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Performance of Stirling-type non-magnetic and non-metallic co-axial pulse tube cryocoolers for high-T_c SQUIDs operation

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Abstract

A set of Stirling-type non-magnetic and non-metallic co-axial pulse tube cryocoolers, intended to achieve portable cryogen-free systems with very low interference for high-T_c SQUIDs operation, have been designed and tested in TIPC/CAS. The key feature is that all cooler components in the vicinity of SQUIDs pick-up loops are made of non-magnetic and non-metallic materials, in order to eliminate complicated interference and realize direct couple with SQUIDs. The cooling options, cooler interference and corresponding solutions are reviewed briefly, and then we focus our attention on the cryogenic design and selection of the materials. Over 30 cooler samples have been fabricated and tested systematically. A typical cooling power of over 100 mW at 80 K with 70 W input electrical power has been achieved. Detailed cooling performance and elementary interference characteristics of the coolers are also analyzed and evaluated.

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Keywords: Stirling-type; Nonmagnetic; Nonmetallic; Pulse tube cryocoolers; High-T_c SQUIDs

1. Introduction

Superconducting Quantum Interference Devices (SQUIDs) are the most sensitive sensors in detecting magnetic flux known till now. Aside from precision measurements of minute magnetic fields or field gradients, they may also be used to measure any physical quantity that can be converted to a magnetic field, such as electrical current or voltage, magnetic susceptibility, physical displacement, etc. Owing to their unsurpassed sensitivity and enormous bandwidth, SQUIDs are essential (sometimes critical) for a wide variety of applications, including biomagnetic research and diagnostics (e.g. MCG and MEG), geophysical survey, nondestructive evaluation (NDE), military applications (e.g. the detection of nuclear submarines) and SQUID-based instrumentation for advanced scientific research [1,2].

Since the early 1970s, commercial low-T_c SQUIDs in the range of the boiling point of liquid helium have been available. And in 1987, the advent of superconductors with transition temperature of 92 K opened the possibility of operating SQUIDs above the boiling point of liquid nitrogen. Both sensors are usually cooled by cryogens (liquid helium or nitrogen) to keep necessary working temperatures, and are operated in magnetically shielded rooms to obtain an extremely low-noise measuring environment. A shielded room is expensive, and makes it impossible to move the SQUIDs system around on occasion for practical applications. When SQUIDs are cooled in cryogen cryostat, there exists a lot of intrinsic inconvenience in supplying and transporting cryogens, and frequent maintenances are required (refilling the cryogens). Especially when the systems are

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required to be free of the impact of directions, the use of low-temperature liquid is forbidden. In many cases, it is the lack of a satisfactory refrigeration system that hinders the wider acceptance of SQUIDs.

With the development and maturity of cryocoolers, cryogen-free systems operated in an unshielded environment for SQUIDs became feasible. One of the first attempts towards developing a cryocooler that has the potential to fulfill this function was made by Zimmerman et al. in 1970s [3]. They designed and constructed some low-cost and low-power Stirling cryocoolers operating at very low pressure (typically substantially less than 0.1 MPa). By using multistage plastic displacer units (fiberglass filament epoxy cylinders and solid nylon pistons), the interference from the cryocoolers was reduced significantly and the temperatures well below the superconducting transition of niobium (about 9 K) could be reached. The operation of low-T_c SQUIDs by such schemes was ever demonstrated, but the progress was slow and extensive applications were not realized. Of one reason was the considerable interference from the cooler itself, the other and more important one was the advent of the high-T_c SQUIDs.

Because of the higher operating temperature of high-T_c SQUIDS, a much more flexible refrigeration system can be realized. The relaxation of the cooling requirements makes the system less complicated and less expensive, moreover, the cryocoolers originally developed for cooling infrared sensors are mature and the relevant technology could be used for reference [4]. Consequently since the early 1990s, many attempts have been made to cool high-T_c SQUIDs by cryocoolers.

2. Cooling options

2.1. High-noise and low-noise cryocoolers

Up to now various types of cryocoolers have been used to cool high-T_c SQUIDs in practice, and they can be divided into two main categories based on the levels of interference they introduced, namely, high-noise and low-noise cryocoolers [5]. Stirling and G–M cryocoolers are representative of high-noise ones, in which Stirling coolers are used more usually. There is a longer history in trying to use these "noisy" cryocoolers to cool high-T_c SQUIDs because of the maturity of the related refrigeration technology and easy availability of the products. But due to the distinct and sometimes severe interference signals coolers introduced, the SQUIDS could not be too near to the cold fingers. In this instance, the coolers should be separated from the SQUID sensors in time or in space, which is named as *time-separation* or *space-separation* method accordingly [5]. In the *time-separation* concept, as Kaiser et al. [6] did when they tried to eliminate the vibrations of a G–M cryocooler, the cooler is turned off during the SQUIDs operation while a latent cold reservoir is used to keep the temperature stable, which has to be re-cooled from time to time. Proper design can minimize the interference, but the disadvantage is also obvious due to the non-continuous operation of SQUID sensors, which is harmful to the measurement of SQUIDs, and frequent switching on and off, which aggravates the wear of the coolers.

To realize non-interrupted operation, the *space-separation* method is usually adopted, which makes the interference reduced substantially by increasing the distance between the cooler and the SQUIDs. The appropriate distance is determined based on the intensity of the noise produced by the coolers. Two ways are usually employed to construct a space-separated system, that is, closed-cycle gas circulation system [7], or conductive strip [5]. Space separation method requires a thermal interface, and then additional cooling power. Moreover, the practical realization of the thermal interface significantly adds to the complexity of the system. For these reasons, the coolers with low-noise become a preferred alternative.

Joule–Thompson cryocoolers and pulse tube cryocoolers (PTCs) are two main types of low-noise cryocoolers. They are more attractive candidates for SQUIDs cooling because of the absence of mechanical moving parts in the cold heads. The feature has the potential for increased reliability, reduced vibrations and damped electromagnetic interference (EMI). So there exists the possibility of continuous operation of SQUID sensors near to or even attached directly to the cold head of the coolers. Here we draw our focus on the PTCs.

2.2. Pulse tube cryocoolers

PTC is an important innovation for regenerative cryocoolers, and great progresses have been achieved since the early 1980s. Now Carnot efficiencies of some practical PTCs have equaled or exceeded those of best Stirling cryocoolers, and commercial PTCs are available [8]. PTCs can be divided into two types based on drivers and operating frequencies. One type is referred to as "Stirling-type" because they are based on the linear compressors as Stirling cryocoolers usually use, which generally provide cooling in the 30–100 K temperature range and is operated at frequencies above 30 Hz; Another type is called as "G–M type" because they use G–M type compressors and operate at much lower frequencies (usually below about 10 Hz) to achieve lower temperatures and larger cooling powers.

Since the middle 1990s, the merits of PTCs have been gradually realized and utilized to supply low-noise cooling for SQUIDs operation. Many efforts have been made and some interesting results been achieved. However, most interests are confined to G–M type PTCs and the applications are nearly limited to biomagnetic measurement and diagnostics only [9–11].

Stirling-type PTCs have many advantages over G–M type counterparts, in terms of compactness, flexibility, portability due to much smaller volume and much lighter weight (a reduction in volume or weight by a factor of above 5–10), so the miniaturization could be realized more easily. Moreover, the mechanical vibrations are damped further due to the absence of rotary valves, and the higher efficiency could be expected due to the elimination of the irreversible losses introduced by valves. These merits give Stirling-type PTCs more potential applications in some special domains such as space and military, where SQUIDs are beginning to play an important role.

During last five years, Stirling-type PTCs for high-T_c SQUIDs have been under development in Technical Institute of Physics and Chemistry, Chinese Academy of Sciences (TIPC/CAS). It is intended to achieve portable cryogen-free systems with very low interference and more potential applications. We shall start introducing our works on the analysis of cooler-generated interference and their solutions.

3. Cooler interference and solutions

3.1. Cooler interference

Compared to cryogen cryostats, cryocoolers have many advantages [3,5,9]. They are mobile systems and easy to handle, and can realize turnkey operation (no refills required). There exists the possibility of operating the system in all directions without any precaution. The most important, the flexible operating temperature (the cryogens can only keep fixed temperatures) could give a potentially better SQUID performance. Unfortunately, they introduce more complicated interference than cryogens.

In general, when the SQUIDs are cooled by cryogens, the main interference signals are from the thermal magnetic noise of cryostats, which could be reduced to acceptable level easily by proper design and selection of materials of cryostats [12]. While a cryocooler may generate severe interference signals in various ways [3,5,9,10,13,14]:

(1) By currents and moving magnets in the compressor, and or the vibration of magnetic cooler components, which generate direct magnetic interferences.
(2) By mechanical vibrations of the cooler (especially the cold head to which SQUIDs attached directly or indirectly), which cause movements of the SQUIDs in the environmental field and then generate indirect magnetic noise.
(3) By the metallic cooler components in the vicinity of the SQUID pick-up loops, which generate Johnson noise and then cause distortion of environmental fields.
(4) By thermal fluctuations, which affect the London penetration depth, and then change the effective sensing area of the SQUIDs.

3.2. Reduction of the interference generated by compressor system

Among the interference signals mentioned above, the part originated from compressor system can be reduced greatly or eliminated by the approaches as follows:

(1) Increasing the distance between the compressor and the cold head (on which SQUIDs are mounted). The reason is that the EMI signals reduce greatly as increasing distance.
(2) Shielding the compressor system when necessary. The distance between the compressor system and the cold head cannot be increased infinitely because the cooling power decreases gradually with the increasing of the distance, and sometimes the EMI signals from the compressor system can not be reduced sufficiently by this method. In this instance, a magnetic shielding is necessary.
(3) Subtracting the field contributions of the compressors [5]. Because a simple and mobile system is desired, so a shielding room should be gotten rid of as could as possible. In the fixed configuration of a cryocooler and SQUIDs, the transfers of the compressor currents to the detected fields in SQUIDs could be measured. As a result, during the SQUIDs operations, the compressor-current field contributions can simply be calculated and subtracted from the SQUIDs outputs.

3.3. Reduction of the interference generated by mechanical vibrations

Vibrations of the cryocooler (especially the cold head) can cause the SQUIDs to move at same or slightly lower frequencies, and the movement of SQUIDs in an inhomogeneous background field could introduce interference signals indirectly. The movement includes translations and rotations, and the latter are more problematic [13,14]. Many attempts have been made to reduce the vibrations of cryocoolers according to their own characteristics. For example, Kaiser et al. [6] simply turned off the G–M cryocooler to eliminate the vibrations when SQUID sensors were working; Rijpma et al. [13] realized vibration reduction in a set-up of two split type Stirling cryocoolers by using coolers with dual opposed pistons in the compressor modules, and using two coolers and combining the two displacer modules into one rigid unit and operating them in a dual opposed manner; And Lienerth et al. [11] tried to minimize the residual vibrations of a pulse tube cooler using additional vibration compensation. A compressor is also an important source of vibrations, but it can be isolated and solved as a unit because of its relative independence. Typical method is replacing rigid metallic tube with flexible plastic line for the connection of the coolers to the compressor to damp the mechanical vibrations. In most case the interference signals generated by mechanical vibrations intertwine with others so that they might be considered and solved together. *Time-separation* and *space-separation* method, which have been discussed in previous paragraphs, are the samples.

3.4. Reduction of the interference signals generated by thermal fluctuations

A temperature variation will affect the calibration factors of a SQUID sensor since the effective measuring area of the SQUID is temperature dependence. The effect generated by the temperature drift should remain below the maximum acceptable imbalance. The upper limits vary with the types of SQUIDs and practical needs. Once the drift exceeds the limit, recalibrations of the SQUIDs are needed. In order to keep the temperature stability, different temperature controllers are often employed. The method introduced by the literature [15], which can realize precision temperature control by actively controlling the input power, is also a feasible alternative, although it is a little complicated.

3.5. Reduction of the interference generated by magnetic and metallic cooler components

Another important cooler-generated interference comes from the magnetic or metallic cooler components. Because they are near to or even attached to the sensors, the problem becomes intractable. *Space-separation* is often employed to deal with it, but additional cooling power is needed. Moreover, the biggest inconvenience of *space-separation* is incompactness of the system. In order to solve above problems in a relatively simple and complete way, we have been working on development of non-magnetic and non-metallic PTCs, named NNPTCs, because all of their key components were fabricated with non-magnetic and non-metallic and electrically insulating materials [15]. Based on this idea, a compact and flexible cooling system with very low-noise would be expected. In the following paragraph, we will discuss the methods in detail combining with the selections of non-magnetic and metallic materials for the PTCs.

4. Selections of non-magnetic and non-metallic materials for PTCs

4.1. Cold head

In a cryocooler, the cold head is the nearest component to the SQUIDs being cooled, and is the crucial impact on the sensitivity of the sensors. First of all, the remanent magnetization of ordinary metallic-made cold heads would generate relatively high permanent magnetic fields on the spot. In practice, the SQUID holders are often attached rigidly to the cold heads to suppress, to some extent, the relative movement between them, hence to damp the interference [14]. Unfortunately, the demagnetization of the cold heads is still unavoidable. In fact, for all types of cryocoolers used to cool SQUIDs, attempts have been tried to realize "non-magnetic" cold head to minimize or eliminated the residual magnetism, i.e. the Stirling cooler by Zimmerman et al. [3], the G–M type PTC by Gerster et al. [10], the J–T cryocooler by Bangma et al. [14]. Secondly, almost all of the cold heads of cryocoolers developed for SQUID operation are manufactured in metallic or partly metallic, therefore, direct attachment of the SQUID to them is impossible because of high Johnson noise introduced [5,10,13,14]. In many cases a cylinder (made of aluminum or sapphire, and so on) has to be used to separate the SQUID from the cold tip. In order to realize the demagnetization of the cold head and eliminate the Johnson noise completely, we introduce here a special ceramic, which can be regarded as non-magnetic, non-metallic, and electrically insulating. Its mechanical properties and the diffusion of helium through the wall meet the requirements of long-term operation. Moreover, it is machinable and can be fabricated into complicated shapes we desired. A disadvantage of this material is of lower thermal conductivity than that of OFHC copper, widely used for cold heads of PTCs, which is about 396 W/m K at 300 K and 529 W/m K at 80 K. Since we can directly attach SQUID sensors on the cold head and no thermal interface is needed, sufficient heat transfer between the cold head and the sensors can be guaranteed. The main properties of the special ceramic are shown in Table 1.

4.2. Regenerator matrix

The magnetic impurities, induced eddy currents, and thermally activated currents in common metallic-made matrix filled in regenerators could inevitably produce considerable magnetic disturbances. An important aspect in designing and fabricating a NNPTC is of a suitable regenerator matrix material with non-magnetic, non-metallic, and electrically insulating, without degrading the efficiency of the cryocooler at the same time.

Table 1
The main properties of the special ceramic

Density (g/cm^3)	2.0
Thermal conductivity at 300 K (W/m K)	54
Thermal conductivity at 80 K (W/m K)	78
Magnetic susceptibility	≤ 0.4
Volume resistivity (Ω cm)	10^{18}
Thermal elongation coefficient (10^{-6}/K)	≤ 1.8
Compressive strength (MPa)	$\geqslant 491$
Tensile strength (MPa)	$\geqslant 98$
Bending strength (MPa)	$\geqslant 108$

For a given regenerator housing, an important factor that influences the performance of regenerators is c_m, the volumetric heat capacity of matrix materials, which indicates how much heat per volume can be stored. We investigated various non-magnetic and non-metallic materials that can be used in cryogenic temperatures, and found that Nylon, Kapton, and Teflon are satisfactory when they are fabricated into stacked screens. Fig. 1 showed c_m of these materials as function of temperature, in which the variations of stainless steel and copper, which are widely used as the regenerator matrix at temperature ranges of liquid nitrogen, were also given for comparison. One can find from Fig. 1 that c_m of Nylon is higher than the other two non-metallic materials at temperature ranges of 60–300 K. Therefore, we selected stacked Nylon screens as the regenerator materials for our NNPTCs, although c_m of Nylon are still smaller than those of copper and stainless.

Besides the volumetric heat capacity, another important factor that influences the performance of the regenerator is of thermal penetration depths in both solid matrix and helium gas. The characteristic matrix dimension, which refers to wire diameter of stacked screens, should not be larger than the thermal penetration depth in the solid, to avoid no contributing to the effective heat capacity [16]. The thermal penetration depth in a semi-infinite medium is given by

$$\lambda_t = \sqrt{\frac{k}{c_m \pi f}} \tag{1}$$

where k is the thermal conductivity, c_m is the volumetric specific heat, and f is the frequency. Figs. 2 and 3 show variations of thermal penetration depth of stainless steel and Nylon as function of temperature at different operating frequencies.

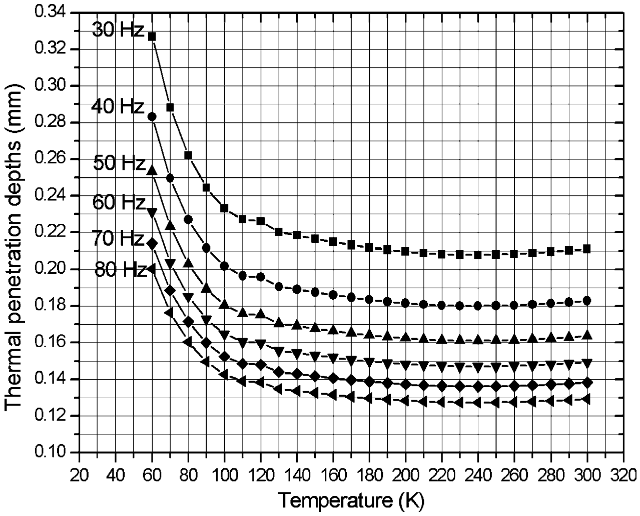

Fig. 2. Variations of thermal penetration depth of stainless steel with temperature.

For high-frequency miniature PTCs working at liquid nitrogen temperature ranges, the stainless steel screens are widely used and the optimum mesh sizes are usually above 300-mesh. The wire diameters of such screens are

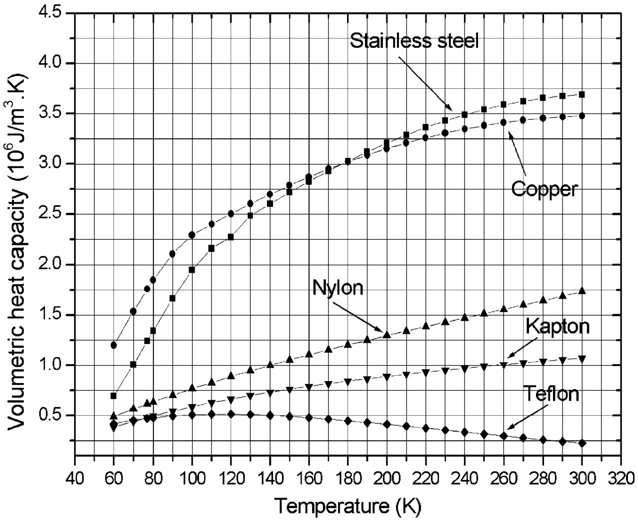

Fig. 1. Variations of volumetric heat capacity of the various materials with temperature.

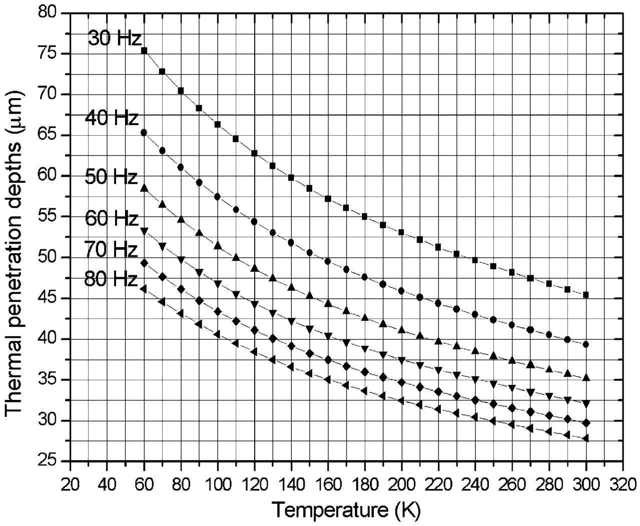

Fig. 3. Variations of thermal penetration depth of Nylon with temperature.

Table 2
The main dimensional parameters of the 400-mesh Nylon screen

Mesh Size	400
Wire diameter, D_w (μm)	25.4
Pitch, λ (μm)	63.5
Mesh distance, β (μm)	38.1
Hydraulic diameter, D_h (μm)	55.4
Theoretical porosity, φ	0.6618

smaller than 40 μm. From Fig. 2 one can see that the value is significantly smaller than the thermal penetration depths of stainless steel operated at frequencies of 30–80 Hz and the temperatures of 60–300 K. As a result, all of the wires are applicable in theory.

It should be noted that the situation is different for the Nylon matrix. From Figs. 2 and 3 we know that at the same frequency the thermal penetration depths of Nylon are only 21.5–28.5% of those of stainless steel in the temperature region of 60–300 K. In this case, the thermal penetrations of Nylon are of the same order of magnitude of the wire diameter of 300-mesh screen, even smaller than it. The higher the frequency, the worse the situation. In order to weaken the effect caused by smaller thermal penetration depths, either lower operating frequency or larger mesh of screens should be adopted. For all experiments shown below, we use 400-mesh Nylon screen. The main dimensional parameters of the 400-mesh Nylon screen are shown in Table 2.

4.3. Other important components

For a compact miniature PTC, other components are also operated in the vicinity of the SQUID pick-up loops. It is of importance avoiding the presence of metals and materials exhibiting marked remnant magnetization for SQUIDs operations. These components include vacuum chamber, tubes (pulse tube and regenerator tube), connecting flanges and flow straighteners and are made of non-metallic, non-magnetic and electronically insulating materials as well.

The specific requirements for different components vary. Of the most important is the tubes for pulse tube and regenerator because of the combined requirements of having excellent mechanical properties to stand considerable tensile force, of fine structure in texture to minimize the diffusions of high-pressured helium gas, which is critical challenge for non-metallic material due to their intrinsic molecular structures. In the current coolers, the regenerator tube is made of a special glassfilled epoxy resin and the pulse tube of Nilon1010. Experiments have been performed to test their mechanical properties. A typical cylinder fabricated by a wall thickness of 2 mm by the special glassfilled epoxy resin filling helium gas at 4.5 MPa, has the same diffusion as that of stainless steel.

The vacuum chambers and connecting flanges are made of acrylic glass to replace the traditional stainless steel or aluminum. All of the straighteners are made of polytetrafluoroethylene plastic.

5. Experimental set-up

The experimental set-up of the whole cooler system specially designed for the cryogen-free operation of SQUIDs is shown in Fig. 4.

We adopt co-axial configuration for our NNPTC in order to minimize the size of the cryocooler, which is the most compact and convenient way for the connection with the cooled sensors. The pulse tube is assembled inside the annular regenerator tube, and the matrices, which consist of a stack of 400-mesh Nylon screens and are annular in shape, are placed concentrically outside the pulse tube. The flange at the hot end is incorporated with the system and serves as the heat exchanger. The connection of tubes to both the cold head and the flange at the hot end are realized by a kind of special synthetic epoxy resin adhesive, to eliminate the interference by metallic welders. The adhesive can be used at temperature regions of 4–333 K for various metallic and non-metallic materials with different expansion coefficients. The lower the temperature, the higher the adhesive strength. During the experiments, no diffusion of helium through the connections into the vacuum chamber was observed. The orifice and double-inlet were adopted as phase shifters, and both of them are realized by needle valves, which are installed inside the holes perforated in the flange at the hot end. The whole cold finger are very light and compact and are less than 300 g excluding compressors.

Four pressure transducers (P1, P2, P3, P4) are used to measure the pressure drops through the orifice and double-inlet valves, and the pressure change in the gas buffer. The measured pressure amplitudes are amplified by four charge amplifiers, and displayed in an oscilloscope. These signals are converted into digital formats through an A/D board, and then monitored by a computer.

The compressor system consists of a frequency converter, a transformer, and a linear compressor. The transformer is used to protect the compressor by separating it from the 220 V alternating current, and the frequency converter is employed to adjust the operating frequency of the system from 30 Hz to 100 Hz. The whole compressor system is connected to the NNPTC by a flexible polyamide tube with an inner diameter of 2 mm and lengths from 1.5 m to 3 m to reduce the vibrations generated by the compressor. A Wattmeter is placed between the compressor and the flexible tube to measure the output electric power of the compressor.

The cold-end temperature is measured by a Pt-100 resistant thermometer, and four other Pt-100 thermo-

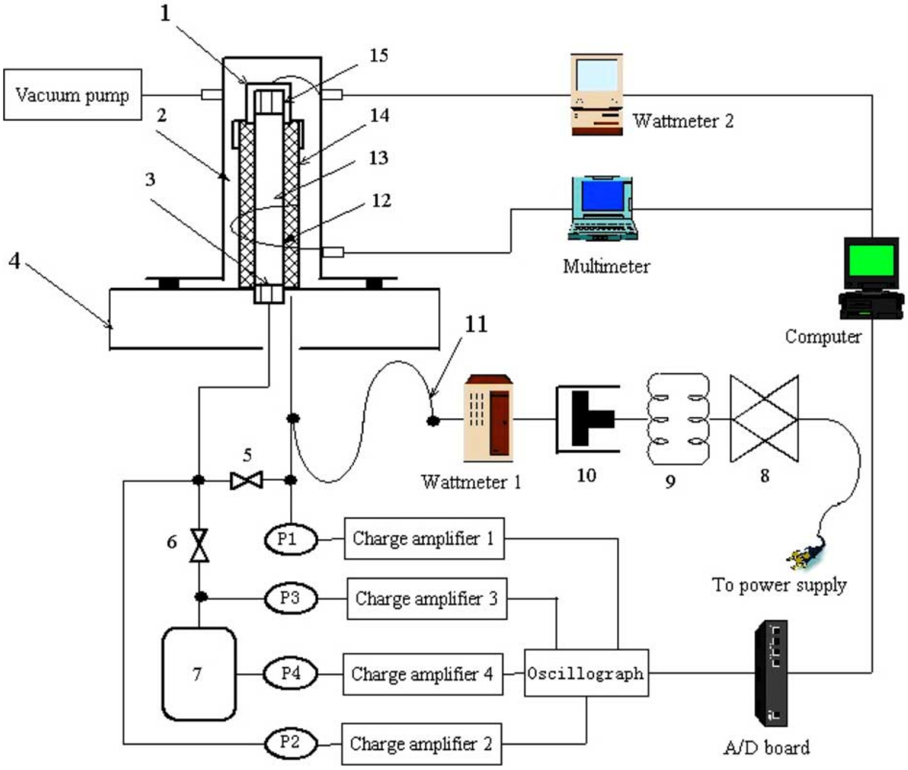

Fig. 4. The schematic diagram of the cooler system. 1. cold head; 2. vacuum chamber; 3. flow straightener; 4. hot end flange; 5. double inlet; 6. orifice valve; 7. gas buffer; 8. frequency converter; 9. transformer; 10. compressor; 11. flexible tube; 12. matrix; 13. pulse tube; 14. regenerator tube; 15. flow straightener.

meters are placed along the external wall of the regenerator to monitor the temperature profile. All of measurements are collected by a multimeter and displayed in the computer. The cooling power is measured by another Wattmeter.

6. Cooling performance of the NNPTCs

During the last four years, over 30 Stirling-type NNPTCs have been fabricated and tested systematically. Firstly, we present the cooling performance of No. 6 cooler, which has the highest refrigeration efficiency. And its basic dimensional parameters are as follows:

Regenerator tube (inner diameter × wall thickness × length): 11 mm × 1.25 mm × 60 mm;
Pulse tube (inner diameter × wall thickness × length): 5 mm × 0.75 mm × 74 mm;
Matrix: 1047 pieces of 400 mesh Nylon screen;
Flexible tube: a length of 1.5 m.

Under the optimum charge pressure (3.5 MPa) and operating frequency (36 Hz), the no-load temperature of the cold head reaches 76.8 K after 80 min, and a cooling power of 130 mW at 80 K can be achieved with 72 W input electric power of the compressor, as shown in Figs. 5 and 6. Since most high-T_c SQUIDs are usually operated in the temperature range of 50–80 K with a cooling power of one to several hundred milliwatts, the cooling capacity of the sample cooler meets the basic cooling requirements.

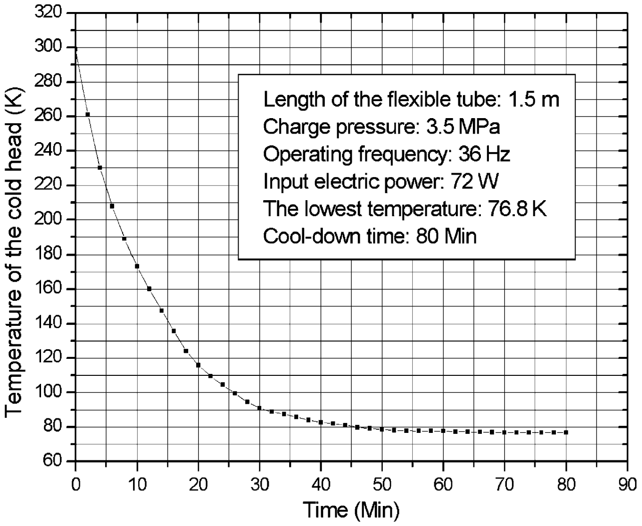

Fig. 5. The typical cooling-down curve of the NNPTC without heat load.

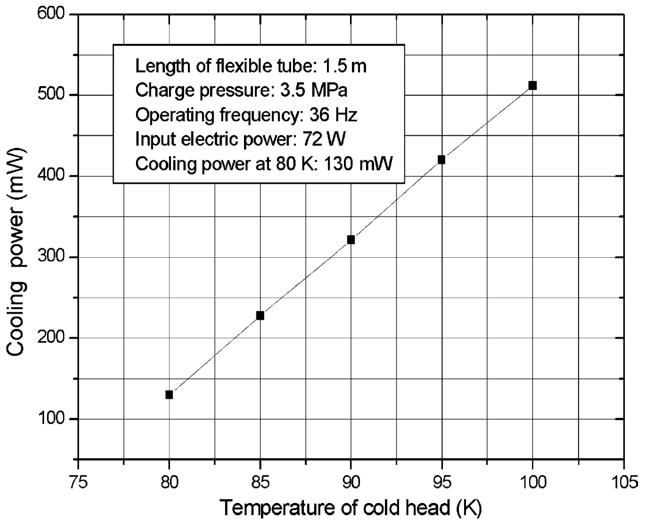

Fig. 6. Temperature dependence of the net cooling power of the NNPTC.

During the design and optimization, 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 been obtained [17]. Then 28 coolers have been fabricated and tested systematically, which mainly focus on the optimization of the dimensional parameters, such as the aspect ratios (the ratio of the length to the inner diameter) of the regenerators and pulse tubes, the ratio of the volume of pulse tube to the void volume of regenerator, and so on. Some important parameters are shown in Table 3. Firstly, two teams of experiments (teams 1 and 2) have been carried out for the dimension optimization of the regenerators, in which the same pulse tube is used and the regenerator geometry is allowed to vary between test items in the same test team. For either team, seven regenerators define a set of constant volume, variable aspect ratio, respectively. The operating conditions are held constant at a mean pressure of 3.5 MPa and a frequency of 40 Hz. Fig. 7 shows the variations of the no-load temperatures of the cold heads with the aspect ratios of the regenerators, from which we see that the optimum aspect ratio of the regenerators is about 5–6. Secondly, another two teams of experiments (teams 3 and 4) have been conducted for the pulse tube optimization. For either team, seven pulse tubes define a set of constant volume, variable aspect ratio, respectively.

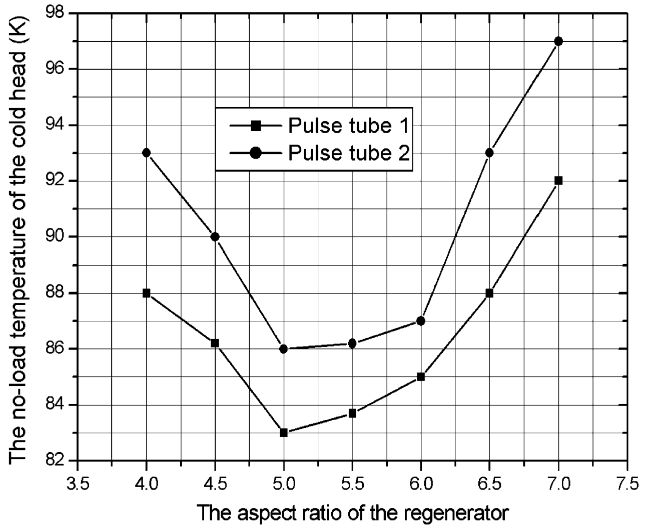

Fig. 7. Variations of the no-load temperatures of the cold heads with the aspect ratios of the regenerators.

The working parameters are as same as those used in teams 1 and 2 except the input electric power. Fig. 8 shows the variations of the no-load temperatures of the cold heads with the aspect ratios of the pulse tubes. One can see that the optimum aspect ratio of the pulse tubes is about 13–16. Similar experiments have been performed about the ratio of the volume of pulse tube to

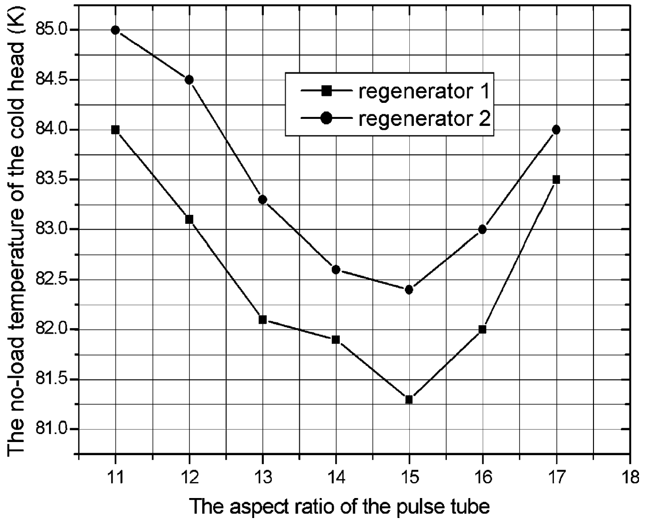

Fig. 8. Variations of the no-load temperatures of the cold heads with the aspect ratios of the pulse tubes.

Table 3
Some experimental parameters of the four teams of NNPTCs

	Pulse tube (inner diameter × wall thickness × length)	Regenerator (inner diameter × wall thickness × length)	Input electric power
Team 1	5 mm × 70 mm × 0.75 mm	The aspect ratios vary	72 W
Team 2	5.5 mm × 76 mm × 0.75 mm	The aspect ratios vary	
Team 3	The aspect ratios vary	11 mm × 57 mm × 1.25 mm	70 W
Team 4	The aspect ratios vary	11 mm × 60 mm × 1.25 mm	

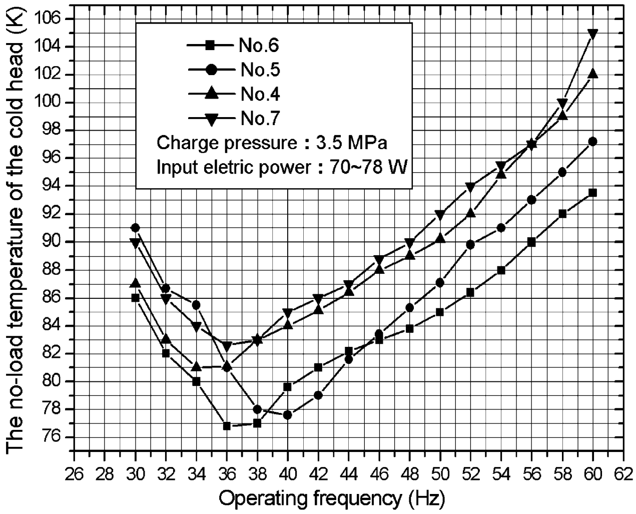

Fig. 9. Frequency dependence of the no-load temperatures of the cold heads for the four sample coolers.

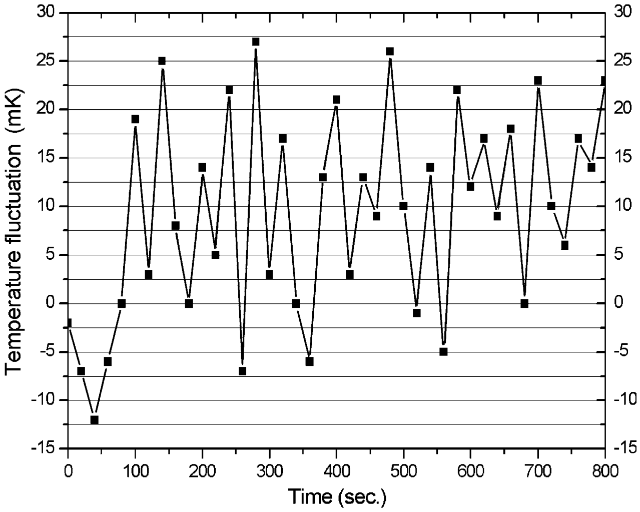

Fig. 10. Short-term temperature fluctuation of the cold head relative to 80 K with 130 mW heat load.

the void volume of the regenerator, and the optimum value is about 0.5–0.6. More details can be found in the literature [17,18]. Based on the above experiments and analysis, two satisfactory coolers (No. 5 and No. 6) have been worked out. For No. 5 cooler, a cooling power of 119 mK at 80 K has been achieved when the input electric power is 70 W.

Fig. 9 shows the frequency dependence of the no-load temperature of the cold head for four sample coolers (No. 4–No. 7). Their optimum operating frequencies are between 36 and 40 Hz. With similar structure and working parameters, the optimum frequencies of the conventional metallic PTCs developed in the same laboratory are usually around 50 Hz. The lower operating frequency of NNPTCs may result from the effect of the heat penetration depth discussed in previous section.

In cooling SQUID sensors with cryocooler, a great advantage over cryogen is of the capability in operating the system in different directions. Unfortunately, the cooling performance of PTCs is often orientation dependence provided that large pulse tube diameters are used [8]. G–M type PTCs developed for SQUIDs operation often encounter the troublesome problem. The miniature Stirling-type NNPTCs we developed are proved to be nearly independent of it. For the No. 6 NNPTC we discussed above, the variation of the no-load temperature of the cold head is within 400 mK, and the corresponding cooling power at 80 K is within 10 mW even the cooler operated at 180° with respect to the vertical axis, which benefit greatly to the SQUIDs operation.

7. The interference characterization of the NNPTCs

The interference characterization of the NNPTCs mainly includes the temperature stability, Johnson noise, the mechanical vibrations, and the electromagnetic interference.

The temperature stability of the cold head, which is usually discussed in short-term and long-term, is important because of influences on the sensitivity of the SQUIDs. Fig. 10 shows the temperature fluctuation of the cold head of the No. 6 cooler at operating temperature (80 K) with 130 mW applied heat load in 800 s. According to the suggestion in the literature [19], the limited acceptable temperature fluctuation is about 0.1 K at 80 K for the SQUIDs operation. The maximum short-term temperature fluctuation of the NNPTC is about 40 mK, well below the requirement. The long-term temperature stabilities are currently underway.

Johnson noise in our NNPTCs can be negligible since all the components near the SQUID sensors are made of non-magnetic and non-metallic materials.

The translation of the cold head along *z*-direction produced by residual vibrations is reduced to an order of 10 μm. The earth field where the experiments performed is about 50 μT with a typical gradient of 220 nT/m, hence the corresponding noises are well below the background field. The rotations of the cold head remain within 10 $\mu\mathrm{rad}/\sqrt{\mathrm{Hz}}$, which is also less than the maximum acceptable value of 20 provided that the upper limit of the noise level is set to 100 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ [14].

As to the EMI, the remanent magnetic field introduced by the magnetic components in common metallic PTCs is also nearly eliminated completely. A remaining problem arises from the compressor. The distance of 1.5 m has been adopted between the compressor and the cold head. The remanent magnetic field of the compressor at this distance is about 40 nT with a gradient of 60 nT/m. Only at about 2.5 m distance does the noise level from the compressor approach to the environmental noise. However, the cooling power decreases

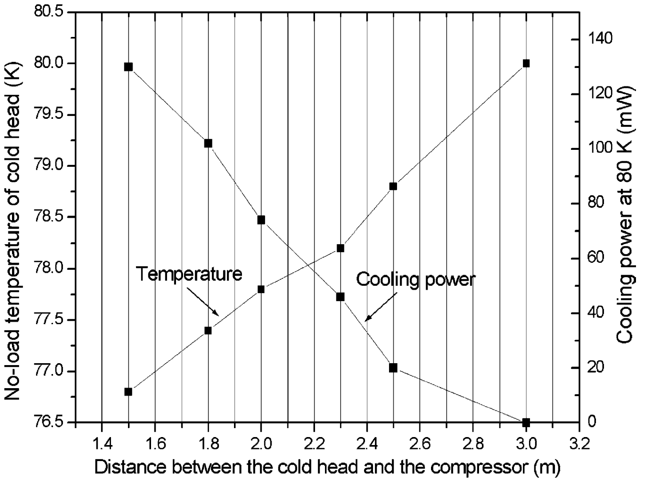

Fig. 11. Variations of the no-load temperature of the cold head and cooling capacity at 80 K with distance between compressor and cold head.

gradually with the increase of the distance. Fig. 11 shows the variations of the no-load temperature of the cold head and cooling power with the distance between the compressor and the cold head. It is found that the cooling power of the cooler at 80 K at 2.5 m distance is not enough for the cooling requirements of the SQUIDs.

8. Summary and discussion

Pulse tube cryocoolers are promising candidates of low-noise cryogen-free cooling system for high-T_c SQUID operation, and Stirling-type PTCs have many advantages over G–M type in terms of compactness, flexibility, portability and lower mechanical vibrations.

Over 30 Stirling-type NNPTCs have been fabricated and tested systematically. The optimum dimensional parameters, such as the aspect ratio of the regenerators and pulse tubes, the ratio of the volume of pulse tube to the void volume of regenerator, have been obtained. A typical cooling power of 130 mW at 80 K for 72 W of input power has been achieved for high-T_c SQUIDs. The optimum operating frequencies of the NNPTCs are a little lower than the ones of their metallic counterparts, provided that the experimental conditions are the same.

Johnson noise, the vibrations and the short-term temperature stability of the NNPTCs satisfy the bottommost requirements, except of the EMI from the unshielded compressor, which is still severe enough to hinder the SQUIDs operations. Longer distances between the compressor and the cooler are required at the cost of decreasing the corresponding cooling capacity. Larger cooling capacity and lower working temperatures are usually necessary in practical applications, so we will focus our attention on the optimization of the coolers, in better understanding of the oscillating flow in the non-metallic regenerators of the Stirling-type NNPTCs. Numerical simulation and dynamic experimental study will be carried out and better cooling performance of the new-type of PTC is foreseeable.

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