Interference characterization of Stirling-type nonmagnetic and nonmetallic pulse tube cryocoolers for high-Tc SQUIDs operation

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

Cryogenics Laboratory, P.O. Box 2711, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100080, P.R. China

In order to achieve portable low-noise cryogen-free cooling systems for continuous high-Tc SQUIDs operation and realize their direct coupling with the sensors, Stirling-type non-magnetic and non-metallic pulse tube cryocoolers (NNPTCs) have been developed and a series of experiments performed. The optimizations of the cooler geometry and working parameters have been carried out. The design and optimization of the system are described, and the analysis and evaluation of the typical cooling performance and interference characterization of the new-type pulse tube coolers are presented.

INTRODUCTION

Superconducting Quantum Interference Devices (SQUIDs) are the most sensitive magnetic flux-to-voltage sensors known so far and have developed a wide variety of important applications [1]. In 1970's, the concept of supplying a cryogen-free mechanical cooling system for low-Tc SQUIDs were proposed and reduced to practice. In the late 1980's, the advent of high-Tc SQUIDs relaxed the cooling requirements, and many attempts have been made to cool high-Tc SQUIDs by various types of cryocoolers from then on.

GM and Stirling cryocoolers were ever the workhorse for cooling high Tc SQUIDs. But the moving displacers introduce severe mechanical vibrations and electro-magnetic interference (EMI) signals, which are often fatal for the SQUID operation, so that the coolers have to be separated from the sensors in time or space, which is named as *time-separation* or *space-separation* method accordingly. T*ime-separation* method results in the non-continuous operation of SQUIDs, while the *space-separation* method usually significantly adds to the incompactness and complexity of the system. Compared with the two conventional regenerative cryocoolers, pulse tube cryocoolers (PTCs) are more attractive candidates for high Tc SQUIDs cooling because of the absence of moving parts at low temperatures, which introduces much less mechanical vibrations and EMI. Therefore, there exists the possibility of continuous operation of SQUID sensors when they are near or even attached directly to the coolers. According to the drivers, PTCs could be divided into "Stirling-type" and "G-M type". Stirling-type PTCs have advantages over their G-M type counterparts in terms of compactness, flexibility, portability and low vibration, due to the much smaller volume and much lighter weight (a reduction in volume or weight by a factor of above 5-10) and the absence of rotary valves, which adds the possibility of the direct coupling. Therefore, we attempt to develop a better cooling system for high Tc SQUIDs based on Stirling-type PTCs other than GM type ones.

NNPTCS, THE WAY TO REALIZE THE DIRECT COUPLE

An intractable problem has to be solved in advance to realize the direct coupling of the SQUIDs with the cooler. Nowadays metallic materials or materials that exhibit marked remanent magnetization are widely used to fabricate the cooler components. The magnetic components introduce direct magnetic interferences, and the metallic ones in the vicinity of the SQUID pick-up loops could generate Johnson noise and then cause distortion of environmental fields. To solve the intractable problem in a simple and advisable way, we fabricate all key components of the PTCs by non-magnetic, non-metallic and electrically insulating materials. Based on a series of systematical experiments, we chose a special machinable ceramic for the cold heads, and stacked Nylon screens for the regenerator matrix. We fabricate the regenerator tube by a special glassfilled epoxy resin and the pulse tube by a kind of Nylon plastics. The vacuum chambers and connecting flanges are made of acrylic glass, and all straighteners of polytetrafluoroethylene plastic. The types of PTCs are named as NNPTCs for short, and they will eliminate the interference introduced by the materials and could realize the direct coupling with the SQUIDs.

NEGATIVE EFFECT OF NONMETALLIC MATERIALS AND EXPERIMENTAL OPTIMIZATION

It is interesting that the use of nonmetallic materials for tubes and regenerator matrix results in a beneficial byproduct, that is, the axial thermal conduction losses are reduced greatly due to the much lower thermal conductivities [2]. But the selected nonmetallic matrix has a negative effect on the performance of the regenerator. For a given regenerator housing, the volumetric heat capacity of matrix materials, c_m, and the thermal penetration depths in solid matrix are two important factors that influence the performance of regenerators. The c_m indicates how much heat per volume can be stored. We have gotten the variations of c_m of stainless steel and three nonmetallic materials, Nylon, Kapton, and Teflon, with the temperature, as shown in **Figure 1**. The c_m of Nylon is the highest one in the three nonmetallic materials, but it is only about 0.38~0.55 times that of stainless steel at temperature ranges of 60~300 K, which indicates a poorer regenerator performance compared with those of the metallic counterparts.

To avoid no contributing to the effective heat capacity, the thermal penetration depth in the solid should not be smaller than the characteristic matrix dimension. For high-frequency miniature PTCs working at liquid nitrogen temperature ranges, we usually needn't consider the effect of the thermal penetration depth [3]. But for Nylon screens, when the frequencies are between 30~80 Hz and the temperatures between 60~300 K, we could not make sure that all of the wires will contribute toward the effective heat capacity. In order to weaken the negative effect, either lower operating frequency or screens with larger mesh number should be adopted. It is difficult to produce the nonmetallic screens with too large mesh number (such as, more than 500). As for lower frequency, according to calculation [2], when the temperature is between 60~300 K, if we guarantee the same thermal penetration depths, the frequency of the NNPTC should be between 1.575~5.85 Hz, which is impossible for Stirling-type PTCs. So the poor performance of the NNPTCs can be expected, and the optimization of the coolers becomes important.

The optimizations focus on the investigations of the effect of the cooler geometry and working parameters on the cooling performance. For the optimization of cooler geometry, a theoretical model based on the analyses of thermodynamic and hydrodynamic behaviors of gas parcels in the oscillating flow regenerators has been developed, and the preliminary rough scope of optimum dimensions obtained. Then a series of experiments have been performed for the practical design and optimization. In our experiments, the optimum aspect ratio of the regenerator and the pulse tube is 5~6 and 13~16, respectively. The experiments have also been conducted for the optimization of the ratio of the volume of the pulse tube to the void volume of the regenerator, and the optimum value is between 0.5 and 0.6 [2].

Based on the geometry optimizations, a series of experiments have been performed for the optimization of the working parameters, which include the operating frequency, charge pressure, input power, temperature of the hot end, opening of the valves, direction of asymmetric double-inlet valve, orientation of the cold head, etc. For example, we got the frequency dependence of the no-load temperature of the cold head for the coolers, and their optimum operating frequencies are between 36~40 Hz. With the same parameters, the optimum frequencies of the metallic PTCs developed in the same laboratory are around 50 Hz. The lower optimum frequencies may result from smaller heat penetration depth discussed previously.

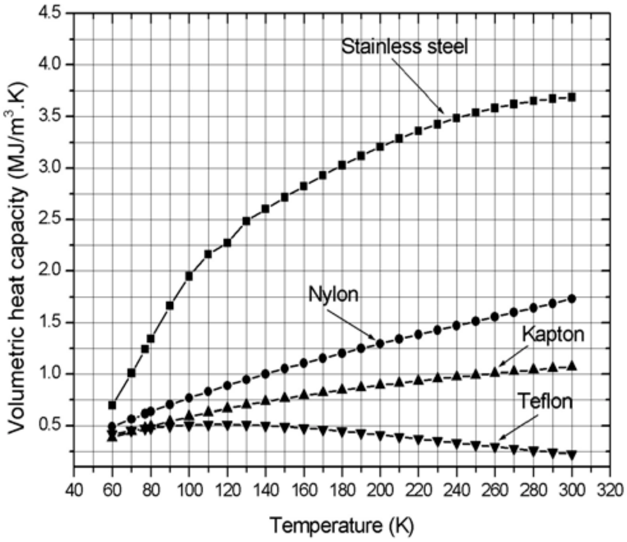

Figure 1. Variations of volumetric heat capacity of the various materials with temperature

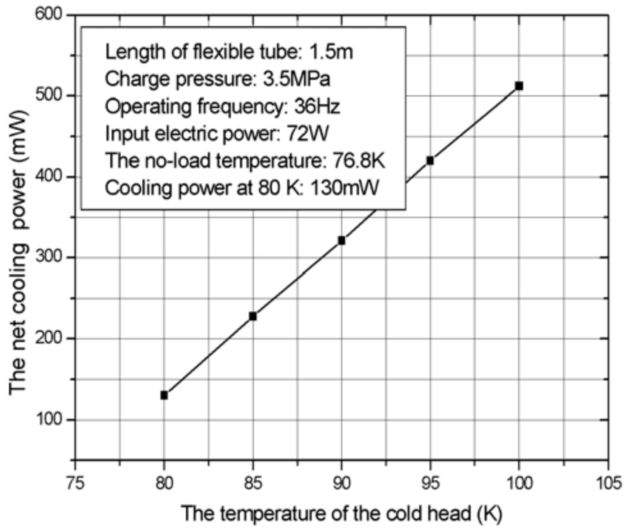

Figure 3. Temperature dependence of the net cooling power of the NNPTC

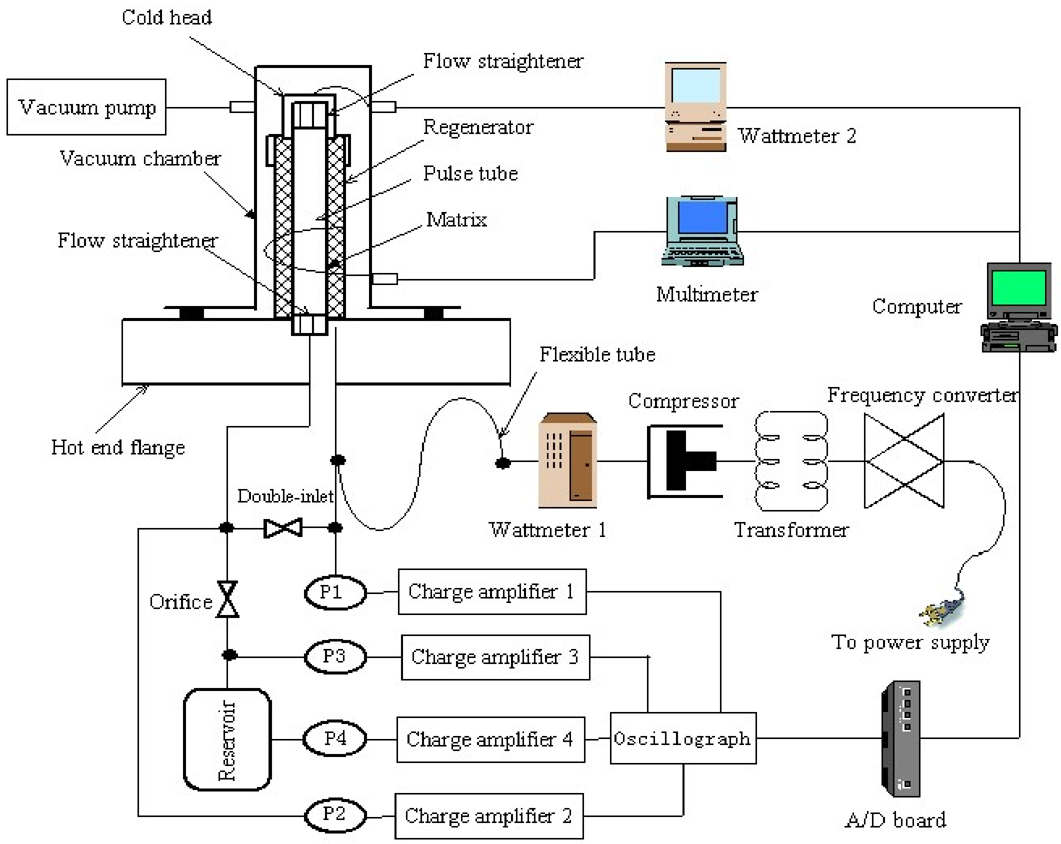

Figure 2. The schematic diagram of the system designed for high Tc SQUIDs.

SYSTEM DESCRIPTION

The schematic diagram of the system specially designed for cooling the high Tc SQUIDs is shown in **Figure 2**. A special synthetic epoxy resin adhesive is used to realize the connection of tubes to the cold head and flanges. The compressor system consists of a frequency converter, a transformer, and a linear compressor. The transformer protects the compressor, and the frequency converter adjusts the operating frequency. To reduce the vibrations generated by the compressor, the connection of it and the NNPTC is realized by a flexible small-diameter tube. The NNPTC is of single stage and coaxial type.

TYPICAL COOLING PERFORMANCE AND INTERFERENCE CHARACTERIZATION

A typical cooling power of over 100mW at 80K with 70 W input electric power for the Stirling-type co-axial NNPTCs developed has been achieved. **Figure 3** shows the temperature dependence of the cooling power of one of the cooler between 80 and 100 K. The efficiency of the NNPTCs at 80 K is about 0.6% of Carnot efficiency, which is much smaller than 4~11%, the corresponding values of their metallic counterparts [3]. The much poorer performance confirms the previous analysis.

The remanent magnetic field and Johnson noise in the NNPTC can be negligible because all the components in the vicinity of the SQUID pick-up loops are made of nonmagnetic and nonmetallic materials. The interferences introduced by the mechanical vibrations include the interference induced by the translation and rotation of the cold head. According to the measurements, the sum is between 50~90 $fT/\sqrt{Hz}$, which is less than the maximum acceptable value of most high Tc SQUIDs (usually 100 $fT/\sqrt{Hz}$). Another troublesome interference is introduced by thermal fluctuations, which affect the London penetration depth, and then change the effective sensing area of the SQUIDs. In our experiments, the maximal temperature fluctuation of the cold head at 80K with 130mW applied heat load in 800 seconds is about 40mK, which is well below the upper limit of the requirement (about 100mK).

CONCLUSIONS

A portable low-noise cryogen-free cooling system based on Stirling-type co-axial NNPTCs for high-Tc SQUIDs operation has been designed and constructed.

A typical cooling power of 130mW at 80K for 70 W of input power has been achieved, which can meet the basic cooling requirements of the high Tc SQUIDs. Preliminary results indicate the interference characteristics of the system can meet the basic noise requirements of the sensors.

A disadvantage is that the performances of the Stirling-type NNPTCs are much poorer than those of their conventional metallic counterparts, and in practical applications, larger cooling power and lower working temperatures are usually desired. So the performance optimization of the coolers is underway.

ACKNOWLEDGMENT

This work was partially supported by the National Natural Science Foundation of China under grant No.50176052 and 50206025.

REFERENCES

1. Cantor, R., DC SQUIDs: Design, optimization and practical applications, SQUID Sensors: Fundamentals, Fabrication and Applications, Kluwer Academic Publishers, Dordrecht (1996) 179-233.

2. Dang, H. Z. Ju, Y. L. Liang, J. T. Cai, J. H. and Zhou Y. Performance investigation of Stirling-type nonmagnetic and nonmetallic pulse tube cryocoolers for high-Tc SQUIDs Operation, The 13th International Cryocooler Conference, New Orleans, U.S.A., (2004)

3. Radebaugh, R., Development of the pulse tube as an efficient and reliable cryocooler, Proc. Institute of Refrigeration(London), (2000), 96 11-29.