SITP's Miniature Coaxial Pulse Tube Cryocooler

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ABSTRACT

A single-stage miniature coaxial pulse tube cryocooler (PTC) has been developed in Shanghai Institute of Technical Physics, Chinese Academy of Sciences (SITP/CAS) to serve as a perfect substitute for an existing Stirling cryocooler for providing reliable low-noise cooling for an infrared detector system. The challenging work is the exacting requirement on its dimensions, which have to adapt to the given dewar. A 1.5 kg dual opposed moving magnet compressor is used to realize light weight and low contamination. A large filling pressure of 3.5 MPa and high operating frequency of up to 67 Hz are adopted to increase the energy density, which will compensate for the decrease in working gas volume due to the miniature structure. The miniature dimensions also limit the phase-shifting ability of the system when the inertance tubes act as the only phase-shifting mechanism. The simulation suggests that a second orifice would be helpful to achieve the desired phase relationship. In the practical development, the inertance tube, composed of two sections with different inner diameter and length, act as the only phase-shifter to realize a reliable system. When the cold finger diameter and length are 10 mm and 53 mm, respectively, the miniature PTC achieves 1.6 W of cooling power at 90 K with 65 W of electric input power. The no-load temperature of 64.5 K is achieved in about 7 minutes. The design approach and trade-offs are discussed, and the parametric studies and the performance characteristics are presented

INTRODUCTION

Cryogenic infrared instruments are by far the largest application of space cryogenics, and Stirling cryocoolers have served as the main source of the regenerative refrigerators for decades.[1] The long history in some specific practical applications has resulted in many specifications being tailored to the specific geometry of these historic Stirling cryocoolers, and thus has made it difficult for newer replacement candidates, like the pulse tube cryocooler (PTC), to adapt to the geometry specifications.[2] As pointed out by Radebaugh[2], compared with Stirling, the PTC often requires a larger diameter cold finger for the same refrigeration power because of the presence of the pulse tube. Besides, the given dewar also limits the cold finger length, which usually deviates from the desired value in terms of a PTC. It is often thorny, but fascinating work to scale a PTC down to the miniature dimensions of an existing Stirling cooler while maintaining the same high efficiency.

One of the deciding factors in limiting the miniaturization of a PTC is the decrease of the working fluid volume. There exists a lower limit where the working substance could not transfer enough energy with unchanged operating parameters. A common, and maybe also the most effective solution for this, is to enhance the energy density of the working fluid to compensate for the decrease in quantity, usually by increasing the operating frequency and the average filling pressure. Radebaugh [3] gives a concise expression in terms of the miniaturization problem about the Stirling-type PTC:

$$\dot{W}_{PV} = \pi f V_1 P_0 \left(\frac{P_1}{P_0}\right) \cos\theta \tag{1}$$

where the term $\dot{W}_{PV}$ is the PV power, P_1 is the amplitude of the sinusoidal pressure, V_1 is the instantaneous volume amplitude, P_0 is the average pressure, and θ is the phase by which the volume flow leads the pressure. Equation (1) shows that the gross refrigeration power will decrease with decreasing size of a PTC, which is indirectly reflected by V_1. On the contrary, however, by increasing the frequency or the average pressure, the volume of the pulse tube can be decreased for the same gross refrigeration power.

The nature of increasing the average pressure is to enhance the energy density of the working fluid per unit volume. Both the principle and its realization are relatively simple. The nature of increasing the frequency is to enhance the energy density per unit time. Although this principle is easy to understand, its realization is quite complicated. The magnitude of the flow and the swept volume at the warm end become very large for a fixed flow and acoustic power at the cold end when the frequency is too high, and thus the regenerator losses become very high.[3] Meaningful attempts have been made to realize a micro PTC operating at very high frequency[4,5], and Petach et al.[6] have successfully worked out a coaxial PTC with an overall weight of 857 g, which can lift 1.3 W at 77 K with a reject temperature of 298 K and operate normally at 100 to 124 Hz. Considering that the cold finger diameter and length are only 11.2 mm and 48 mm, respectively, these geometric and performance characteristics give the micro coaxial PTC a potential to replace some existing typical Stirling cryocoolers for a given dewar without any change. Moreover, it even has the potential to replace J-T cryocoolers in special applications requiring very fast cool down.

SIMULATION AND DESIGN

Design Considerations and Method

In the Shanghai Institute of Technical Physics, Chinese Academy of Sciences (SITP/CAS), a single-stage high frequency miniature coaxial PTC has been developed to provide reliable low-noise cooling for an infrared detector system in a future space mission. The main aim of the development is to achieve a perfect substitute for the existing Stirling cryocooler. The required cooling capacity is 1.6 W at 90 K with an input electric power below 60 W. The more challenging work is the exacting requirement on its dimensions. In order to minimize the influence of the substitute on the overall system, the design and optimization work have to be fully responsive to the given interface restrictions. In particular, the newly developed PTC has to be inserted into the given miniature dewar, which determines that the length and outer diameter of the PTC cold finger must be smaller than 60 mm and 10 mm, respectively. The approach to the design and optimization of the miniature PTC is to employ an increased operating frequency and increased average filling pressure as discussed in the first paragraph.

In order to realize light weight, high efficiency, and low contamination, a 1.5 kg dual opposed linear compressor was selected to generate the oscillating pressure wave; it is based on moving magnet technology developed in SITP/CAS. Unlike the moving coil compressor, its motor coil is placed outside the working gas space, and thus eliminates the coil epoxy (the primary source of contamination) and electrical feed-throughs from the working gas space. Figure 1 shows the light moving magnet compressor with an overall length of 165 mm, a maximum swept volume of 3 cc, and a maximum electric input power of 100 W.

The design and optimization principle is to maximize the COP and/or the cooling capacity of the coaxial PTC under the restrictions of the cold finger dimensions. A computer simulation model has been established for performance prediction and optimization. The model is based on a finite difference method to solve the mass, energy and momentum conservation equations, and some empirical coefficients have been added considering the multidimensional effects in practical pulse tubes.[7] In the model, the geometrical and operating parameters are optimized at the same time to

Figure 1. The used 1.5 kg dual moving magnet linear compressor

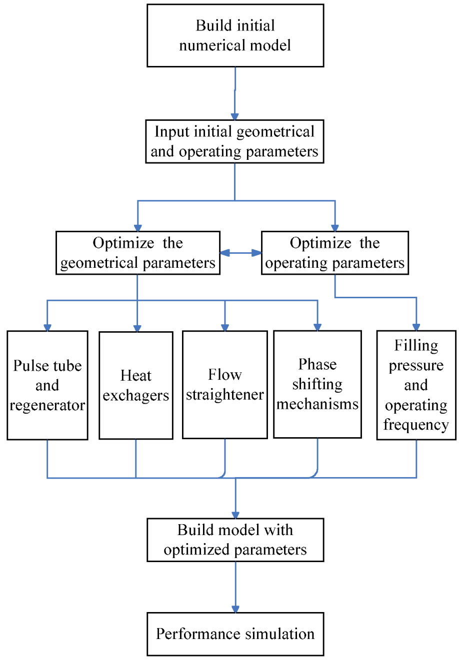

Figure 2. The working principle and flow diagram of the simulation model.

achieve the maximum COP and/or cooling capacity. Figure 2 shows the basic working principle and flow diagram.

Because the PTC adopts the coaxial arrangement in which the pulse tube is inserted into the regenerator, the dimension of the cold finger is the outer dimension of the regenerator. Therefore, for the dimensional optimization, the main problem has changed into determining the appropriate length of the regenerator and the optimum dimension of the pulse tube when the outer diameter of the regenerator is restricted to 10 mm.

In the simulation, the regenerator tube is made of stainless steel and the regenerator matrix uses #400 mesh stainless steel screens. For the coaxial arrangement, heat transfer between the pulse tube and regenerator due to the temperature mismatch can be a significant loss. And thus the pulse tube uses a special type of titanium alloy with low thermal conductivity to minimize the heat transfer along the radial direction. Also, the pulse tube and regenerator will be designed with different lengths to get the ideal temperature match.

Simulation and Optimization of Regenerator and Pulse Tube Dimensions

Fig. 3 shows the simulation results of the variation of COP and cooling capacity at 90 K with the regenerator length from 45 mm to 60 mm. A 53 mm long regenerator was selected, based on simultaneous considerations of its effect on the COP and cooling capacity.

After the regenerator dimensions were fixed, the inner diameter and length of the pulse tube were optimized together to find their optimum dimensions. Figs. 4 and 5 show the effects of the length and inner diameter of the pulse tube on the cooler performance at 90 K. The model suggests a larger pulse tube length and inner diameter. However, for the coaxial configuration with a fixed outer diameter of the regenerator, a large pulse tube volume means that a large phase angle has to be produced by the phase-shifting mechanism in order to obtain satisfactory performance. Thus, a moderate inner diameter of 5 mm and a length of 76 mm were selected considering the design trade-offs.

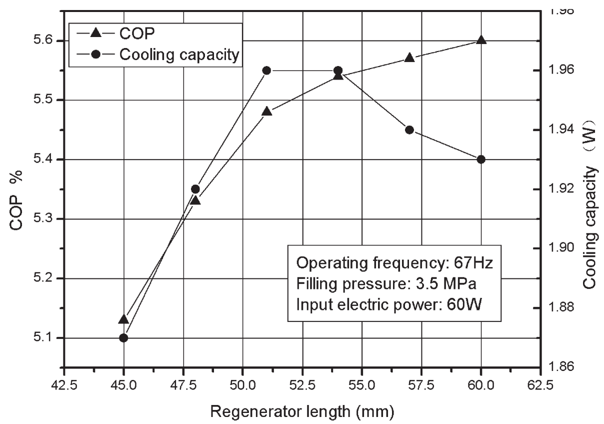

Figure 3. Simulation result of COP and cooling capacity at 90 K versus regenerator length.

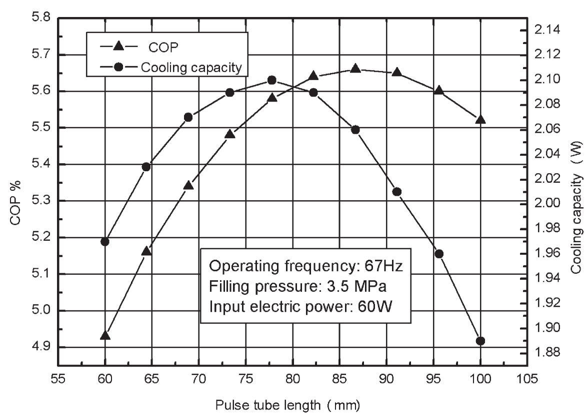

Figure 4. Simulation result of COP and cooling capacity at 90 K versus regenerator length.

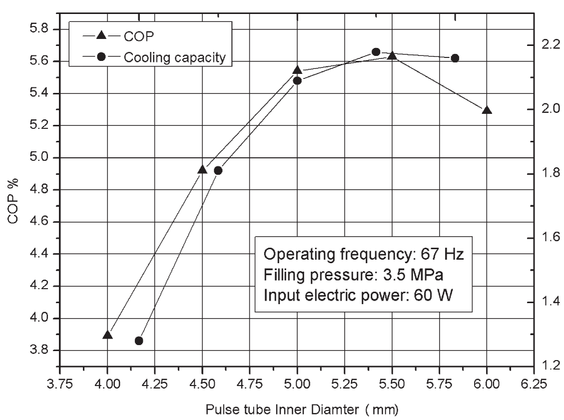

Figure 5. Simulation result of COP and cooling capacity at 90 K versus pulse tube inner diameter.

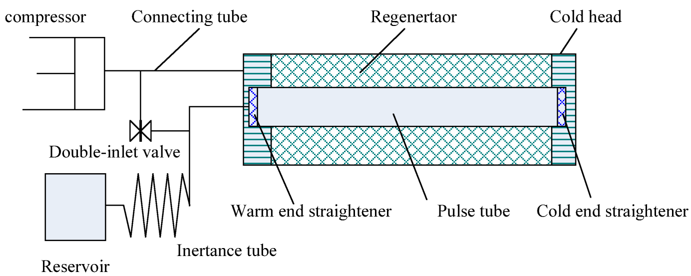

Figure 6. The schematic of the arrangement of the simulated miniature PTC.

Table 1. Simulated results under different phase shifting mechanisms.

Phase shifting mechanisms	$T_{no\text{-}load}$ (K)	Q@90K (W)	COP (%)	θ (degree)	$\dot{m}_h$ (g/s)	$\dot{m}_c$ (g/s)	$\dot{m}_{DC}$ (g/s)	Pr1	Pr2
Use only Inertance tube	59	2.09	5.54	-7.46	0.93	0.85	---	1.258	1.179
Add a symmetric double inlet	55	2.1	5.7	-9.59	1.028	0.96	-5.86E-04	1.26	1.19
Add an asymmetric double inlet	55	2.16	5.75	-9.56	1.024	1.09	-6.02E-14	1.26	1.19

Simulation and Optimization on Phase Shifting Mechanism

Once the dimensions of the pulse tube and regenerator were obtained, the simulation was used to predict the oscillating flow characteristics and determine the optimal dimensions of the phase-shifters. In the model, three types of phase-shifters are used: inertance tubes, symmetric double-inlet valves, and asymmetric double-inlet valves. A schematic of the arrangement is shown in Figure 6. The wall temperature of the cold-end and warm-end heat exchangers were set as 90K and 300K, respectively. The mean filling pressure was set as 3.5MPa, and the operating frequency is 67 Hz.

Table 1 shows some key parameters under optimal conditions with different phase shifting mechanisms. The data suggest that the phase difference between mass flow and pressure at the cold end of the regenerator (θ) would be only -7.46 degree if only an inertance tubes were used for phase-shifting. The value is far below -30 degree, which is the optimal phase difference in a PTC. This is also one of the reasons why a miniature pulse tube of these dimensions has difficulty achieving a satisfactory performance.

When a symmetric double inlet opening was added as an additional phase-shifter, the no-load temperature decreased 4 K, and the efficiency increased somewhat. Table 1 also shows that the pressure ratio at the cold end of the regenerator (Pr_2) increased from 1.179 to 1.19 , while the phase difference increased from -7.46 degree to -9.59 degrees, which accounts for the improvement in performance. The pressure ratio at the compression space (Pr_1) also increased somewhat. However, the mass flow rate of the regenerator at the warm and cold end ($\dot{m}_h$and $\dot{m}_c$) also increased, which results in higher entropy generation. That is why the cryocooler's efficiency doesn't increase remarkably. An asymmetric double inlet valve was also investigated to eliminate the DC mass flow caused by the double inlet circuit. As shown in Table 1, the DC mass flow $\dot{m}_{DC}$ is almost eliminated under the optimized asymmetric degree. Additionally, the cryocooler performance has a little increase. Although the simulation results predict that a better performance can be obtained by a double inlet mechanism, it was not adopted in the present design to avoid adding complexity that could negatively affect the system reliability.

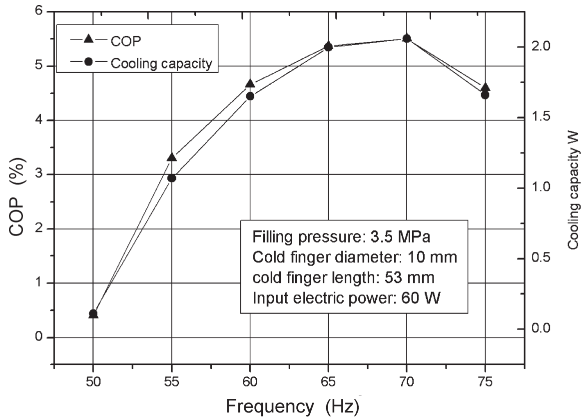

Figure 7. Simulation result of performance at 90 K versus operating frequency.

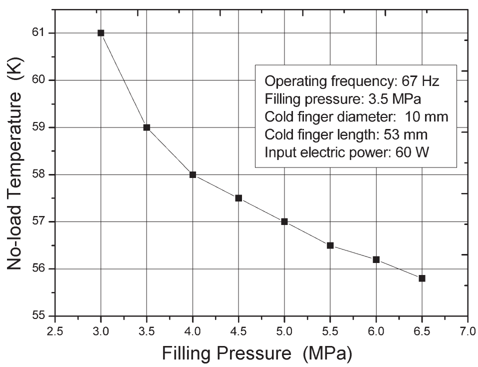

Figure 8. Simulation result of no-load temperature at 90 K versus filling pressure.

Simulation and Optimization on Frequency and Filling Pressure

The simulation has been completed on the effects of the mean pressure and operating frequency for the optimized cooler dimensions and phase-shifting mechanism. Finger 7 shows the predicted variation of the cooling performance at 90 K with operating frequency. The optimum frequency is between 65 to 70 Hz. Figure 8 shows the variation of the no-load temperature with filling pressure.

The no-load temperature decreases monotonically with increasing average pressure up to 6.5 MPa. However, for safety considerations with the thin walled tubes, the filling pressure was set to 3.5 MPa. The numerical simulation suggests that the cooler can provide about 2.0 W of cooling at 90 K with 60 W of input electric power and a reject temperature of 300 K.

PRELIMINARY EXPERIMENTAL RESULTS

Figure 9 shows several finished cold fingers with and without warm heat exchangers, and with or without vacuum bonnets. Figure 10 shows an experimental prototype, in which the inertance tube is still out of the gas reservoir. The system is a split arrangement, and a 30cm flexible copper tube is used to connect the compressor with the pulse tube cold finger. The regenerator was bolted to the warm-end flange and will be finally hermetically welded in the future EM.

Figure 11 shows a typical cooldown curve. With an input electric power of 80 W and a reject temperature of 310 K, the cooler reaches a no-load temperature of 64.5 K in 7 minutes. Figure 12 shows the variation of cooling capacity with input electrical power. A typical cooling performance of 1.6W at 90K was achieved with 65W of input electric power.

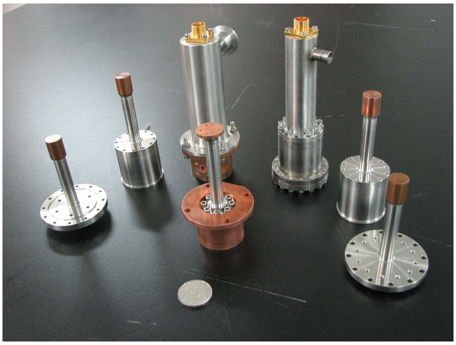

Figure 9. A series of finished cold fingers.

Figure 10. Experimental prototype

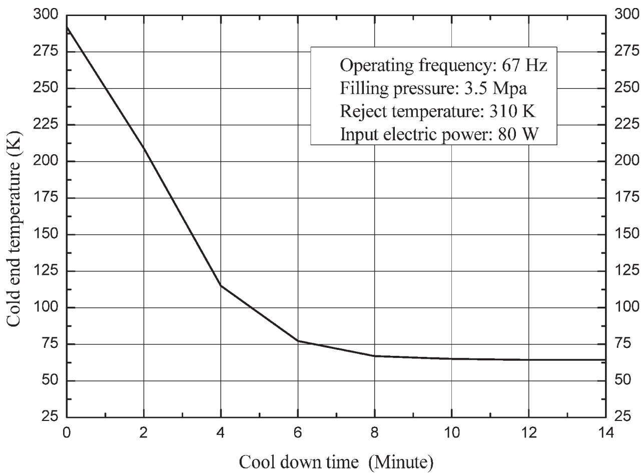

Figure 11. Cool down curves.

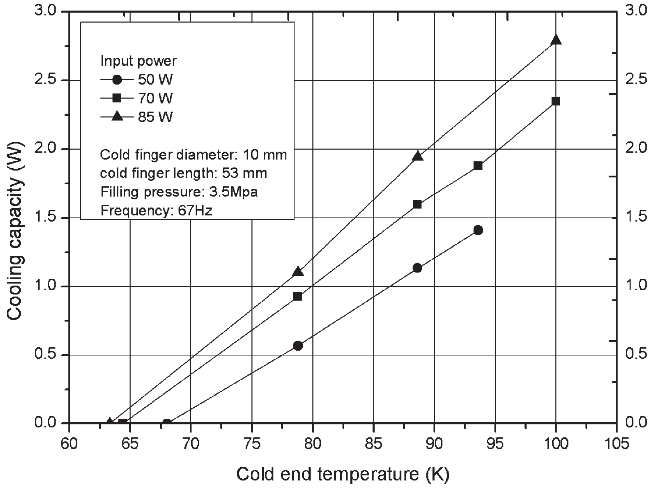

Figure 12. The experimental cooling performance.

DISCUSSION AND CONCLUSIONS

PTC technology has made rapid advancements in recent years, and two remarkable advantages of PTCs have emerged. These include the elimination of moving parts and potential wear at the cold end, and the significantly reduced vibration output level of the cold finger due to the absence of a moving displacer. These advantages have provided the PTC with the potential to replace Stirling coolers in cooling infrared sensors. However, the long history in some specific practical applications has resulted in many specifications being tailored to the geometry characteristics of the Stirling cryocoolers, especially for the miniature cryocoolers. It is therefore a significant challenge to scale a PTC down to match the miniature dimensions of a Stirling, while maintaining high efficiency. The use of a higher drive frequency and a higher filling pressure provides one feasible solution for achieving the necessary match. However, the optimization of dimensional and operational parameters for minimizing the losses still needs to be improved.

SITP/CAS has developed a single-stage miniature coaxial PTC to serve as a perfect substitute for an existing Stirling cryocooler. Preliminary experiments shows that it can achieve 1.6 W of cooling power at 90 K with 65 W of electric input power, and the no-load temperature of 64.5 K can be achieved in about 7 minutes. The cold finger diameter and length are 10 mm and 53 mm, respectively, and it operates at 67 Hz with a filling pressure of 3.5 MPa. The overall weight including the moving magnet compressor is below 2.5 kg. The above performance and characteristics suggest that it is feasible for the miniature PTC to substitute for the exiting Stirling system in the near future. Optimization experiments and efforts to realize an engineering model of the prototype cooler are underway.

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