# Theoretical and Experimental Research on a Two-Cold-Finger Pulse Tube Cooler

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## ABSTRACT

Due to the demands of multiple refrigeration temperatures for infrared devices in space applications, a research study was performed for a two-cold-finger pulse tube cryocooler (TCFPTC). In the TCFPTC, two different coaxial pulse tube (PT) are driven by one linear compressor. In this paper, an experimental study and a theoretical analysis are presented. The coupling performance (mutual effect) of two PTs in the TCFPTC is investigated. The experimental results show that the thermal load and PT size have more effects on the coupling performance of the TCFPTC than electrical input power. The effects of the heat sinking temperature on the refrigeration temperature are also studied. Furthermore, the TCFPTC coupling efficiency which is the ratio of the TCFPTC compressor output power to the sum of two single PTCs is investigated in the paper. In our further research, the mass flow vector diagram and acoustic theory are used to explain coupling performance of the TCFPTC.

## INTRODUCTION

The pulse tube cryocooler (PTC) has some advantages, such as no moving parts at its cold head, mechanical simplicity, high reliability, and high cooling performance. Therefore, the PTC is praised as the new generation of space cryocooler. The multi-finger PTC has broad application prospects in space refrigeration, because of the requirements for the multi-temperature zone, multi-thermal load, and multi-position.

Before the first TCFPTC was presented, the two-stage PTC was thought as a proper way to achieve multi-temperature cooling. In 2009, NGST presented a cryocooler system which consisted of a linear pulse tube cold head that was integrated to the compressor assembly and a coaxial remote pulse tube cold head. The two cold head design afforded a way of cooling a detector array to its operational temperature while remotely cooling optical elements and a second detector array. In 2010, Technical Institute of Physics and Chemistry, CAS designed and tested a TCFPTC system which consisted of one linear compressor and two distinct coaxial pulse tube cold head and achieved two different cooling temperature requirements. In 2011, Shanghai Institute of Technical Physics, CAS researched and designed a TCFPTC which consisted of two identical coaxial pulse tube cold head and one linear compressor.

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According to the experimental and theoretical research, the mutual influence between the two PTs always exists. It will be difficult to couple two PTs with different sizes. For example, the refrigeration performance of the TCFPTC will be poor when a super-high frequency PTC and a high capacity PTC are coupled together. In the experimental investigation, two different sized coaxial PTs are chosen and the coupling efficiency of the TCFPTC reaches about 90%.

In this paper, the TCFPTC's coupling performance of various thermal loads, input powers and heat sinking temperatures are presented and analyzed. Furthermore, we investigate the TCFPTC coupling efficiency by comparing the compressor output power of two single PTCs with that of the TCFPTC. Lastly, the mass vector diagram and acoustic theory are used to explain the coupling performance of the TCFPTC.

## CRYOCOOLER CONFIGURATION

Figure 1 is a schematic of the cryocooler. The TCFPTC consists of a linear compressor and two single-stage coaxial-type pulse tubes. The compressor and the two pulse tubes are connected by a T-branch pipe and the two pulse tubes are placed in a horizontal position. The diameters of the regenerator of the PTA and the regenerator of the PTB are 20 mm and 14mm, respectively. Inertance tubes and reservoirs are used for phase shifting and the heat sinking temperature is 290K in the experiment. The thermal load of the PT is provided by a heating block. The temperatures of the cold heads are measured by PT100 RTD thermocouples.

## EXPERIMENTAL RESEARCH OF TWO PTS COUPLING PERFORMANCE

According to the experimental study, the optimal operational frequency and charge pressure of the TCFPTC are 50 Hz and 4.0 MPa, respectively. RA, ITA, RB and ITB of TCFPTC are the optimal phase shifters for PTCA and PTCB in their respective PTC. The TCFPTC coupling performance of various thermal loads, input powers and heat sinking temperatures are presented and analyzed in the remainder of this section.

### Effects of thermal load on Two PTs Coupling Performance

In this paper, when one PT's thermal load is constant, the effect of the change on the other PT's cooling performance is investigated. Experiment results are shown in Figure 2. This figure illustrates that the vertical curve slope is smaller than the horizontal curve slope, which indicates the influence of PTA on PTB is more than PTB on PTA. In the experimental investigation, the linear compressor's electrical parameters change slightly. Therefore, we can ideally assume that the mass flow rate produced by the linear compressor is constant. PTA has greater mass flow than PTB does in the TCFPTC. Therefore, the percentage change in PTB's mass flow rate is greater than PTA when they experience the same mass flow rate variation. Thus, the cooling performance of PTB is more sensitive to the mass flow rate or the PV power than PTA.

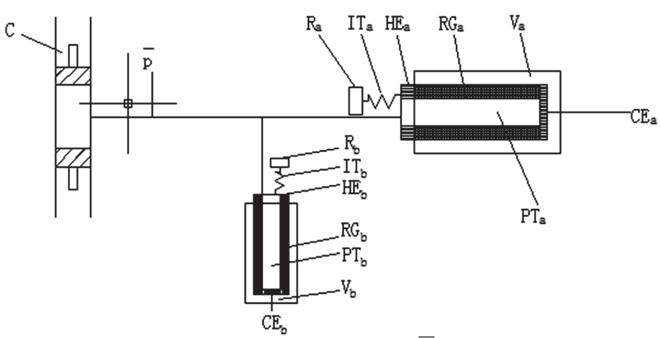


**Figure 1.** The TCFPTC configuration. C: compressor, $\overline{P}$ : pressure sensor, HE: hot head heat exchanger, CE: cold head heat exchanger, RG: regenerator, PT: pulse tube, IT: inertance tube, R: reservoir, V: vacuum vessel.

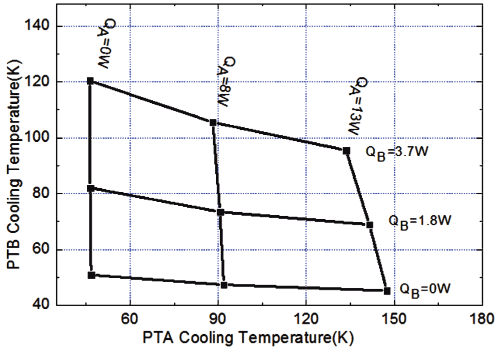


**Figure 2.** Refrigeration temperature, 250W input power

With different thermal loads on one PT, the change in the refrigeration temperature or thermal load of the other PT has different effects on this PT, as shown in Figure 2. With an increase in one PT's thermal loads, the effects on the other PT will increase. For example, changes in PTB's thermal loads have more impacts on PTA with 13W thermal loads than it does with an 8W load. Similarly, PTB also has this variability. When the thermal load or the refrigeration temperature increases, the gas density will decrease and the gas mass in refrigeration will decrease. Thus, the PT having the high refrigeration temperature will be more sensitive to mass flow rate variations.

### Effects of Input Electric Power and Heat Sinking Temperature on Coupling Performance

Figure 3 demonstrates the effect of input electric power on the TCFPTC performance when the refrigeration temperature or thermal load increases. This characteristic is the same as the single PTC's. It also suggests two PTs coupling performance vary slightly in different input power. Input electric power has a smaller effect on the coupling performance of TCFPTC than the thermal load and the PT's size.

It is necessary to study the effect of the heat sinking temperature on the TCFPTC's cooling performance. Figure 4 and 5 indicate the PT refrigeration temperature will increase by 1K when the heat sinking temperature increases 3-5K in the TCFPTC. For a single PTC system, the result is similar.

## EXPERIMENTAL INVESTIGATION OF TCFPTC COUPLING EFFICIENCY

Compared with a single pulse tube driven by a single linear compressor, the refrigeration performance of the TCFPTC will decrease. The coupling system is more complicated than a single PTC. In order to understand the coupling efficiency of TCFPTC the refrigeration performance of single PTC is necessary. In the single PTC experimental study, the optimal frequency of

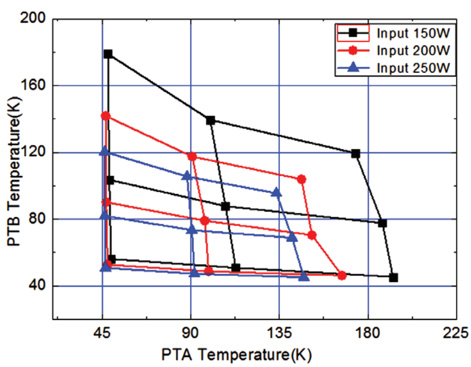


**Figure 3.** Two PTs' coupling performance in different input electric powers.

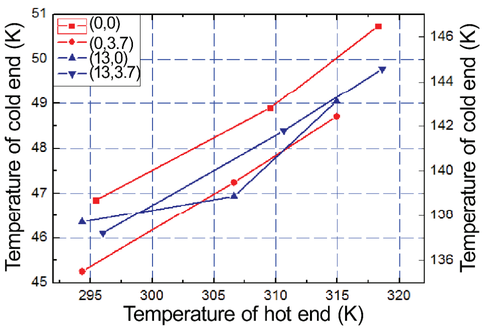


**Figure 4.** PTA Heat sinking temperature influence curve

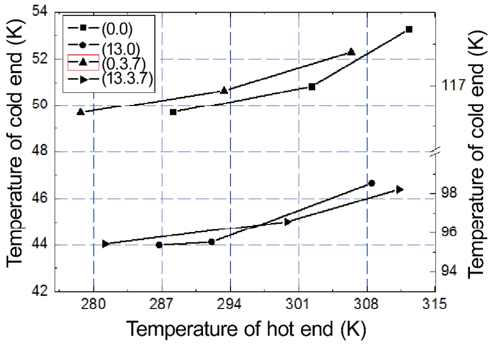


**Figure 5.** PTB Heat sinking temperature influence curve

PTCA and PTCB are 52Hz and 54Hz, respectively. Charging pressure is maintained at 4.0MPa and the heat sinking temperature is 290K.

For the same cooling performance, the input PV power is a key parameter to evaluate the cooling performance of the pulse tube cryocooler. In this paper, we define the coupling efficiency shown in Eq. 2. Eq. 1 is the compressor's output PV power computational formula. In Table 1, $T_c$ and $Q_C$ are the refrigeration temperature and thermal load respectively. Table 1 displays the coupling efficiency of TCFPTC under different thermal loads. The experimental results demonstrate the TCFPTC coupling efficiency increases as the TCFPTC thermal load increases.

$$W_{pv} = P_{output} - Q_L = P_{input} S_f - I^2 R \tag{1}$$

where $W_{PV}$ is the compressor PV power, $P_{output}$ is the compressor electrical power, $P_{input}$ is the input electrical power, $S_f$ is the power factor, I is the current of compressor, R is the resistance of compressor (0.61 Ω in this experimental study), $Q_L$ is the heat loss of compressor.

$$\eta = \frac{W_{PV20} + W_{PV14}}{W_{PV20+14}} \times 100\% \tag{2}$$

where $\eta$ is the coupling efficiency, $W_{PV20}$ is the output PV power in the single PTCA, $W_{PV14}$ is the output PV power in the single PTCB, $W_{PV20+14}$ is the output power in the TCFPTC.

**Table 1.** TCFPTC coupling efficiency

| | $Q_c$(W) | $T_c$(K) | $P_{input}$(W) | $S_f$ | $Q_f$(W) | $W_{pv}$(W) | $\eta$(%) |
|---|---|---|---|---|---|---|---|
| PTCB | 0 | 48 | 81.1 | 0.985 | 19.66 | 60.22 | |
| | 6.5 | 97 | 127.3 | 0.954 | 31.28 | 90.16 | |
| | 13 | 155 | 133.7 | 0.918 | 33.93 | 88.81 | |
| PTCA | 0 | 51 | 80.5 | 0.893 | 28.15 | 43.74 | |
| | 1.8 | 86 | 78.2 | 0.857 | 29.47 | 37.55 | |
| | 3.7 | 113 | 85 | 0.828 | 34.33 | 36.05 | |
| TCFPTC | (0,0) | (48,51) | 200 | 0.991 | 50.46 | 147.74 | 70.34 |
| | (6.5,1.8) | (97,86) | 200 | 0.973 | 49.46 | 145.14 | 88 |
| | (13,3.7) | (155,113) | 200 | 0.942 | 55.34 | 133.06 | 93.8 |

## THEORETICAL ANALYSIS

According to the enthalpy flow theory, the performance of pulse tube crycooler is mainly determined by the pressure, mass flow rate and the phase angle between them. It can be assumed that the pressure at the entrance of each pulse tube is equal to the compressor outlet pressure because the T-shape tube is short and smooth. Based on the mass conservation equation, the mass flow exported by the compressor is equal to the vectorial sum of the two pulse tube cold head entrance mass flow. The corresponding equation is:

$$\vec{m}_{total} = \vec{m}_{in1} + \vec{m}_{in2} \tag{3}$$

where $\vec{m}_{total}$ is a vector of the mass flow rate exported by the compressor, $\vec{m}_{in1}$and $\vec{m}_{in2}$ are the vectors of the entrance mass flow rate of PTA and PTB.

Figure 6 can qualitatively explain the coupling performance, stated above. Supposing $\vec{m}_{total}$ is constant, when $\vec{m}_{in1}$ value or direction changes, $\vec{m}_{in2}$ will change in the value and direction. Actually, $\vec{m}_{total}$ is also variable when $\vec{m}_{in1}$ value or direction changes, which contributes to the variation of $\vec{m}_{in1}$. In one word, with the variation of one of the three parameters, the other two ones will change accordingly.

Accord to the thermoacoustic theory, there is an accurate analogy the between acoustic systems and the AC electric circuits. Table 2 displays the corresponding relation between acoustic parameters and electrical parameters. The variation of temperature or thermal load in the pulse tube cold head will lead to the change of the impedance of the pulse tube cold head. The impedance of one pulse tube cold head will affect compressor impedance and pressure, mass flow rate and the phase between them in the other pulse tube cold head.

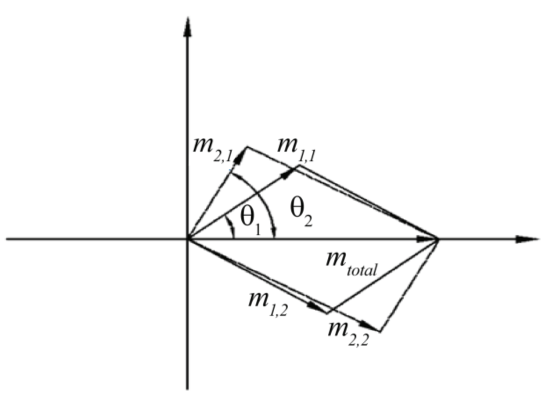


**Figure 6.** Mass vector diagram of TCFPTC

**Table 2.** An analogy between acoustic system and AC electric circuits

| Acoustic systems | AC electric circuits |
|---|---|
| Pressure(P) | Voltage (U) |
| Volume flow rate(U) | Current (I) |
| Compliance(C) | Compliance(C) |
| Intertance(L) | Intertance(L) |
| Resistance(R) | Resistance(R) |

## CONCLUSION

A TCFPTC which consists of two coaxial pulse tube cold heads driven by one linear compressor has been built and tested. The TCFPTC coupling performance of various input power, thermal load and Heat sinking temperature are studied experimentally. The results demonstrate thermal load and the size of pulse tube have more effects on coupling performance of TCFPTC than input electrical power. And the experiments show that the cold-end temperature increases 1K when hot-end temperature increases 3K-5K, with the same input electric power and thermal load. Coupling efficiency of TCFPTC designed and tested is about 90%, in this article. Reasonable explanations about coupling performance are given by mass vector diagram and thermoacoustic theory. However, this article does not give exactly PV power distributions of each PT in the TCFPTC. In the further research, the PV power distributions of TCFPTC will be discussed in details by experimental research and numerical simulation.

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