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10 W/90 K single-stage pulse tube cryocoolers

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ABSTRACT

A single-stage 10 W/90 K coaxial pulse tube cryocooler has been developed for space-borne optics cooling. The design considerations are described, and the optimizations on the double-segmented inertance tubes are presented. The preliminary engineering model (EM) of the cooler has been worked out, which typically provides the cooling of 10 W at 90 K with the input power of 175.6 W at 310 K reject temperature, and achieves around 14% of Carnot efficiency at 90 K. The reject temperature dependence experiments on the EM show a smaller slope of 10.2 W/10 K and indicate a good adaptability to the reject temperature range from 290 K to 333 K.

1. Introduction

In some space-based systems in terms of long wave infrared (LWIR) focal plane arrays (FPAs), there are strong demands on cooling their optics at the same time when the FPAs are cooled [1–15]. The cooled optics contributes to minimize background thermal noise and noticeably enhance the detection sensitivity of the detectors. The cooling requirements vary with the specific applications, and generally, the working temperatures are relatively high (normally 85–150 K) and the heat loads are considerably large (normally 6–20 W). A variety of cryocoolers have ever been developed to meet the needs. For example, both NGAS's 95 K single-stage high efficiency pulse tube cryocoolers (PTCs) [5] and Raytheon's 95 K high efficiency hybrid Stirling/pulse tube coolers [6] were originally developed dedicatedly for the optics cooling. NGAS's high capacity two-stage PTCs [7,8], Lockheed Martin's two-stage PTCs [9–11], Raytheon's two-stage hybrid cryocoolers [12–14] and CEA/SBT's two-stage high-temperature PTC [15] were all developed to simultaneously cool the LWIRFPAs at the second stage, as well as provide cooling for optics at the first stage.

The similar attempts have been made in the authors' group using a single-stage U-type PTC with the base cooling capacity of 8 W at 150 K for the potential application of a small-scale optics system [16]. Recently, with the rapid progress of the related technologies, the cooling demands become much more strict for the larger-scale or more complicated optics systems, of which two important aspects are emphasized, that is, lower operating temperatures (such as lower than 100 K) and higher cooling capacity (such as over 10 W). The lightweight is stressed on. The more challenging problem is caused by the high heat loads and the limited radiator capacity, and thus the high cooler efficiency is specially emphasized in order to counteract the adverse effects [5,6]. The cooling system also faces the harsh heat rejection conditions (normally at 310 K). In response to the above requirements, high efficiency, high capacities at lower temperatures, lightweight, and the ability to working at high reject temperature have thus become the main concerns.

2. Cooler design and optimization

2.1. Design considerations and development goals

In recent years, some important technical progresses have been made on the high frequency single stage coaxial PTCs in the authors' group, and the developed coaxial prototypes operating over 50 K become relatively mature and their efficiencies have already exceeded those of U-type rivals [17,18]. While the additional advantages such as the compactness and lightweight are also considered, the coaxial arrangement rather than the U-type has been chosen for the development.

At the same time, although the two-stage coolers capable of cooling the LWIRFPAs and optics simultaneously are flourishing [7–11,15], a separate single-stage cooler dedicated for optics cooling is still attractive since it is beneficial to achieving a more flexible system. Therefore, a single-stage cooler is determined in the program.

The double-inlet [19] had been proven to be an effective means to increase the thermodynamic performance of the PTC and has been used widely since 1990s [20]. However, the potential performance instability induced by the possible DC effect [21] becomes a knotty problem for special fields such as in space where high reliability and long life are of premium importance [20]. The inertance tube, normally accompanying with a gas reservoir, if used only,

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Table 1
Key development goals of the PTC for optics cooling.

Parameters	Design goal
Stage arrangement	Single-stage
Geometrical arrangement	Coaxial
Phase-shifting mechanism	Inertance tube together with gas reservoir
Cooling requirement	⩾10 W@90 K
Reject temperature	310 K
Power consumption (electric input power)	⩽180 W
Mass (excluding control electronics)	⩽9.0 kg
Ambient temperature adaptability	243–333 K
Temperature stability	±0.1 K
Vibration output of the cold head	⩽0.1 N (rms)
Expected lifetime	⩾50,000 h

will rule out the possibility of DC flow in the PTC system [20]. Therefore, in order to achieve the high reliability for the space-borne optics cooling, the phase-shifting mechanism of the developed PTC is limited to the inertance tube and its accompanying gas reservoir in the present development.

Table 1 gives the key development goals of the PTC for optics cooling. The cooler is expected to provide at least 10 W at 90 K with no more than 180 W into the compressor at the reject temperature of 310 K. The lightweight and the demanding ambient adaptability (up to 333 K) are especially emphasized.

2.2. Optimizations on the double-segmented inertance tubes

Fig. 1 shows the schematic of the developed single-stage coaxial inertance PTC. It uses a dual opposed piston linear compressor with a maximum swept volume of 8.5 cc, which is connected to the cold finger by a 32 cm flexible tube with an inner diameter of 5.0 mm. The inner diameters of the regenerator and pulse tube are determined to be 28.6 mm and 13 mm, respectively. The gas reservoir volume is 450 cc. The constant 400 mesh stainless steel stacked screens are used as the regenerator matrix. The working gas is helium and the mean filling pressure is 3.2 MPa. The 52 Hz is chosen as the operating frequency. The cooler optimization is based on the above initial dimensional and operating parameters.

For a PTC with the high potential cooling capacity, after the key dimensional and operating parameters are given, the phase-shifting mechanism becomes critical since it is the phase-shifter that exploits the cooling potentialities under the given cooler dimensions and geometrical construction. Based on our previous experience on designing high-capacity coaxial PTCs operating above 50 K, a single inertance tube with a constant inner diameter often has great difficulty in obtaining the desired phase relationships [17,22]. Therefore, the double-segmented inertance tube with different diameters and lengths, respectively, has been used to achieve a satisfactory phase shift within the acceptable tube length, as shown in Fig. 1. Because the combinations of the two segments are nearly infinite, in order to simplify the optimization process, the inner diameters of the two inertance tubes are fixed to be 3.5 mm and 5.0 mm based on the practical experiences, respectively.

The simulation model [17,23] is based on a finite difference method to solve the mass, energy, and momentum conservation equations of the working gas in the PTC. For the inertance tube PTC, the conservation of momentum equation for the working fluid is [20]:

$$-\frac{\partial \boldsymbol{P}}{\partial x} = \frac{f_r|\dot{m}|\dot{\boldsymbol{m}}}{2r_h\rho A_g^2} + \frac{\partial}{\partial t}\left(\frac{\dot{\boldsymbol{m}}}{A_g}\right) + \frac{\partial}{\partial x}\left\{\frac{1}{\rho}\left(\frac{\dot{\boldsymbol{m}}}{A_g}\right)^2\right\} \tag{1}$$

and the conservation of mass equation is [20]:

$$\frac{\partial}{\partial t}\left(\frac{\dot{\boldsymbol{m}}}{A_g}\right) = -\frac{\partial \dot{\rho}}{\partial t} = -\frac{\dot{\boldsymbol{P}}}{RT_0} \tag{2}$$

where the bold variables represent time-varying complex variables or phasor quantities, x is the coordinate in the flow direction, f_r is the Darcy friction factor, r_h is the hydraulic radius, ρ_0 is the density at the average temperature and pressure, A_g is the cross-sectional area of the gas perpendicular to the flow direction, and t is time. Eqs. (1) and (2) show phase relationships between flow and pressure.

In the model, some empirical coefficients have been added considering the multi-dimensional effects in the practical pulse tubes. The optimization principle is to maximize COP and/or cooling capacity. The process of the inertance tube lengths optimization is given as follows. During the simulations, the temperatures at warm and cold ends are set as 310 K and 90 K, respectively, and the piston amplitude is set at its 80% stroke. A summary of initial dimensional and operating parameters for the inertance tube optimization is shown in Table 2.

Fig. 2 shows the simulation results of the variations of COP and cooling capacity at 90 K with the length of the first segment (Inertance I) between 0.5 m and 2.0 m. It should be mentioned

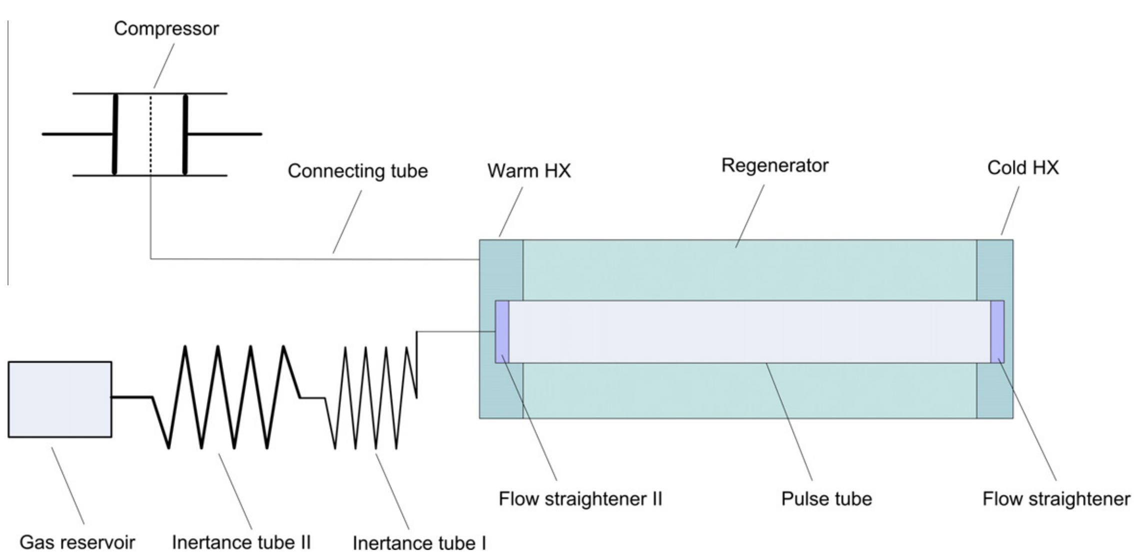

Fig. 1. Schematic of the high frequency PTC with three typical geometrical arrangements.

Table 2
A summary of initial parameters for inertance tube optimization.

Parameters	Values
Maximum swept volume of compressor	8.5 cc
Regenerator matrix	Constant 400-mesh stainless steel stacked screens
Connecting tube	32 cm long with an inner diameter of 5.0 mm
Inner diameter of regenerator	28.6 mm
Inner diameter of pulse tube	13 mm
Gas reservoir volume	450 cc
Inner diameter of Inertance tube I	3.5 mm
Inner diameter of Inertance tube II	5.0 mm
Filling pressure	3.2 MPa
Operating frequency	52 Hz
Cold temperature	90 K
Warm temperature	310 K
Piston amplitude	80% stroke

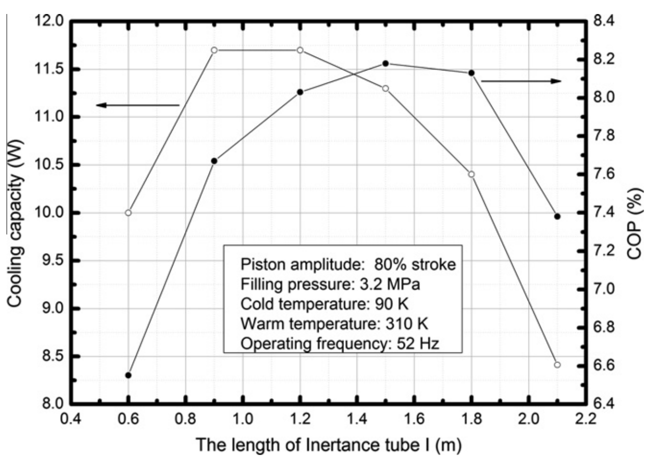

Fig. 2. Simulation results of variations of COP and cooling capacity at 90 K with the length of Inertance I.

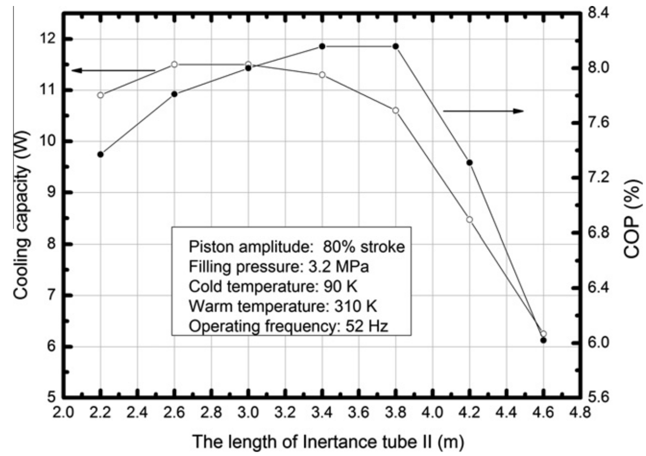

Fig. 3. Simulation results of variations of COP and cooling capacity at 90 K with the length of Inertance II.

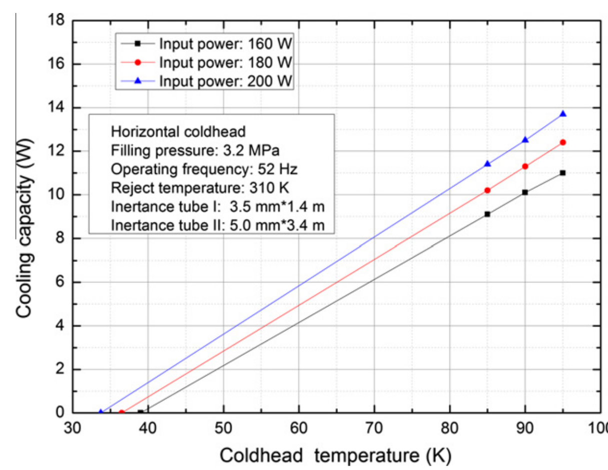

Fig. 4. Simulation results of cooling performance based on the optimized inertance tube dimensions.

that, when the optimal length of Inertance I is being traced, the length of the second segment (Inertance II) also changes as a variable. However, at this step only the variation of Inertance I is focused on. As shown in Fig. 5, when both COP and cooling capacity are considered, 1.5 m is chosen to be an optimal value. According to the same principle, the optimum value of the length of the second segment (Inertance I) is determined to be 3.4 m, as shown in Fig. 3.

Based on the above optimized dimensions of the inertance tubes, the cooling performance of the cooler can be simulated, as shown in Fig. 4. The cooling capacity of 10.1 W at 90 K can be achieved when the input power of 160 W into the compressor is provided. The cooling capacities increase to 11.3 W and 12.5 W at 90 K, respectively, when the corresponding input powers increase to 180 W and 200 W. About 15.4% of Carnot efficiency at 90 K can be achieved in the simulations.

The performances at 85 K and 95 K are also shown in Fig. 4 as supplements. It should be mentioned that when the performances at 85 K and 95 K are simulated, the cold temperatures in the simulations should be set as 85 K and 95 K, respectively.

2.3. Engineering model

The design and fabrication of the 90 K/10 W coaxial PTC are relatively mature. At present, its preliminary engineering model (EM) has already been worked out. Fig. 5 shows the photograph of the EM without the control electronics. The main cooler components are marked.

The major difference between the EM and the schematic shown in Fig. 1 is that the inertance tubes are completely inserted into the gas reservoir in the EM, and then the reservoir is coupled directly to the warm heat exchanger. The main aim of the improvement is to acquire a compact and robust cooler system suitable for the future practical application.

3. Experimental performance characteristics

The experiments have been conducted on the EM described above. During all the measurements, the cold head is kept horizontally. The filling pressure is 3.2 MPa, and the operating frequency and reject temperature are kept constant at 52 Hz and 310 K, respectively.

3.1. Experimental cooling performance

Fig. 6 shows the typical cool-down curve of the EM. It takes about 32 min for the cold head to cool down from 298 K to the no-load temperature of 41.2 K.

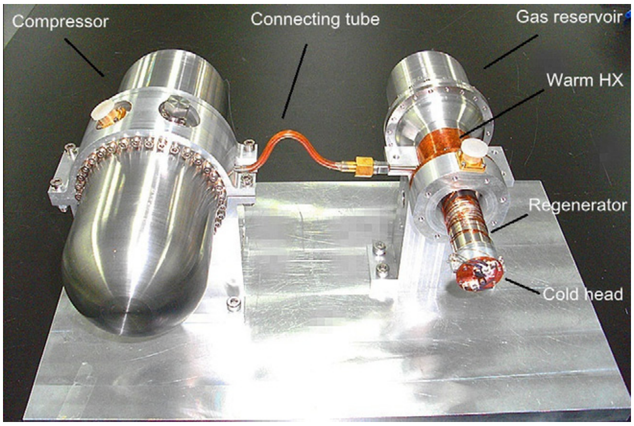

Fig. 5. The engineering model (EM) of the developed PTC.

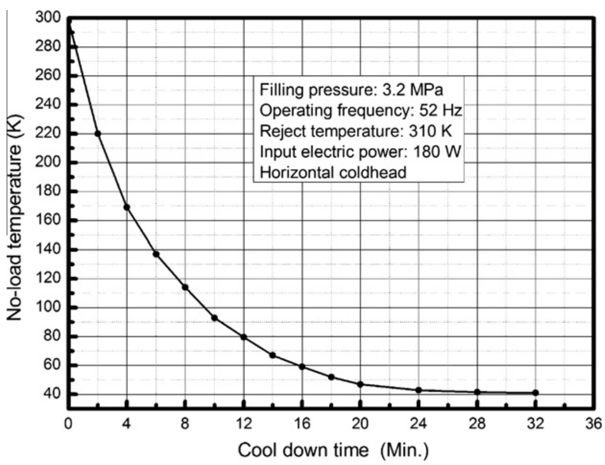

Fig. 6. The typical cool-down curve.

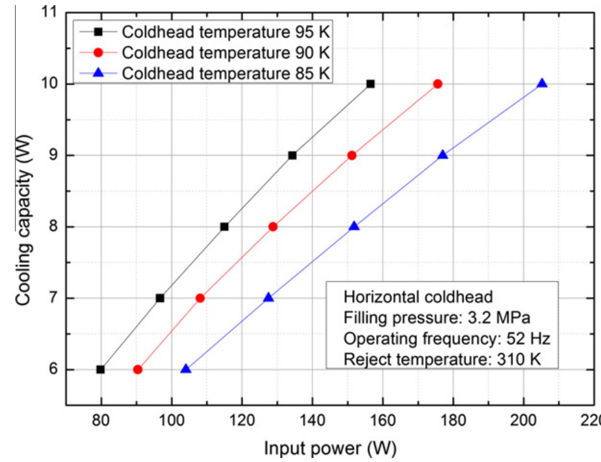

Fig. 7. Typical experimental performances at 85 K, 90 K, and 95 K, respectively. Horizontal cold head. 310 K reject temperature.

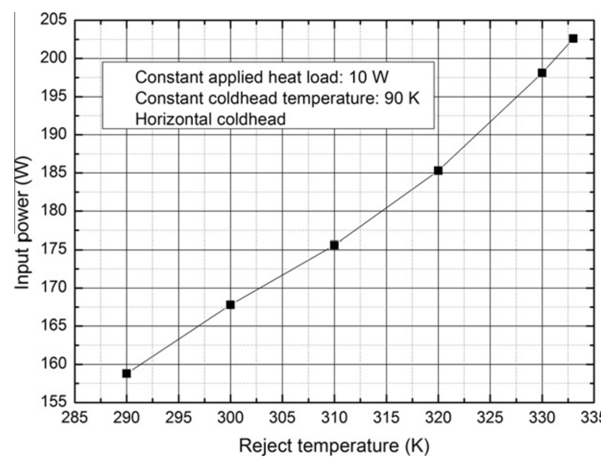

Fig. 8. Reject temperature dependence experiment with constant heat load and cold temperature of 10 W and 90 K, respectively. Horizontal cold head.

Fig. 7 shows the experimental results of the cooling performances of the EM at 85 K, 90 K, and 95 K, respectively. The typical performance is to provide the cooling power of 10 W at 90 K with an input power of 175.6 W into the compressor at 310 K reject temperature. About 14% of Carnot efficiency at 90 K has been realized. The cooling capacity of 10 W at 85 K and 10 W at 95 K can also be achieved when the corresponding input power of 205.2 W or 156.5 W are provided, respectively.

The experimental cooling performances are poorer than the corresponding simulation results in Fig. 4 to a certain extent. In the preliminary analyses, besides the model needs to be further improved, another two factors are found to be important. One is the slight flow oscillation in the gas reservoir caused by inserting the inertance tubes into the reservoir in the EM, while in the model the inertance tube is outside, and the reservoir is also assumed to be large enough so that the gas inside can be regarded as be in absolute stability. The other factor is that coupling the reservoir directly to the warm heat exchanger deteriorates the heat dissipation. The cooling efficiency often has to be sacrificed when the cooler steps from an experimental prototype to the EM.

3.2. Reject temperature dependence

One of the main development goals of the 10 W/90 K PTC is the ability of working well at high reject temperatures. Therefore, the reject temperature dependence experiments have been conducted on the EM in a wide reject temperature range from 290 K to 333 K. Fig. 8 shows the variations of the input power with the reject temperature when the heat load and cold head temperature are kept at constant 10 W and 90 K, respectively. The input power increases from 158.8 W to 202.6 W while the reject temperature changes from 290 K to 333 K. The mean increasing slope is about 10.2 W/10 K, which is evidently lower than the corresponding value of 16.3 W/10 K of the single-stage 40 K PTC [24], or 23 W/10 K of the high capacity 60 K PTC [25], respectively, developed in the same group. It indicates that the developed 10 W/90 K PTC apparently has a much better adaptability to the adverse rejection conditions.

4. Discussions and conclusions

A single-stage 10 W/90 K coaxial pulse tube cryocooler has been developed for space-borne optics cooling. The development goals are high efficiency, lightweight and adaptability to high reject temperatures up to 310 K. The design considerations are described, and the optimizations on the double-segmented inertance tubes are presented.

The preliminary engineering model (EM) has been worked out, which typically provide the cooling capacity of 10 W at 90 K with the input power of 175.6 W at 310 K reject temperature. Around 14% of Carnot efficiency at 90 K has been realized. The cooling capacity of 10 W at 85 K and 10 W at 95 K can also be achieved when the corresponding input power of 205.2 W and 156.5 W are provided, respectively.

With the constant heat load of 10 W and cold temperature of 90 K, the input power increases from 158.8 W to 202.6 W while the reject temperature changes from 290 K to 333 K. The mean increasing slope of 10.2 W/10 K is obviously lower than the corresponding values of the single-stage 40 K PTC and high capacity 60 K PTC developed in the same group, respectively. The experiments indicate that the developed 10 W/90 K PTC apparently has a much better adaptability to the harsh heat rejection conditions.

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