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Comparative analysis of in-line and coaxial pulse tube cryocoolers at 90 K

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Abstract: Linear and coaxial pulse tube cryocoolers (PTCs) are widely used in space, especially coaxial PTCs. The coaxial PTC has a compact structure and is more convenient to use, while the linear structure is simple with high cooling efficiency. At present, the research on the difference between the two PTCs based on theoretical research is relatively rare. Therefore, it is very valuable to carry out some comparative studies between the two PTCs. Two kinds of Stirling-type single-stage PTCs (in-line and coaxial type) are analyzed due to their different structures in this paper. One-dimensional numerical model is established to analyze the changes of the relevant thermodynamic parameters in the two cryocoolers. The mechanism is revealed that different structural changes could lead to different cooling performance. The differences between the PTCs are compared by analyzing the energy flows, acoustic impedance networks. Also, two experimental setups are established, and the performance of the two pulse tube cryocoolers is tested and analyzed. The results show that the in-line cryocooler has higher cooling efficiency, and the coaxial one could reach lower cooling temperature at the same input power because the pulse tube is placed in the regenerator of the coaxial system and precooled by the regenerator. By comparing the simulation data with the experimental results, it is found that there is a good consistency.

Key words: pulse tube cryocooler, in-line type, coaxial type

直线型和同轴型脉管制冷机在90 K的对比分析

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摘要：直线型和同轴型脉管制冷机被广泛应用于空间领域，尤其是同轴型脉管制冷机。同轴型脉管制冷机结构紧凑且使用便利，而直线型脉管制冷机结构简单且制冷效率高。目前，对于两类脉管制冷机的理论比较研究相对较少，因此开展相应的比较研究很有意义。本文分析了两款不同结构的单级脉管制冷机(直线型和同轴型)。通过建立一维数值模型分析两款制冷机相关热力学参数的不同之处，从机理上揭示了不同结构会导致不同的制冷性能。通过比较两款制冷机的能量流及声功阻抗图，开展实验对两款制冷机性能进行测试和分析。结果表明：在相同的输入功率时，直线型脉管制冷机具有更高的制冷效率，而同轴型脉管制冷机可以达到更低的制冷温度(原因在于同轴型冷指的脉冲管置于回热器内部，会被回热器预冷)。通过比较发现，模拟数据和实验结果具有较好的一致性。

关 键 词：脉管制冷机；直线型；同轴型

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Introduction

At present, Stirling cryocoolers and Stirling type pulse tube cryocoolers have been commonly used in space applications in the past few years and the absence of a moving displacer in PTCs makes them have many potential advantages over Stirling cryocoolers for the cooling of infrared sensors [1-4]. Stirling cryocoolers and PTCs have long service life and low failure rates [5]. There are

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three different geometries that have been used in PTCs: in-line, coaxial and U-tube. The in-line arrangement is the most effective because the gas flow goes and returns without turbulence from the flow reversal at the cold head, but the disadvantage that the cold head is located between the two hot ends limits its development. U-tube type PTC uses a thin tube to connect the regenerator and pulse tube so that the gas cross-section flow and large dead volume produce large energy loss, which results in low efficiency. The most widely used arrangement in space applications is the coaxial arrangement because of its compact structure. The coaxial PTC places pulse tube inside of regenerator so that its cold head is on one side, which greatly improves its coupling efficiency with detector Dewar. However, helium gas flowing in and out of the cold head will have a 180 degrees transition, and there is a mismatch of temperature profiles in the regenerator and pulse tube that would lead to radial irreversible heat flow because of temperature distribution. Therefore, it is of great significance to analyze the thermal effect of coaxial PTC, especially to compare with the other two kinds of PTCs. A general analysis has been carried out for the experimental performance comparison between linear and U-type pulsed-tube cryocoolers by Tendolkar M V, et al. [6]. They pointed out that the performance of the linear PTC is apparently better than that of the U-type configuration respect to cooling down time, minimum temperature, and cooling power at the same pulse tube and regenerator dimensions. Although the effects of some different operating parameters were considered, the detailed thermodynamic behaviors of various components in PTC were not further discussed. In addition, linear and coaxial PTCs are widely used in space, especially coaxial PTCs. The coaxial PTC has a compact structure and is more convenient to use, while the linear structure is simple with high cooling efficiency. At present, the research on the difference between the two PTCs is relatively rare. Therefore, it is very valuable to carry out some comparative studies between the two PTCs.

This paper introduces a Stirling single-stage linear pulse tube cryocooler for cooling space infrared detectors. The linear chiller is based on the existing one coaxial pulse tube cryocooler transformation. The basic dimensions of the key components of both structures are the same. Through the establishment of one-dimensional numerical model, the energy loss and gas pressure ratio of linear and coaxial pulse tube system are compared and analyzed. The comparison between the experimental value and the simulated value is carried out to verify the accuracy of the model.

1 Physical models and governing equations

Figure 1 shows the schematics of two PTCs. In the in-line PTC shown in Fig. 1(a), the acoustic power flowing out of the compressor flows alternately in the aftercooler, regenerator, CHX, pulse tube, inertance tube and the reservoir. When the pulse tube is placed into the regenerator, the linear chiller becomes coaxial as shown in Fig. 1(b). The volume of the two regenerators and the filling rate of the screen are basically the same. The gas flows through the regenerator and then enters the pulse tube reversely, resulting in energy losses. The main component parameters of the coaxial PTC (Case 1) and the in-line PTC (Case 2) are the same so that it is beneficial to carry out some comparative study. The main dimensions of the two PTCs are listed in Table 1.

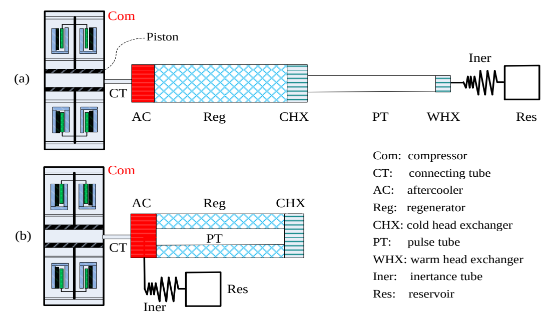

Fig. 1 Schematics for (a) in-line PTC and (b) coaxial PTC
图1 直线型和同轴型脉管制冷机结构图

Table 1 The main dimensions of the two PTCs
表1 两款脉管制冷机的主要尺寸

Component	Coaxial PTC (Case 1)	In-line PTC (Case 2)
Piston (dia.)	20 mm	20 mm
Connecting tube (inner dia. ×length)	4 mm×150 mm	4 mm×150 mm
Aftercooler	0. 2 in porosity of slit	0. 2 in porosity of slit
Regenerator (dia. ×length)	26. 7/12. 6×65 mm	23. 5×65 mm
CHX	0. 2 in porosity of slit	0. 2 in porosity of slit
Pulse tube (length)	12 mm×80 mm	12 mm×80 mm
Phase shift mechanism	Inertance tube together with reservoir	

The behavior of the PTC is predicted by a classical thermodynamic model and the mass and energy balance equations are applied to the control volumes of the cryocooler components. The working process of the pulse tube cryocooler is complicated due to the nature of unsteady, oscillating compressible gas flow. To trace the process, it is considered to be one dimensional, periodic and unsteady compressible flow. The following assumptions are introduced into the model as well [7]:

1. The outer sidewall of the regenerator is thermally insulated.
2. The gas is ideal gas.
3. The entrance effects are neglected.
4. The fluid phase satisfies the no-slip condition on the fluid-solid interface.
5. The porosity is constant.

The general governing equations: mass equation, momentum equation, energy equation, gas equation of state for the solids in the regenerator and equation of state for ideal gas are as follows:

$$\frac{\partial}{\partial x}(\rho uA)+\frac{\partial}{\partial t}(\rho A)=0 \quad , \qquad (1)$$

$$\frac{\partial}{\partial x}(u\rho uA)+\frac{\partial}{\partial t}(\rho uA)+A\frac{\partial P}{\partial x}-AF=0 \quad , \qquad (2)$$

$$\frac{\partial}{\partial x}\left[Au\rho\left(C_p+\frac{u^2}{2}\right)\right]+\frac{\partial}{\partial t}\left[A\rho\left(C_vT+\frac{u^2}{2}\right)\right]+\alpha A_L(T-T_m)=0 \quad , \qquad (3)$$

$$P=\rho RT \quad . \qquad (4)$$

After the physical properties of working fluid in Stirling-type PTC are estimated according to these equations, the enthalpy and the expansion work at the cold side of pulse tube are calculated. Then, the losses transferred to the CHX are considered with the enthalpy and the expansion work, and the cooling capacity of Stirling-type PTC is finally predicted. Therefore, the accurate estimation of the physical property and losses is important to accurately predict the cooling capacity.

2 Experimental system

Figure 2 is the experimental bench of the linear and coaxial pulse tube cryocooler. The whole system includes single-stage pulse tube cryocooler, control power supply, measurement system, data acquisition system, vacuum pump and water-cooling system, etc. In order to reduce the radiation and convective heat transfer loss of the cold end heat exchanger. The whole cold finger is packed with aluminum foil and placed in a vacuum cover to maintain a high vacuum degree about 10^{-4} Pa.

The compressor is cooled by air force. The hot end heat exchanger is connected with the water cooler through water pipes, and the temperature of hot end heat exchanger is accurately controlled by the water cooler. The experimental temperature is 300 K. The phase regulation parts of the cryocooler are the inertance tube and the gas storage, which is used to adjust and optimize the mass flow, pressure wave and the phase difference between them.

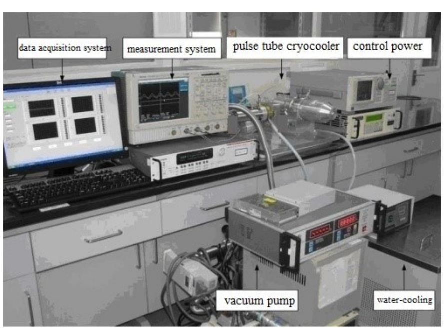

Fig. 2 Pulse tube cryocooler test system
图2 脉管制冷机测试系统

3 Results and discussion

3.1 Enthalpy flow in PTCs

Figure 3 shows the behavior of the enthalpy at various locations. When the power flows alternately and reaches the steady state, its enthalpy value hardly changes until the helium fluid begins to flow through the aftercooler, which causes greater enthalpy drop because of bulk heat exchange by water-cooling. In the regenerator, the enthalpy of the isothermal heat transfer state almost does not change, while the enthalpy in the cold heat exchanger increases because of the transfer of cooling power. Under the same power, the enthalpy of the cold heat exchanger of the linear PTC is slightly higher than that of the coaxial PTC, and this phenomenon is reflected in the performance comparison between the two PTCs.

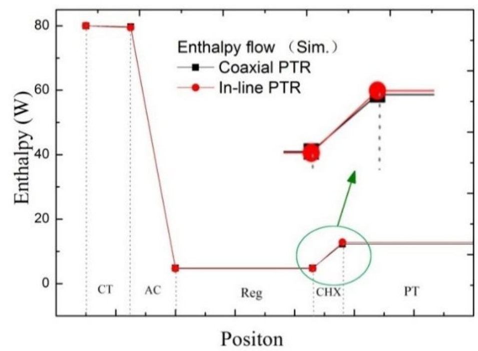

Fig. 3 Enthalpy flows of the two PTCs
图3 两款脉管制冷机的能量流

3.2 Energy losses of the two PTCs

Figure 4 shows the comparison diagram of the energy losses in each part of the two PTCs. It is shown obviously that the main losses of the two PTCs are mainly concentrated in the regenerator, inertance tube, pulse tube, heat exchanger and other components. Under the same PV input power, the coaxial PTC has higher losses in its regenerator and pulse tube, and lower heat exchanger losses and heat dissipation losses in the inertance tube compared with in-line PTC. The main reason is that the optimized length of inertance tube in the former is smaller than that in the latter. The coaxial system cooling capacity is also significantly smaller than that of the in-line PTC because of the following reasons. On the one hand, the pulse tube is placed in the regenerator of the coaxial system. When the working gas flows alternately in the system, the direction of internal gas flow in the regenerator is opposite to that in the pulse tube, resulting in turbulence generation and increasing friction losses. On the other hand, the heat exchanger of the hot end of the coaxial PTC is placed inside. Thus, it is difficult to fully transfer the heat and the heat dissipation of the system is small, which makes the performance of the whole system worse. Moreover, the pressure ratio of working gas in coaxial PTC system is relatively small, as shown in Fig. 5.

Figure 5 shows the behavior of pressure ratio. With the operation of working gas in the system, its pressure ratio gradually decreases from left to right and its value is close to 1 in gas reservoir. The aftercooler, cold and hot end heat exchangers are all slit structures, and the pressure ratio changes very small when the working gas flows through the three heat exchangers. However, the pressure ratio changes smaller quickly in the inertance tube,

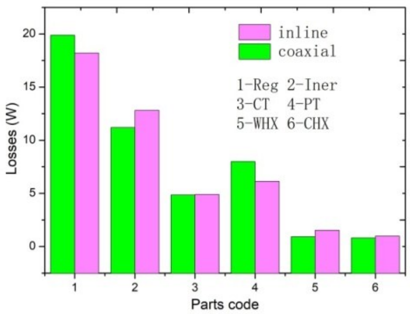

Fig. 4 Energy losses of the two PTCs
图4 两款脉管制冷机的能量损失

which is thin and long. Under the same PV power, the pressure wave of the working gas in the coaxial PTC varies greatly. The pressure in the outlet of the compressor is relatively larger, and the internal pressure ratio of other parts is smaller in the coaxial PTC system. The pressure ratio is only 1.116 in the regenerator, which is smaller than the linear regenerator pressure ratio of 1.124. The small regenerator pressure ratio is not conducive to improve the performance of the PTC[8], so the cooling capacity is lower.

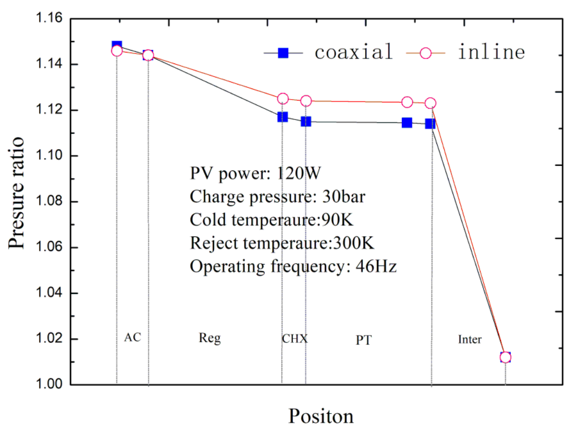

Fig. 5 The pressure ratio change of the two PTCs
图5 两款脉管制冷机的压比变化

3.3 Effects of impedance in PTCs

The design of PTC system should match the impedance of the linear compressor [9]. Fig. 6 shows the relationship between the electric-to-acoustic efficiency of the compressor and the real and imaginary parts of its impedance. It can be seen from the figure that the electric-to-acoustic efficiency of the coaxial PTC is slightly higher than that of the linear type no matter the cooling temperature is high or low. This phenomenon is also reflected in the experiment.

3.4 Measured cooling performance of the two PTCs

Figure 7 shows the relationship between the performance of the two PTCs with different frequencies. When the frequency increases, the input power required by the two PTCs decreases firstly and then increases. The optimum frequency is about 46 Hz. Higher frequency would accelerate the helium flow of working medium and increase heat exchange frequency, while the excessive flow of working medium is not conducive to the heat transfer between helium and the regenerator. The heat penetration depth is reduced and heat exchange is insufficient. Therefore, the regenerator loss and frictional resistance loss of the cold storage are increased, and the cooling efficiency of the PTC is reduced. The optimal operating frequency of the PTC mainly depends on the size of the inertance tube. The lengths of the inertance tubes of the two PTCs are obtained separately based on 46 Hz optimization, which also verifies the accuracy of the built model. In addition, a cooling capacity of 6 W is obtained, and the input electric power of the linear PTC is less than that of the coaxial type.

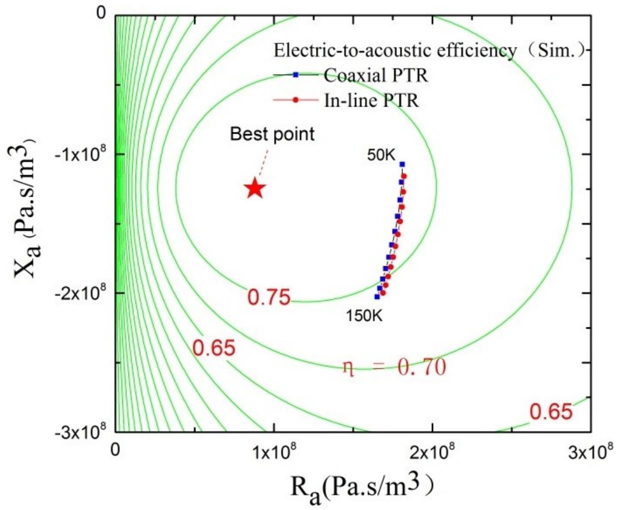

Fig. 6 Compressor efficiency vs. impedance of the two PTCs
图6 两款脉管制冷机-压缩机效率与阻抗关系

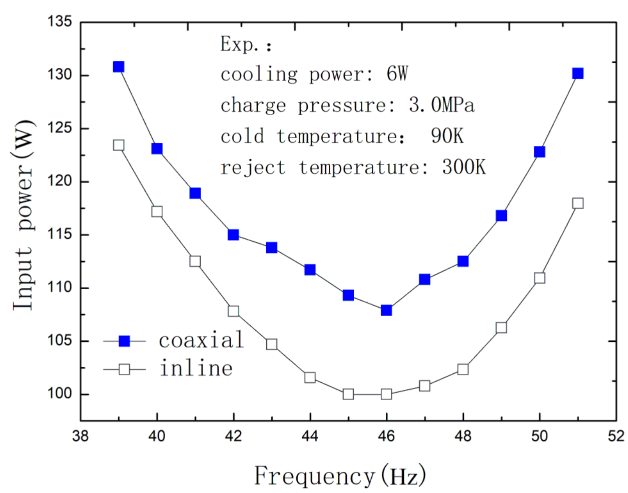

Fig. 7 Performance of the two PTCs with different frequencies
图7 两款脉管制冷机不同频率的性能

Figure 8 shows the cooling down characteristics of the two PTCs and that the PTCs work efficiently at 46 Hz with 30 bar average pressure. The temperatures of the two PTCs are close to the lowest points after running for about 20 minutes. The minimum cooling temperatures of the coaxial and linear PTCs are the no-load low-temperatures of 45.3 K and 50 K, respectively. The coaxial PTC could reach lower cooling temperature at the same input power because the pulse tube is placed in the regenerator of the coaxial system and precooled by the regenerator.

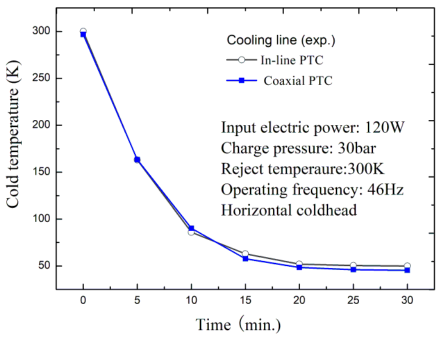

Fig. 8　Cooling curve of the two PTCs
图8　两款脉管制冷机的降温曲线

Figure 9 is a comparison diagram of the refrigeration performance of two PTCs under the same operating conditions between simulated and experimental values. The temperatures of cold and hot end are maintained at 90 K and 300 K, respectively. It can be seen from the figure that the refrigeration load significantly decreases as one moves from in-line (6.21 W @ 90 K) to coaxial type configuration (5.23 W @ 90 K) for a given charging pressure (30 bar) and an input power (100 Wac). No matter a simulation value or an experimental value, the input PV power/electric power of the PTC value is almost linearly distributed over the cooling capacity. The ratio of the corresponding PV power to the input electric power is about 63%. The performance difference between the two PTCs is small when the cooling capacity is not large. However, the input PV power/electric power of the coaxial PTC is significantly higher than that of the linear PTC when the cooling capacity is large.

The coaxial PTC can provide 0 W or 8 W cooling power at a cold temperature of 90 K if the input electric power is kept at 35.5 W or 143 W, respectively. In addition, the in-line PTC can efficiently provide 0 W or 10 W cooling power at a cold temperature of 90 K if the input electric power is kept at 34 W or 149 W, respectively.

4 Conclusion

In-line and coaxial pulse tube cryocoolers are commonly used in space for cooling infrared detectors. Many published papers investigating this topic have been carried out by experimental results, but there is very little theoretical research. In this paper, the in-line and coaxial PTCs are compared by simulation and experiment. The results show that the in-line PTC has a relatively stronger cooling capacity, while the coaxial PTC can be cooled at a lower cooling temperature. Due to the changes in system parameters such as energy losses, enthalpy flow distribution and electric-to-acoustic efficiency in the system caused by the structural differences between the two PTCs, the in-line PTC has better cooling performance than the coaxial one under the same working conditions. In addition, by comparing the simulation value with the experimental value, the accuracy of the model is verified.

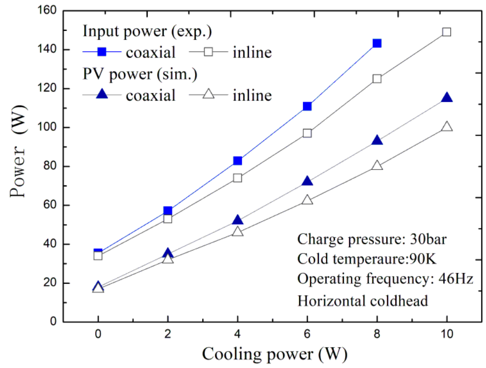

Fig. 9　Cooling performance map of the two PTCs
图9　两款脉管制冷机的制冷性能图

References

[1] Radebaugh R. Pulse Tube Cryocoolers for Cooling Infrared Sensors [C]. Proceedings of SPIE: **2000**: 363-379.
[2] Rogalski A. Recent progress in infrared detector technologies [J]. *Infrared Physics Technology*: 2011, **54**(3): 136 - 154.
[3] Zhang An-Kuo, Wu Yi-Nong, Liu Shao-Shuai, *et al.* Development of Pulse Tube Cryocoolers at SITP for Space Application [J]. *Journal of Low Temperature Physics*: 2018, **191**: 228 - 241.
[4] Liu Shao-Shuai, Jiang Zhen-Hua, Zhang An-Kuo, *et al.* Study on high energy efficiency 30K sigle-stage pulse tube cryocooler for a space infrared detector [J]. *J. Infrared Millim Waves*: 2018, **37**(4): 403-410.
[5] Gao Sheng, Wu Yi-Nong, Jiang Zhen-Hua. Static and dynamic rubbing positions identification of cryocooler based on wavelet packet analysis and support vector machine [J]. *J. Infrared Millim Waves*: 2019, **38**(5): 628-632.
[6] Tendolkar M V, Narayankhedkar K G, Atrey M D. Performance comparison of Stirling-type single-stage pulse tube cryocoolers of in-line and 'U' configurations [C]. Cryocooler 15, California: 2009: 209-216.
[7] Zhang An-Kuo, Liu Shao-Shuai, Wu Yi-Nong, *et al.* Effect of low temperature on a 4W/60K pulse-tube cryocooler for cooling HgCdTe detector [J]. *Journal of Low Temperature Physics*: 2018, 192: 184-200.
[8] Qiu L M, He Y L, Gan Z H, *et al.* Regenerator performance improvement of a single-stage pulse tube cooler reached 11.1 K [J]. *Cryogenics*. 2007, **47**: 49 - 55.
[9] Zhang An-Kuo, Wu Yi-Nong, Liu Shao-Shuai, *et al.* Effect of impedance on a compressor driving pulse tube refrigerator [J]. *Applied Thermal Engineering*: 2017, **124**: 688 - 694.