Design and Construction of a Non-magnetic and Non-metallic Miniature Pulse Tube Cooler

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The pulse tube cryocoolers (PTCs) are promising candidates for SQUIDs cooling because of the increased reliability and reduced vibrations. But the Electromagnetic Interference and eddy currents originated from the metallic-made components of PTCs are still enormous obstacles for practical applications. The paper first analyzed the main sources of interference signals of a PTC system, and found solutions to minimize and/or eliminate them. Then a non-metallic and non-magnetic miniature PTC (NNMPTC) for the low-noise cooling of high-Tc SQUIDs was designed and fabricated. The cryogen-free operation of high-Tc SQUIDs by the NNMPTC is currently underway.

INTRODUCTION

In many cases, it is the lack of a satisfactory refrigeration system that hinders the wider acceptance of the high-Tc SQUIDs, which demand that the system-generated disturbances must be below the intrinsic noise level of the sensors. For many years, liquid nitrogen (or liquid helium) was usually used to cool high-Tc SQUIDs. But many disadvantages exist in transferring, supplying low-temperature liquids and operation by them. And in some special places, the use of low-temperature liquids is restricted or forbidden. So providing appropriate low-noise cryocooler for a high-Tc SQUID other than by liquid nitrogen filled dewars is highly desirable.

Compared with other traditional regenerative cryocoolers such as G-M and Stirling coolers, the pulse tube cryocoolers (PTCs) are more promising candidates for low noise cooling of high-Tc SQUIDs because they offer the advantage of having no moving parts in the cold finger and thus have the potential for mechanical simplicity and reduced vibrations. But the Electromagnetic Interference (EMI) and eddy currents originated from the metallic-made components of a PTC are still enormous obstacles for practical applications. It is a crucial and unavoidable problem in designing and fabricating a PTC for high-Tc SQUIDs operation, unfortunately, little work has been published so far on this challenging subject.

Here we first analyze the main sources of interference signals of a PTC system and find solutions to minimize and/or eliminate them, then report on the design and construction of a non-metallic and non-magnetic miniature PTC (NNMPTC) for the low-noise cooling of high-Tc SQUIDs.

DESIGN CONSIDERATIONS

High-Tc SQUIDS are usually operated in a temperature range between 50 and 80K and require a cooling power of several hundred milliwatts. This requirement is relative simple for even a single-stage PTC nowadays. The key problem is how to damp the EMI noise and eddy currents originated from the magnetic or metallic-made components of cryocoolers being below the intrinsic noise level of the SQUIDs. It is an enormous challenge for the PTCs because the noise from a common metallic-made PTC

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will be so large that the outputs of SQUIDs become meaningless.

Main interference sources of a PTC system

The main interference signals of a PTC system are of mechanical vibrations and EMI and eddy currents. The sources of the signals are mainly as following:

(1). Compressor system. The main interference signals originated from the 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.

(2). Gas pressure oscillation in a PTC system. The elastic oscillations of the pulse tube and cold head induced by pressure wave are the main source of the periodic interference signals [1]. 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].

(3). The magnetic materials in a PTC system and the eddy currents originated from the movement of the metallic materials of a PTC system in an inhomogeneous field. Nowadays almost all the components of a PTC are made of metallic and magnetic materials, such as stainless steel tubes, copper cold head and regenerator matrix composed by a stack of stainless screens, and so on. 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 produces inevitably the eddy currents, which can bring interference to the SQUIDs operation.

Solutions for the interference

The interference signals originated from compressor system can be reduced greatly or eliminated by three approaches: increasing the distance between the compressor system and the cold head on which SQUIDs are mounted so that the EMI signals from the compressor can be reduced greatly; shielding the compressor system by μ-metal; employing flexible plastic or polyimide line for the connection of the coolers to the compressor in order to reduce the mechanical vibrations of the compressor system.

Two approaches are employed to minimize the vibrations of a PTC system. The length change of pulse tube ΔL is a linear function of the peak-to-peak pressure amplitude Δp[2], so after 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][3]. 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 for the interference from the metallic and magnetic materials, the best solution is fabricating a PTC, including all the components, completely with non-metallic, non-magnetic and electronically insulating materials so that the EMI noise and eddy currents can be reduced to negligible levels. Here we report on the design details to achieve the goal.

DESIGN DETAILS

Experimental Set-up

We adopt 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. The experimental set-up and the main components chosen are shown in Figure 1 and Figure 2, respectively.

Selections of Materials

Pulse Tube and Regenerator Tube: Many kinds of widely used materials have been investigated. Thin stainless steel tubes exhibits marked remnant magnetization, Ti-Al3-V2.5 [2] belongs to metallic materials, so it can't eliminate the impact of the eddy currents. Glassfilled epoxy resins [4] 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. In addition,

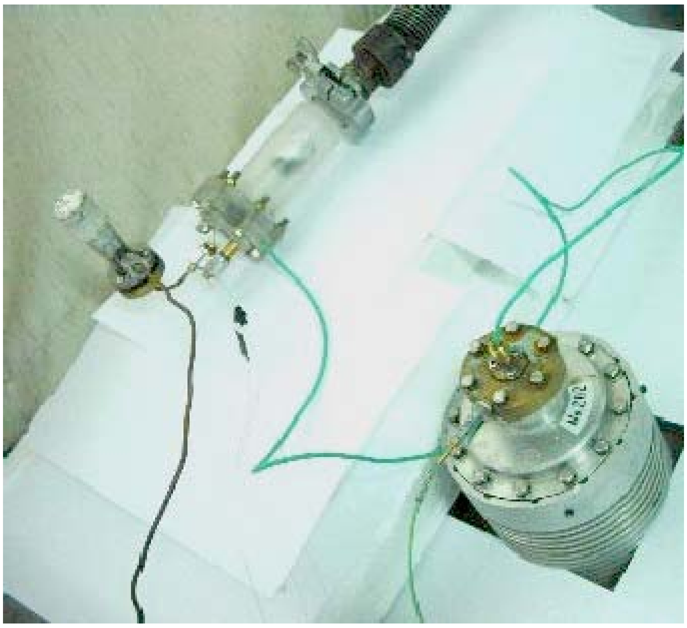

Figure 1 Experimental set-up of the NNMPTC

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. The regenerator tube has an inner diameter of 11mm, a wall thickness of 1.25mm and a length of 52mm. The main properties of the machinable ceramic are shown in Table 1.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 also reduced greatly due to its much lower thermal conductivity than that of stainless steel.

Cold Head: Pure copper is widely used to fabricate a cold head in a common PTC due to its high thermal conductivity. However, for high sensitively cooing SQUIDs, the eddy currents induced by it remains as a severe problem [4]. Pure titanium was ever recommended due to its weaker magnetization [3], but it can't eliminate eddy currents. Gerster et al [4] 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 aluminum. In our experiments a special boron nitride ceramic is chose because it is nonmagnetic, nonmetallic, electrically insulating and has considerable thermal conductivity. In addition, it is machinable and can be fabricated into more complicated shapes. The main properties of the boron nitride ceramic are shown in Table 1.

Figure 2 The nonmetallic and nonmagnetic components

Regenerator Matrix: The magnetic impurities, eddy currents, and thermally activated currents in metallic regenerator could produce considerable magnetic disturbances [4]. The ideal regenerator material 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 different materials have been tested experimentally, and the screens made of PA6.6 and Teflon are found to be competent, as described in Ref [4,5]. 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.

Table 1 The properties of the machinable ceramic and the boron nitride ceramic

	Machinable ceramic	Boron nitride ceramic
Density (g/cm^3)	2.65	2.0
Thermal conductivity (W/m. K)	1.5	54
Thermal elongation coefficient (/□)	≤94□10^{-7}	1.8~2.0□10^{-6}
Working temperature range (□)	-273-1000	-273-2000
Magnetic susceptibility	≤1.2□10^{-6}	≤1.0□10^{-7}
Compressive strength (MPa)	≥491	
Tensile strength (MPa)	≥98	
Bending strength (MPa)	≥108	60~80

Connecting Flanges, Vacuum Chamber and Flow Straighteners: In order to replace the material exhibiting marked remnant magnetization, acrylic glass is selected, which is non-metallic, non-magnetic and electronically insulating, and whose mechanical strengths can meet the requirements of vacuum chamber and connecting flanges. Four flow straighteners are used in the system and all of them are made of polytetrafluoroethylene plastic other than the traditional copper or stainless steel.

Adhesive technology: 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, which can be used at the temperature between -269℃～+60℃ to bond various kinds of metallic and non-metallic materials with different expansion coefficients.

In our experiments, a linear compressor with a swept volume of 2cc is used. To reduce EMI signals from the 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. The working fluid is pure helium gas, and the operating frequency of the compressor is around 50Hz. The charge mean pressure is from 2.0 to 3.0Mpa.

CONCLUSIONS

The main sources of interference signals of a PTC system are analyzed and solutions to minimize and/or eliminate them have been found. Three approaches are employed to eliminate the interference signals originated from compressor system, and the two methods are adopted to damp the vibrations of the PTC system. 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. Both the cold head and the flange are glued with the regenerator tube by a special epoxy resin adhesive. The cryogen-free operation of high-Tc SQUIDs by the NNPTC is currently underway in our laboratory, and detailed experiment data will be presented later.

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