On the Development of a Non-metallic and Non-magnetic Miniature Pulse Tube Cooler

H.Z.Dang, Y.L.Ju*, J.T.Liang and Y.Zhou

Cryogenic Laboratory, Technical Institute of Physics and Chemistry
Chinese Academy of Sciences, P.O. Box2711, Beijing 100080, China

ABSTRACT

For continuous low-noise cooling of a highly magnetic flux sensitive high-Tc SQUID by using a cryocooler, the cooler systems have to meet rather stringent requirements concerning mechanical vibrations and electromagnetic interferences (EMI). These cooler-generated disturbances must be below the intrinsic noise level of the sensors. Pulse tube cooler (PTC) is an attractive candidate for the SQUID operation due to the absence of mechanical moving parts in the cold head. But the vibrations and EMI noise originated from the metallic-made cold head of a PTC are still enormous obstacles for practical applications.

In the paper, we first analyzed the main sources of interference signals of a PTC system, then a non-metallic and non-magnetic miniature PTC (NNPTC) for the low-noise cooling of high-Tc SQUIDs was designed and fabricated. The cooler itself, including all the components, was entirely made of non-metallic, non-magnetic and electronically insulating materials, in order to reduce the local magnetic fields and eddy currents from the metallic-made cooler. System design of the cooler was described by focusing on the selections of non-metallic, non-magnetic materials in the NNPTC system and dimensional layout of each component. The cryogen-free operation of high-Tc SQUIDs by the NNPTC is under way in our laboratory.

INTRODUCTION

Successful applications of high-Tc Superconducting Quantum Interference Devices (SQUIDs) are strongly tied to the development of satisfactory refrigeration technology. For many years, liquid nitrogen (or liquid helium) was usually used to cool high-Tc SQUIDs. But there exists a lot of intrinsic inconvenience in transferring, supplying low-temperature liquids and operation by them. Especially in some special places, like in space shuttles, which demands a refrigeration system to be free of the impact of directions, or in submarines, which do not allow vaporized gas to pollute the narrow room, thereby the use of low-temperature liquid are restricted or forbidden. In many cases, it is the lack of a satisfactory refrigeration system that hinders the wider acceptance of the high-Tc SQUIDS.

In recent years, many efforts have been made to provide mechanical cooling for high-Tc SQUIDs other than by liquid nitrogen [3]. High-Tc SQUIDs are usually operated in a temperature range between 50 and 80K and require a cooling power of several hundred milliwatts. Now

*Corresponding author: Tel: +86-10-62627302; Fax: +86-10-62564049; Email: yonglin@cl.cryo.ac.cn (Y.L.Ju)

single-stage cryocoolers can meet this relatively “simple” requirement. In fact, the difficulties of providing appropriate mechanical cooling for high-Tc SQUIDs other than by liquid nitrogen filled dewars lie mainly in mechanical vibrations and electromagnetic interferences (EMI) from the refrigeration systems themselves. These cooler-generated disturbances must be below the intrinsic noise level of the SQUIDs. It is an enormous challenge for a cryocooler. For example, the sensitivity of typical SQUIDs used to measure geomagnetic field is 10^{-10} times than the intensity of local magnetic field. Normal commercial cryocoolers can’t be used to cool SQUIDs because their intrinsic noise is so large that the outputs of SQUIDs become meaningless.

Compared with other regenerative cryocoolers such as G-M and Stirling refrigerators, pulse tube cooler (PTC) is a more attractive candidate for SQUID cooling because of the absence of mechanical moving parts in the cold head. The feature has the potential for increased reliability and reduced vibrations. Another problem for the low noise cooling is the EMI noise originated from the magnetic or metallic-made components of cryocoolers. If a PTC, including all the components, can be entirely made of non-metallic, non-magnetic and electronically insulating materials, the EMI noise and eddy currents from the refrigeration system could be reduced to negligible levels. In this paper, the development and design considerations of a new non-metallic and non-magnetic miniature PTC are presented.

MAIN SOURCES OF INTERFERENCE SIGNALS OF A PTC

In general, the main interference signals of a PTC system are of mechanical vibrations and EMI (including magnetic signals and eddy currents). The EMI signals can be caused by additional moving magnetic fields in the proximity of the SQUIDs, or by movement of the SQUIDs in an inhomogeneous field; the mechanical vibrations caused mainly by the vibrations of the system.

In conclusion, the sources of interference signals are mainly as following:

(1). Compressor system;

(2). The vibrations of a PTC system, especially that of the cold head;

(3). The magnetic materials in a PTC system; the eddy currents originated from the movement of the metallic materials of a PTC system in an inhomogeneous field;

Compressor System. The main interference signals originate from compressor system comprises two sources: one is of the EMI noise from the movement of the magnetic or metallic-made components of compressors in magnetic field; the other is of the mechanical vibrations from the moving components of compressor system, which disturb the cold head.

The above two kinds of interference signals can be reduced greatly or eliminated by three approaches as follows:

A. Increasing the distance between the compressor system and the cold head (on which SQUIDs are mounted) so that the EMI signals from it can be reduced greatly.

B. Shielding the compressor system when necessary. The distance between the compressor system and the cold head can not be increased infinitely because the cooling power and the lowest temperature decrease gradually with the distance increasing, so that the EMI signals from the compressor system can not be reduced sufficiently by increasing the distance. In this instance, we may supply a magnetic shielding for the compressor system;

C. Employing flexible plastic or polyimide line for the connection of the coolers to the linear compressor in order to reduce the mechanical vibrations of the compressor system.

The Vibrations of a PTC System. Pressure wave induced elastic oscillations of the pulse tube and cold head are the main source of the periodic interference signals. This kind of “breathing” of the cold head can generate obviously observed signals. For example, in a field gradient of the order of 250 nT/m along the cold head axis (z-direction), a motion of 10 μm will lead to a field variation of about 2.5Pt[2].

The length change of pulse tube ΔL can be determined by Hooker’s law [6]:

$$\Delta L=(L\cdot r\cdot \Delta p)/(2\cdot E\cdot h) \tag{1}$$

Where, L is the length of the pulse tube, r is the radius of the pulse tube, Δp is the peak-to-peak pressure amplitude, E is the Young's Modulus, h is the wall thickness of the pulse tube.

ΔL is a linear function of the Δp. When tube dimension and materials are determined, reducing Δp to some extent can damp the periodic interference signals without degrading the performance of the cryocooler too much.

Another method to further decrease the vibrations is the vibration compensation method [2]. The sensor is mounted on a separate cold platform that is thermally, but not mechanically connected to the cold tip of the PTC. The cold head of the new cold platform is mechanically supported by means of a tube that are fixed at the warm end of the PTC, as described in Ref [2]

The Magnetic Materials and the Eddy Currents. The magnetic materials in a PTC system introduce directly an additional magnetic field to the local magnetic field. The metallic components moving in an inhomogeneous field (for example geomagnetic field) produce inevitably the eddy currents, which can bring interference to the SQUIDs operation. The best solution for them is of avoiding adopting any magnetic or metallic material while manufacturing the PTC. At present, it is a crucial and unavoidable problem in designing and fabricating a non-magnetic PTC, unfortunately, there is little work on this challenging subject till now.

The main components of a PTC include pulse tube, regenerator tube, connecting flanges, cold head, regenerator matrix, flow straighteners, and vacuum chamber. In this paper we focus our attention on designing and fabricating all of them by using non-magnetic and non-metallic and electrically insulating materials.

DESCRIPTIONS OF SYSTEM DESIGN

Experimental Set-up

We adopted co-axial configuration for our NNPTC in order to minimize the size of the cryocooler, which is the most compact and convenient for the connection with the cooled sensors. A schematic diagram of specially designed for the cryogen-free operation of SQUIDs is shown in Figure 1.

Selections of Materials

Pulse Tube and Regenerator Tube. Thin stainless steel tubes are widely used for pulse tube and regenerator tube. However, stainless steel exhibits marked remnant magnetization. For example, the magnetic susceptibilities of most stainless steels at temperature about 77K are greater than 1.02. Therefore, one recommended Ti-Al3-V2.5 [2] and glassfilled epoxy resins [1] instead of stainless steel. Ti-Al3-V2.5 exhibits very weak magnetization, but it still belongs to metallic material, so that the eddy currents remains as a severe problem for the high sensitive SQUIDs; Glassfilled epoxy resin is a kind of non-magnetic and non-metallic material, however, due to its intrinsic molecular structure, the high-pressured helium gas will diffuse unavoidably, which has been proved by our experiments. We had ever designed and fabricated a regenerator tube with an inner diameter of 11mm, a wall thickness of 2 mm and a length of 52 mm by using glassfilled epoxy. When the charge pressure of working helium gas was about 1.6 MPa, obvious diffusion from the tube wall was detected. In addition, the mechanical strength of this kind of material is not satisfactory.

In our experiments, the regenerator tube is made of a special machinable ceramic and the pulse tube of Nilon1010. As shown in Figure1, the pulse tube is assembled inside the annular regenerator tube. The regenerator tube has an inner diameter of 11mm, a wall thickness of 1.25mm and a length of 52mm. The pulse tube has an inner diameter of 5.5mm, a wall thickness of 0.5mm and a length of 65mm.

The main properties of the machinable ceramic are shown in Table 1. It should be pointed out that the diffusion of helium through the machinable ceramic tube is almost the same as that of stainless steel, and the axial thermal conduction losses from the hot end to the cold end are

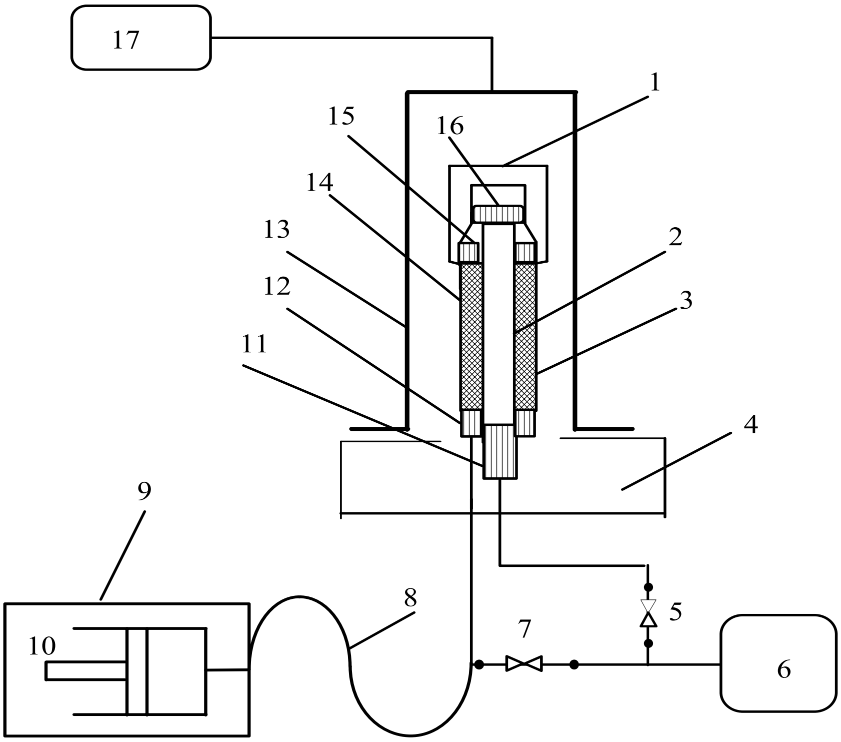

Figure 1. Schematic diagram of the Coaxial Non-Magnetic and Non-Metallic Pulse Tube

1.Cold head; 2.Pulse tube; 3.Regenerator tube; 4. Hot end flange; 5.Throttling orifice; 6.Gas buffer; 7.double-inlet tube; 8.Flexible tube; 9. Shielding metal; 10. Compressor; 11. Flow straightener; 12. Flow straightener; 13. Vacuum chamber; 14. Regenerator matrix; 15. Flow straightener; 16. Flow straightener; 17. vacuum pump

also reduced greatly due to its much lower thermal conductivity than that of stainless steel (13 W/m. K @ 200K).

Cold Head. The cold head is usually directly coupled to the cooled SQUIDs, so it has the strongest impact on the sensors. Therefore, the selection of the materials of cold head is much more crucial. Pure copper is often used in a common commercial PTC to make cold head due to its high thermal conductivity. However, for high sensitively cooing SQUIDs, it is obviously unsuitable because of the eddy currents problem, which has been tested experimentally by Gerster [1]. Pure titanium was ever recommended due to its weaker magnetization [2], but it can't eliminate eddy currents since titanium is still a kind of metal. Gerster et al [1] ever reported that they made a solid cold tip of polycarbonate, then glued 17 pieces M1.6 threaded pin made of aluminum into the polycarbonate cold tip to guarantee sufficient heat transportation. Although it damped the eddy currents greatly compared with traditional metallic cold head, the impact of eddy currents was not eliminated completely because of the metallic material (aluminum). In order to make an ideal cold head for a nonmagnetic PTC, the material should be completely nonmagnetic, nonmetallic, and electrically insulating. In addition, it should have relatively high thermal conductivity for the heat transfer between the cold head and the SQUIDs. After carefully considerations, a special boron nitride ceramic is adopted for the cold head.

The main properties of the boron nitride ceramic are shown in Table 2. Another advantage of the boron nitride ceramic is easy fabrication. The cold head is designed to a columnar shape so that it can be glued with the outer wall of regenerator tube conveniently. The cross section of the cold head is showed in Figure 2.

Regenerator Matrix. The magnetic impurities, induced eddy currents, and thermally activated currents in metallic regenerator could produce considerable magnetic disturbances [1]. An important task in designing and fabricating a NNPTC is to find a kind of regenerator material, which should be non-magnetic, non-metallic, and electrically insulating, and not degrade the efficiency of the cryocooler with respect to the dimensions of the regenerator housing. A lot of

Table 1. The properties of the machinable ceramic

Density (g/cm^3)	2.65
Thermal conductivity (W/m. K)	1.5
Thermal elongation coefficient (/□)	≤94□10^{-7}
Working temperature range (□)	-273-1000
Magnetic susceptibility	≤1.2□10^{-6}
Compressive strength (MPa)	≥491
Tensile strength (MPa)	≥98
Bending strength (MPa)	≥108

Table 2. The properties of the boron nitride ceramic

Density (g/cm^3)	2.0
Thermal conductivity (W/m. K)	54
Thermal elongation coefficient (/□)	1.8~2.0□10^{-6}
Working temperature range (□)	-273-2000
Magnetic susceptibility	≤1.0□10^{-7}
Bending strength (MPa)	60~80

different materials have been tested experimentally, and the screens made of PA6.6 and Teflon are found to be competent, as described in Ref [1,4]. In fact, these two kinds of materials are satisfactory to some extent, and many efforts have been carried out in our laboratory to find the better one. It will be reported in other papers. In our experiments, the regenerator matrix consists of a stack of 350-mesh PA6.6 screens, which are annular in shape, and placed concentrically between the pulse and regenerator tubes (see Figure 1).

Connecting Flanges, Vacuum Chamber and Flow Straighteners. In a common pulse tube cryocooler, stainless steel is usually used to fabricate the connecting flanges and vacuum chamber. In order to replace the material exhibiting marked remnant magnetization, acrylic glass is used which is a kind of non-metallic, non-magnetic and electronically insulating material, and its mechanical strengths can meet the requirements of vacuum chamber and connecting flanges.

In the NNPTC system, we have designed four flow straighteners. Two of them are placed at the inlets of the pulse tube and the regenerator tube, and the other two are located at outlets of

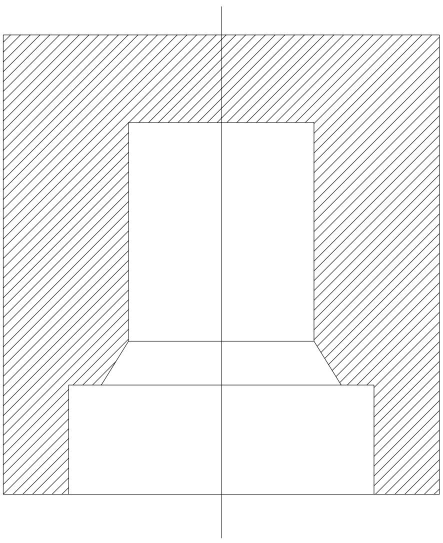

Figure 2. Cross-section of the cold head

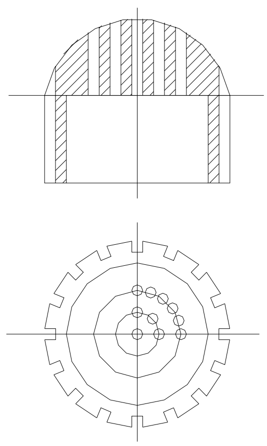

Figure 3. Cross section of the flow straightener16

them. All of the straighteners are made of polytetrafluoroethylene plastic other than the traditional copper or stainless steel to eliminate the impacts of the magnetic impurities and eddy currents. Flow straightener 16 is placed between the cold head and the pulse tube (as shown in Figure1). It is vaulted shape with some serried holes at the bottom and well-proportioned grooves in the outer wall (see Figure 3) so that the gas flows straightly and evenly.

Adhesive technology. As shown in Figure 1, both the cold head and the flange at the hot ends are connected to the regenerator tube by a kind of special synthetic epoxy resin adhesive named DW-3, which can be used at the temperature between -269℃～+60℃ to bond various kinds of metallic and non-metallic materials with different expansion coefficients. The lower the temperature, the higher the adhesive strength.

Compressor System. In our experiments, we use a linear compressor with a swept volume of 2cc. To reduce EMI signals from compressor system, the connection flexible line between the compressor system and the cold head can be as long as 1.5m. The flexible tube has an inner diameter of 2mm and a length of 2m. The compressor system is shielded by μ-metal plates to eliminate its EMI signals (see Figure1).

Others. The working fluid is pure helium gas, and the operating frequency of the compressor is around 50Hz. The charge mean pressure is from 1.6 to 2 Mpa.

CONCLUSIONS

A non-metallic and non-magnetic miniature coaxial pulse tube cryocooler for cooling high-Tc SQUIDs has been designed and fabricated. All of the components of the PTC are fabricated with non-magnetic and non-metallic and electrically insulating materials to minimize EMI signals. The regenerator tube is made of a kind of special machinable ceramic without diffusion of helium into the vacuum chamber and less thermal conduction loss. The pulse tube is made of Nilon1010 and the regenerator matrix consists of a stack of 350-mesh PA6.6 screens. The connecting flanges at the hot ends and the vacuum chamber are made of acrylic glass. The cold head is made of a special boron nitride ceramic with high thermal conductivity. Both the cold head and the flange at the hot ends are connected with the regenerator tube by a kind of special synthetic epoxy resin adhesive, and all of flow straighteners are made of polytetrafluoroethylene plastic.

Three approaches were employed to eliminate the interference signals originated from compressor system: increasing the distance between the compressor system and the cryocooler; shielding the compressor system; fabricating the tube linking the compressor system to the cryocooler by flexible materials.

The cryogen-free operation of high-Tc SQUIDs by the NNPTC is under way in our laboratory, and detailed experiment data will be presented later.

ACKNOWLEDGMENT

This work is funded by the National Natural Science Foundation of China (Grant No. 50176052) and the Chinese Academy of Sciences.

REFERENCES

1. Gerster, J., Kaiser, G., Reibig, L., Thurk, M., and Seidel, P., "Low Noise Cold Head of a Four-Valve Pulse Tube Refrigerator," *Advances in Cryogenic engineering,* Vol. 43(1998), pp. 2077-2084.
2. Lienerth, C., Thummes, G., and Heiden, C., "Progress in Low Noise Cooling Performance of a Pulse-Tube Cooler for HT-SQUID Operation," *ASC 2000,* Virginia USA Paper: 3EF04(2000), pp. 353-362

3. Heiden, C., "Pulse Tube Refrigerators: a Cooling Option for High-Tc SQUIDs," *SQUID Sensors: Fundamentals, Fabrication and Applications,* Kluwer Academic Publishers, Netherlands (1996), pp. 289-305.
4. Gerster, J., Krause, J., Thurk, M., and Seidel, P., "Use of Polymer Materials for the Regenerator of a Pulse Tube Regenerator," *ICEC17* (1998), pp. 97-100
5. Thummes, G., Landgraf, R., Giebeler, F., Muck, M., Heiden, C., "Pulse Tube Refrigerator for High-Tc SQUID Operation," *Advances in Cryogenic engineering,* Vol. 41(1996), pp. 1463-1470.
6. Lienerth, C., Thummes, G., and Heiden, C., "Low-Noise Cooling of HTc-SQUIDs by Means of a Pulse-Tube Cooler with Additional Vibration compression," *ICEC18* (2000), pp. 555-558