $T_{OSC}$ of the GM cryocooler without compromising cooling power. Therefore, it is expected that GM cryocooler can be used to applications such as precise physical property measurements and THz detection. We note here that a similar method using a pulse tube cryocooler to reduce temperature oscillation exist [4].

Acknowledgments

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References

[1] Walker G 1983 Cryocoolers (New York: Plenum Press).
[2] Nishioka T, Sumida T, Takesaka T, Kawamura Y, Kato H and Matsumura M 2009 J. Phys.: Conf. Ser. 150 012030.
[3] Atkins P and de Paula J 2009 Atkins’ Physical Chemistry (London: Oxford University Press)
[4] Wang C and Hartnett J G 2010 Cryogenics 50 336.