Performance and System Design of 60K Pulse Tube Coolers Driven by a Linear Compressor for HTS Filter Subsystems

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ABSTRACT

We report here on performance study and system design of 60K pulse tube coolers driven by a linear compressor for the purpose of developing a fully integrated, cryogen-free operation of HTS RF filter subsystems for wireless telecommunications. Two different cold finger geometries of U-type and co-axial single-stage pulse tube coolers are designed and analyzed. The objective is for 3.5W of cooling capacity at 65K with a specific power of 30W/W. Based on quantitative optimizations, the U-type cold finger can provide 3.5W at 65K with a specific P-V work of 89W. The corresponding COP and the specific power are about 3.8% and 25W/W, respectively. In contracts, for the co-axial cold finger, operated at the same conditions, it requires 112W P-V work to get the same cooling capacity. The corresponding COP and the specific power are about 3.1% and 32W/W, respectively, which is slightly lower than the design goal. Thus we propose a two-stage co-axial pulse tube cooler, driven by the same compressor, in order to minimize power consumption at the same total effective cooling capacity. The predicted result demonstrates that it provides 0.5W at 65K on the 2nd-stage cold head with simultaneous 3.0W on the 1st-stage cold head around 90K with P-V work of 73W and the integral COP is up to 4.8%. The construction of the cooled HTS filter subsystem integrated on the cold fingers is also described.

INTRODUCTION

With the worldwide applications of superconducting electronic (SCE) devices, cooling with easy, reliable and compact cryocoolers is highly desirable [1,2]. GM and Stirling coolers are reliable machines and are regarded as matured technology and widely used in many areas. However, they have a moving piston at cold head, which causes inevitably mechanical vibrations and electromagnetic interference (EMI), thereby unreliability and high-cost of sliding seals, remains as a severe problem for many applications.

In the past decade the progress in pulse tube coolers (PTCs) has been impressive. Many new ideas, incorporated with refined thermo-mechanical design and fabrication, lead to significant improvements in thermal efficiency as high as Stirling coolers [3,4]. The PTC has no moving mechanical parts and no displacer seals in the cold head, so that the mechanical vibration and EMI noise can be reduced to negligible levels with higher reliability, longer lifetime, and lower cost than other coolers. All these advantages provide a high degree of design flexibility that adapts this cooler to the replacement of Stirling coolers in several applications.

It has been found that there is a long-term growth application of cryocoolers for HTS filter subsystem in wireless phone systems. The initial incentive for using HTS RF filters was mainly the possible size reduction, but later mostly the improvement in overall performance such as broader coverage, lower interference, and better quality of service. In order to improve the voice transmission quality by reducing inter-channel EMI of cellular phone systems, the HTS filters integrated with an array of Low Noise Amplifiers (LNAs) are usually used. The HTS (usually YBCO) RF filters are passive devices and must be cooled below their transition temperature to superconducting stage (usually 65-80K) in order to operate properly. The HTS filters are usually connected through a coaxial cable to an array of LNAs, which are active devices and induce a few hundreds milliwatts of thermal load. In additions, the LNA array is connected to a feedthrough of the vacuum chamber by coaxial cable, which introduces also a few hundreds milliwatts of heat. The third contributor to the heat load is the thermal radiation from the vacuum jacket wall to the cooled surfaces. The heat load is estimated as hundreds of milliwatts. The signal-to-noise ratio of LNAs is improved significantly when cooled to temperature of 90~110K.

Cooling is being performed either by GM coolers with separate compressors or by totally integrated Stirling coolers with linear compressors, both in ground-mounted and tower-top units. The mechanical vibrations and EMI noise caused by the moving piston in the cold head of GM and Stirling coolers are of the severe problems for the operation of high quality HTS devices and of the main technical obstacles against a more general acceptance of these machines. Acceleration measurements [5] showed that the vibrations of the PTCs are one order of magnitude smaller than that of GM and Stirling coolers. Fig.1 presented the frequency responses of a HTS (YBCO thin film deposited on gem substrate) microwave filters cooled by a G-M type co-axial PTC at different temperatures [6]. The central frequency moves gradually to low frequencies with increasing temperatures. The shift of the central frequency becomes obviously at temperature above 75K, but the bandwidth and insert loss are nearly constant, except at temperature up to 86K.It has demonstrated that a properly designed PTC has great advantage and is capable of low-noise cooling of highly sensitive HTS devices.

This paper gives the performance and system design of 60K-PTCs driven by a commercial dual opposed piston linear compressor with a swept volume of 10cc. The coolers are specially designed for the purpose of developing a fully integrated, cryogen-free operation HTS filters subsystems. The design objective is for 3.5W of cooling capacity at 65K with a specific power (ratio of PV-work to cooling capacity) of 30W/W.

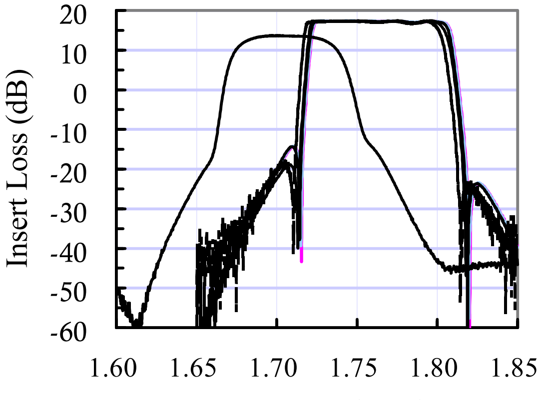

Figure 1. Frequency responses of the HTS filters at different temperatures
(From left to right: 86K, 80K, 77K, 75K, 71K, 69K and 66K)

THEORETICAL OPTIMIZATION

A comprehensive computer model [7] is applied for quantitative analysis of performance, optimization and as a guide in the early stage of cooler system design. The model is a 1-D, unsteady compressible flow numerical model that is based on a mixed Eulerian-Lagrangian method developed by the present author. The model is established and updated from the long-time developments of finite difference methodology (FDM) [8-10] for calculating the time-variations of dynamic parameters and internal processes occurring in the pulse tube coolers.

Our design approach by using the computer simulation program to the PTCs involves three stages. The first stage of design considerations is the geometrical arrangement of the pulse tube and regenerator. There are three different arrangements, in-line type, U type and co-axial (concentric) type. Obviously, the in-line arrangement has the high efficiency as high as 24% of Carnot [3], since it avoids losses from curved gas flow and dead volume at the junction between the pulse tube and the regenerator. However, the cold head located at the middle region of the two warm ends is the main disadvantage for connecting to the cooled devices. The most compact and convenient for practical application, just like Stirling coolers, is the co-axial type. It can replace Stirling cooler without any change to the Dewar or the connection to the cooled devices. However, there are several inferior elements, like mismatch of temperature profiles between the regenerator and pulse tube, void space at the cold end, and the reversal of gas flow direction in the cold end space, that retard the efficiency. They have been minimized by various techniques, i.e. multi-bypass, symmetric nozzle, inertance tube, low thermal conductivity materials.

When the geometrical arrangements of PTCs have been determined. The second stage is to optimize cooler system with respect to the dimensional layout of the pulse tube, regenerator, cold and hot end heat exchangers, and inertance tube based on the swept volume and input power of the compressor. First of all, the cooler volume must be adjusted to match the swept volume of the compressor in order to gain the proper pressure amplitude in the cold finger. Secondly, the volume ratio of the regenerator to pulse tube must be optimized to achieve a load balance. Thirdly, the arrangement of the regenerator matrix must be optimized based on the gas and matrix temperature profiles along the regenerator to reach a low no-load temperature and high cooling efficiency. Finally, the heat exchange surface area per unit volume of the hot and cold heat exchangers must be high for the improvement of the thermal linked between the cold end and the cooled SCE devices, and of heat extract between the hot end and the environments.

The third stage is to choose the optimal system mean pressure and operating frequency to the maximum cooling capacity and minimum power consumption at the same effective cooling capacity on the optimal size of each component and the optimal opening condition of the orifice, double-inlet, multi-bypass and inertance tube.

Based on above considerations, quantitative analysis of two cold finger geometries of U-type and co-axial single-stage PTCs was first carried out by our computer code, through which the power consumption and cooling capacity, the main system and operating parameters, like the size of each component, volume ratio, arrangement of the regenerator matrix, the charge pressure, pressure ratio, and operating frequency, could be evaluated.

Figure 2 shows the predicted performance of U-type PTC as a function of the volume ratios of the regenerator and pulse tube to the 10cc compressor at an average pressure of 3.0MPa and a frequency of 50Hz. The optimal design point of the regenerator and pulse tube is clearly found to achieve the maximum COP (cooling capacity divided by power consumption, %) at 65K. It shows that the optimum ratios of the regenerator and pulse tube volumes to the compressor volume are in the range of 1.0-1.2 and 0.5-0.7, respectively. At its most efficient operating point, the U-type cold finger can provide 3.5W of cooling capacity at 65K with a specific P-V work of 89W. The corresponding COP and the specific power are about 3.8% and 25W/W, respectively. In contracts, for the co-axial cold finger, operated at the same conditions, it requires 112W P-V work to get the same cooling capacity of 3.5W at 65K. The corresponding COP and the specific power are about 3.1% and 32W/W, respectively, which is slightly lower than the design goal.

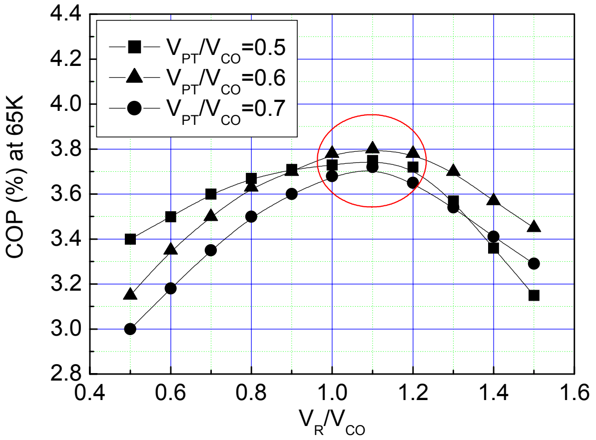

Figure 2. The COP as a function of regenerator volume and pulse tube volume of PTC

As an alternative approach, we proposed and analyzed a two-stage co-axial pulse tube cooler, driven by the same linear compressor unit, in order to minimize power consumption at the same total effective cooling capacity. Table1 presents the optimization highlights of the main parameters of the single (U-type and co-axial type) and two-stage (co-axial) cold finger configurations. The other parameters (operating and geometric) of the coolers were the same during computer optimization for both of cold finger configurations.

Table 2 gives the general output parameters after optimization by the computer simulation program at an average pressure of 3.0MPa and a frequency of 50Hz. The predicted result shows that the two-stage co-axial cold finger can provide a cooling capacity of 0.5W at 65K on the 2^{nd}-stage cold head with simultaneous 3.0W on the 1^{st}-stage cold head around 90K with a specific P-V work of 72W. The integral COP (Sum of 1^{st}. and 2^{nd}. stages effective cooling capacities divided by power consumption, %) and the specific power are up to 4.8% and 21W/W, respectively. Comparison of general optimization parameters in the Table 2 demonstrates that the specific PV work is saving about 35% and the heat generated by the compressor is decreasing about 30% by using the two-stage cold finger than the single-stage option.

In addition to the cooler itself there are still two problems corresponding to the overall system efficiency: the compressor, and the compressor power and control electronics. For our PTCs we use a commercial double opposed piston linear compressor (Leybold Polar), which is driven by a POLAR DRIVE control unit with specific electronic and control components, which can be easily be integrate into the cooler system.

Table 1. Optimization highlights of the single and two-stage cold finger configurations.

Parameters	Single-stage cold finger (U-type and co-axial type)	Two-stage cold finger (Co-axial type)
Optimization object	COP	Integral COP
System parameters	Regenerator diameter Regenerator length Pulse tube diameter Pulse tube length	Regenerator diameter (1^{st}. and 2^{nd}. Stage) Regenerator length (1^{st}. and 2^{nd}. Stage) Pulse tube diameter (1^{st}. and 2^{nd}. Stage) Pulse tube length (1^{st}. and 2^{nd}. Stage)
Operating parameters	Average pressure Operating frequency	Average pressure Operating frequency
Cold temperatures	65K	90K (1^{st}.) and 65K (2^{nd}.)
Cooling capacity	3.5W	3W (1^{st}.) and 0.5W (2^{nd}.)
Specific power	<30W/W	30W/W

Table 2. Optimization outputs of the single and two-stage cold finger configurations.

Parameters	Single-stage U-type	Single-stage co-axial	Two-stage co-axial
Regenerator diameter Regenerator length Pulse tube diameter Pulse tube length	16mm 80mm 9mm 80mm	21mm 70mm 8.5mm 80mm	21mm(1st) and 14mm(2nd) 55mm(1st) and 25mm(2nd) 8.5mm(1st) and 5.5mm(2nd) 60mm(1st) and 30mm(2nd)
Cooling capacity	3.5W	3.5W	3W (1st.) and 0.5W (2nd.)
Power consumption	89W	112W	73W
Specific power	25W/W	32W/W	21W/W
COP	3.8 %	3.1 %	4.8 %

DESCRIPTION OF SYSTEM DESIGN

Based on the quantitative optimizations of cooler performances guided by the computer simulation and the above technology developments, two different geometries of cold fingers of the co-axial pulse tube coolers, single-stage (type 1) and two-stage (type 2), for the purpose of developing a fully integrated, cryogen-free of HTS RF filter subsystems in base stations for wireless telecommunications, has been proposed and designed.

Figure 3 shows the schematic diagram of the Stirling-type single-stage co-axial PTC, which consists of a commercial twin-piston linear motor-driven compressor (Leybold Polar) (1), a flexible connection tube (2), an integrated gas buffer (3) in combination with one or more flow impedances of symmetric nozzles as orifice and double-inlet for gaining proper phase shift between the gas mass flow and pressure wave at the warm end of pulse tube, a hot end flange (4), which is also a gas flow control unit on which the hot ends of the pulse tube and regenerator are mounted, a regenerator (5), a pulse tube (6) and a cold head (7).

The regenerator is made of thin-walled stainless steel tube with thickness of 0.15mm and is filled with 400-mesh stainless steel screen as regenerator matrix. The pulse tube is made of Teflon with a wall thickness of 0.5mm and is placed within the annular regenerator. The cooper cold head consists of a cold end heat exchanger with a cooper base face (platform) on which the superconducting electronic devices can be easily coupled. This design is very compact and could be made into a commercially available pulse tube cooler.

Besides the cooler itself, it is also essential to design and provide cryopackage, which is the means of high degree of integration (thermally, mechanically and electronically) of the cold head of the cooler to the HTS RF filters and LNAs within an evacuated chamber while providing electronically and/or optical connections through the enclosure and vacuum space. The cryopackage should be reliable, adequate integration with HTS RF filters and LNAs and easy fabrication. The approaches are addressed as bellows.

The construction of the cooled HTS filters integrated with the cold finger of the single-stage PTC is also illustrated in Fig. 3, which is arranged to operate at a temperature of about 65K in order to meet the demands of HTS filters cooling. An array of LNAs (14), RF filters (13) and radiation shield (12) are thermally mounted on a copper base platform (8), which is anchored to the single cold head (7) of the cooler through thin indium foils with highly thermal conductivity. The whole construction is placed in a vacuum chamber (11), which provides the electrical connections of the RF filters, LNA array and vacuum feedthrough carried out by coaxial cables (9,10). The advantage of such design is of the simple construction of the cooler and HTS filter subsystem. The disadvantages lie in the high power required to operate the cooler, and in cooling the radiation shield and the LNA array to a temperature lower than necessary, resulting in the fact that these components contribute most of the cooling capacity. In addition, the cooling-down time of the cooler is delayed at start up in achieving the operation temperature required by the filters during the time it is extracting heat from the LNAs and radiation shield.

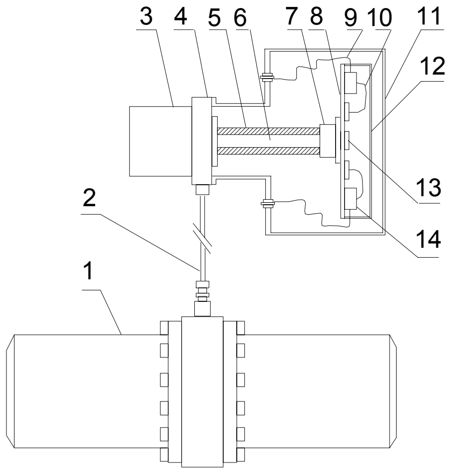

Figure 3. The construction of the HTS filters integrated with the single-stage PTC

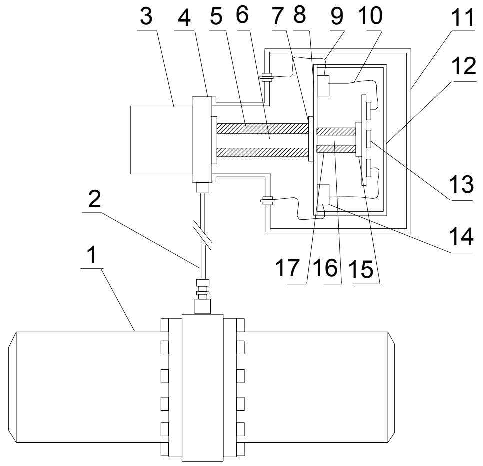

Figure 4. The construction of the HTS filters integrated with the two-stage co-axial PTC

In order to overcome the disadvantages of above cooler design, the HTS filter subsystem has been integrated with the two-stage co-axial PTC, as shown in Fig.4, equipped with the same linear compressor unit and with two cold heads operated at different cryogenic temperatures. The construction allows simultaneous cooling of HTS RF filters and LNA array to different specific cryogenic temperatures, which are sufficient for their operation. The RF filters (13) are mounted on a copper base platform thermally coupled to the second-stage cold head (15), which is set to operate at a temperature of about 65K in order to meet the demands of RF filters cooling. Both the LNA array (14) and radiation shield (12) are mounted on another cooper base platform (8) thermally coupled with the first-stage cold head (7), which is arranged to operate around 90K. Such design of the cryopackage allows the HTS RF filters and LNA array to operate at their different sufficient specific temperatures, resulting in reducing the heat load and power consumption and increasing cooler reliability. In addition, the two-stage configuration is capable of accommodating large HTS devices and the necessary electronic circuits, and the HTS filter subsystems construction is more rigid than the single stage option.

It should be pointed out that two specific challenges need more attention: (1) Ensure low losses in electronically connections without allowing too much heat to transfer from room temperature to the HTS RF filters and the LNA array, and (2) Guarantee the vacuum chamber to maintain its high vacuum for adequate thermal insulation for the cooling performance and the lifetime of the coolers.

CONCLUSIONS

In this paper we presented the performance study and system design of 60K pulse tube coolers for the purpose of developing a fully integrated, cryogen-free HTS RF filter subsystem for wireless telecommunications. Two different cold finger geometries of single-stage and two-stage pulse tube coolers were analyzed and designed. The construction of the cooled HTS filter subsystem integrated on the cold finger of the coolers was also described.

Comparison of general optimization parameters demonstrates that the specific PV work is saving about 35% and the heat generated by the compressor is decreasing about 30% by using the two-stage configuration than the single-stage option. The two-stage cold finger allows the operation of the HTS RF filters and LNA array at their different efficient specific temperatures, resulting in reducing the heat dissipation and increasing the cooler's reliability. In addition, the two-stage geometry is capable of accommodating large HTS devices and the necessary electronic circuits, and the HTS filter subsystems construction is more rigid than the single stage option.

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