Development of 150 K-200 K Pulse Tube Cooler for Infrared Detector

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ABSTRACT

To meet the needs of infrared imaging systems for space observation, an Infrared Focal Plane Array (IRFPA) detector must maintain low dark noise. This is achieved by cooling the detector to a cryogenic temperature. Due to its advantages of low vibration and high efficiency, a Stirling-type pulse tube cryocooler (PTC) is well positioned to fulfill this need for detector cooling.

The present work introduces a PTC prototype that is composed of a moving-magnet linear compressor and a coaxial pulse tube cold finger for compactness and integration ease. This cooler provides a cooling power between 40 W - 90 W at 150 K - 200 K. The oscillating linear compressor has a pair of opposing pistons to eliminate vibration, and the maximum electrical input is 500W. Using Maxwell software, parametric optimization of the linear motor has been carried out. A method of co-simulation has been used based on a combined electrical-mechanical-acoustic model. Upgrades to the mass-spring system of the compressor have been accomplished to improve the cooler resonance. Several matching experiments of the compressor and cold finger have been conducted.

A typical cooling performance of 50 W at 170 K has been achieved with 230 W electrical power input at a rejection temperature of 293 K. The motor efficiency and specified Carnot efficiency are 92% and 16%, respectively.

INTRODUCTION

Stirling-type pulse tube coolers (PTC) are used widely due to high efficiency and reliability.[1] For high-temperature infrared detectors, the required operating temperatures are above 150 K. Air Liquide has developed a pulse tube cooler to cool infrared detectors for microsatellite missions. The required cooler temperature is from 150 K to 200 K with a cooling power between 1 W - 3 W.[2] Lockheed Martin has developed a micro pulse tube cryocooler for Avionics and space applications. The system is compact and can provide cooling loads of 0.85 W at 150 K with 10 W of power input.[3] Northrop Grumman Aerospace Systems has designed and tested a very small, low vibration, high frequency cooler to be directly integrated into space SWIR. Despite its small size, the tested cooler is capable of providing nearly 5 W of cooling at 150 K when rejecting heat to 300 K.[4] A high performance cryocooler (RAM) has been built by Raytheon. It provides 10 W of cooling at 150 K with ~100 W input power.[5] As can be seen, pulse tube coolers operated above 150 K are in great demand for infrared detectors. With the development of large FPA detectors, more CCDs or CMOSs are integrated into the system. Therefore, increased cooling power will be needed to eliminate the dark noise induced by these larger detectors.

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At the Shanghai Institute of Technical Physics (SITP), Chinese Academy of Science (CAS), a series of pulse tube coolers has been manufactured. The typical cooling capacity is about 5 W-10 W at 60 K-90 K.[6] In recent work, a 150 K-200 K pulse tube cooler has been designed, fabricated and tested for cooling large FPA detectors generating 100 W of heat. This cooler provides a cooling power between 40 W-90 W at 150 K - 200 K. The oscillating linear compressor has a pair of opposing pistons to eliminate vibration, and the maximum electrical input power is 500W. A typical cooling performance of 50 W at 170 K has been achieved with 230 W electrical power input at a rejection temperature of 293 K. The motor efficiency and specified Carnot efficiency are 92% and 16%, respectively. The cooling performance of the PTC at 200 K - 230 K has also been examined.

PULSE TUBE COOLER

The coaxial PTC is comprised of a linear compressor, a pulse tube cold finger assembly, and a connecting tube, as shown in Fig. 1. The linear compressor consists of two moving magnet linear motor modules with dual-opposed pistons and a cylindrical hub. The cold finger (including regenerator, pulse tube, heat exchanger and cold exchanger) and the phase shifter (including inertance tube and reservoir) are connected with the compressor by a transfer tube.

Figure 2 shows the split configuration PTC without the drive electronics. The cooler weighs 11.8 kilogram. This includes the 9.5 kilogram compressor and the 2.3 kilogram cold finger assembly.

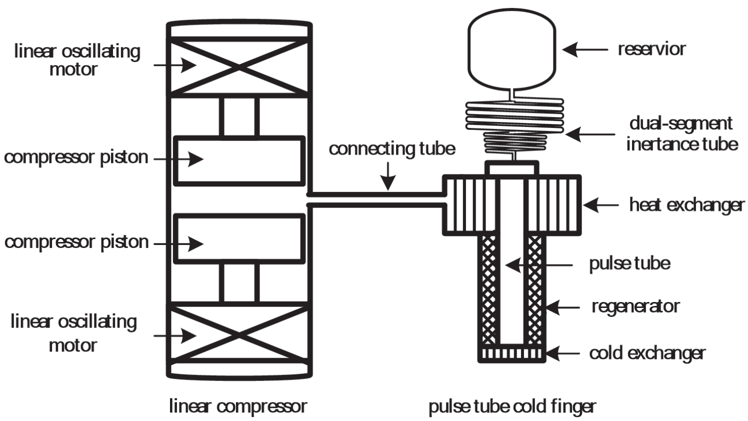

Figure 1. Main structural drawing of coaxial PTC

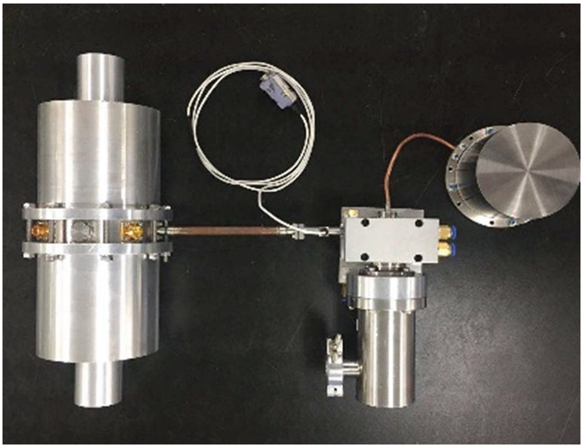

Figure 2. Photo of the PTC

The regenerator is a typical micro-porous metallic structure, and the working gas flows back and forth periodically. Some improvements have been made to reduce the irreversible thermal and hydrodynamic losses in the regenerator. Based on the working temperature range, stainless steel screens have been chosen as the matrix.

The heat exchanger and cold exchanger are made of copper, and an optimized flow straightener has been added to avoid turbulence in the PT. High quantity slits are fabricated in the exchangers to enhance the heat transfer.

The pulse tube is a hollow tube made of 316L stainless steel. Compression and expansion processes of the working gas in the pulse tube are adiabatic; therefore a 'gas piston' is generated in the middle of the tube that maintains the temperature gradient between the ends of the pulse tube.

In addition, the inertance tube and the reservoir help to adjust the phase angle between mass and pressure to achieve good cooling performance at the cold end.

Also shown in Figure 2 is the configuration of the PTC instrumentation with a linear velocity differential transducer (LVDT) at both ends of the compressor, and a pressure transducer at the inlet of the cold finger. The measured PV power can be obtained by the following calculation,

$$W_{pv} = 2P \cdot Ax \cdot \cos\theta \qquad (1)$$

where P is the average pressure, A is piston area, x is operating stroke of each opposed piston, and θ is the phase angle between pressure and mass flow. The total measured PV power is double for the pair of compressor pistons. This allows easy calculation of the PV efficiency, which is one of the best ways to evaluate the performance of the compressor.

EXPERIMENTS

The compressor was driven by an AC power supply, with a power meter used to monitor the voltage, current, input power and the power factor. The movement of the pistons was measured in real time by linear variable displacement transducers (LVDTs) anchored at the axial ends of the compressor. The pressure wave was measured by a pressure transducer between the compressor and cold finger. The experimental setup is illustrated in Fig. 3.

Figure 4 shows that the PTC cold head can be cooled to its lowest temperature under no load in less than 5 minutes. The no-load temperatures are 61.2 K and 59.5 K with 200 W and 250 W input power, respectively, at 293 K rejection.

The effect of different charging pressures on the cooling performance of the PTC has been studied at a cooling performance of 50 W at 170 K and 60 Hz. As shown in Fig. 4, it can be seen that under different charging pressures only a slightly difference (less than 5 W) occurred in input power of the compressor. The minimum required input power is 230 W at the cooling performance of 50 W at 170 K.

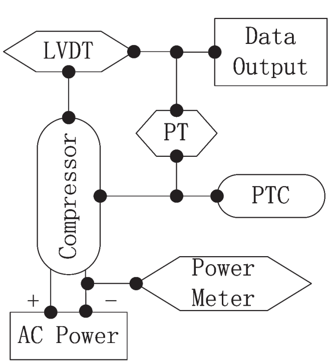

Figure 3. Experimental setup

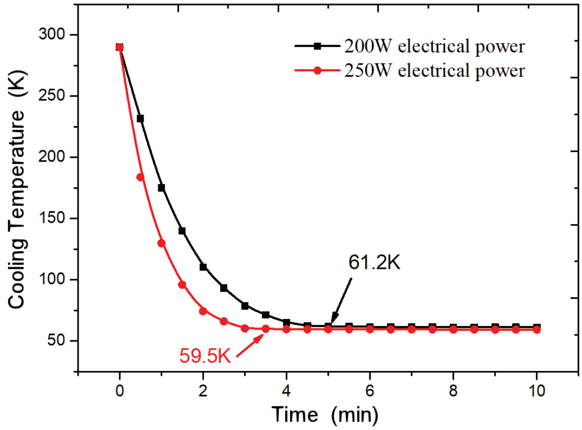

Figure 4. Cooling down of the PTC under no load

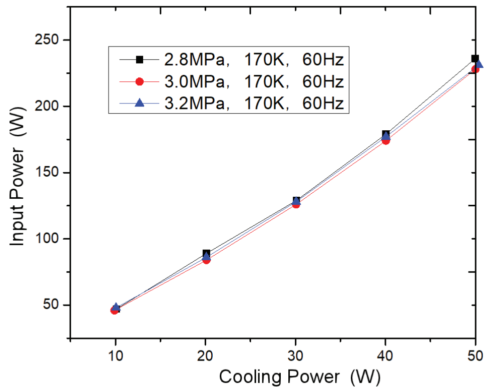

Figure 5. Cooling performance of the PTC at 170 K

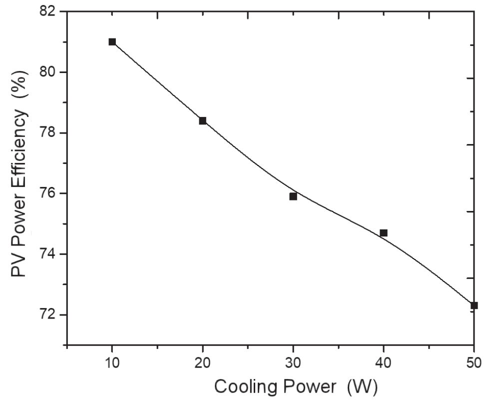

Figure 6. PV power efficiency vs. cooling power at 170 K

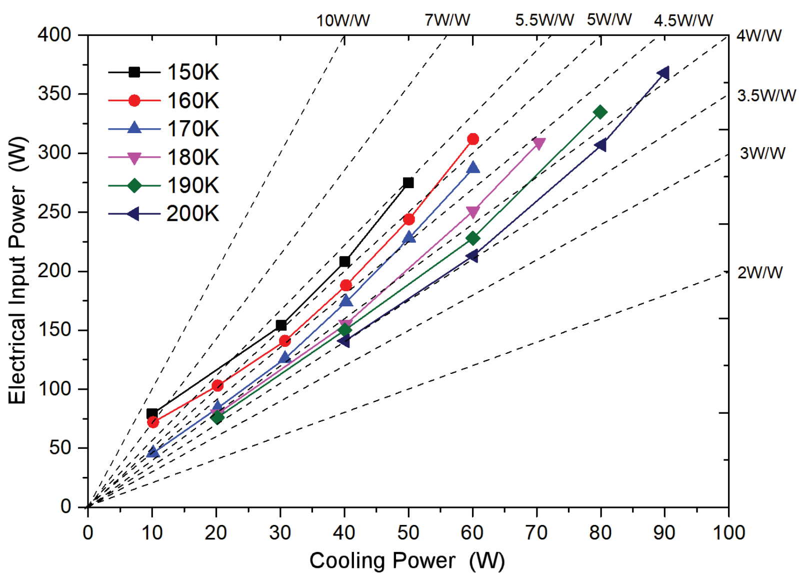

Figure 7. Cooling performance of the PTC at 170 K - 200 K

When the PTC operates at 170 K, the PV power efficiency vs. cooling power is shown in Fig. 6. The PV efficiency decreases from 81% to 72% as the cooling power increases from 10 W to 50 W. The reason is that the mechanical friction loss between pistons and cylinder and irreversible losses in the working gas both increase as the displacement increases. Better manufacturing can help to reduce these relative losses and improve the performance of the PTC.

Figure 7 shows the performance of the PTC over a range of temperatures and cooling powers for a reject temperature of 293 K. The measured datapoints are shown in reference to specific power (cooling power divided by electrical power) denoted by the dashed lines. The input power is the measured electrical power to the cooler not including any power dissipated in its drive electronics. Note the excellent specific power of ~3.5 W/W at 200 K, ~4.5 W/W at 170 K and ~5.5 W/W at 150 K for the PTC. The maximum cooling power is 60 W at 170 K with 275 W input power at 293 K reject temperature. In addition, the maximum cooling powers are 50 W at 150 K, 60 W at 160 K, 70 W at 180 K, 80 W at 90 K, and 90 W at 200 K, all at the same 293 K reject temperature. This makes the PTC useful for a variety of IRFPA applications.

CONCLUSIONS

A high capacity pulse tube cooler has been developed to cool down a multispectral infrared detector. A typical cooling performance of 50 W at 170 K has been achieved with 230 W electrical power input at 293 K reject temperature. The motor efficiency and specific Carnot efficiency are 92% and 16.5%, respectively. Because of its compactness, low mass (11.8 kg), and high reliability, not only can the PTC be used for space missions, it is also a promising alternative to other refrigerators used in some domestic low-temperature applications.

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