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Design and preliminary experimental investigation of a 4 K Stirling-type pulse tube cryocooler with precooling*

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Abstract: A Stirling-type pulse tube cryocooler (PTC) with precooling was designed and manufactured to investigate its performance at 4 K. Numerical simulation was carried out based on the well-known regenerator model REGEN with an emphasis on the performance of a 4 K stage regenerator of the Stirling-type PTC as influenced by the warm end temperature, pressure ratio, frequency and average pressure with helium-4 and helium-3 as the working fluid respectively. This study demonstrates that the use of a cold inertance tube can significantly improve the efficiency of a 4 K Stirling-type PTC. A preliminary experimental investigation was carried out with helium-4 as the working fluid and a refrigeration temperature of 4.23 K was achieved. The experimental results show that the operating frequency has a significant influence on the performance of the Stirling-type PTC and a relatively low average pressure is favorable for decreasing the loss associated with the real gas effects of a 4 K Stirling-type PTC.

Key words: Stirling-type pulse tube cryocooler (PTC), Regenerator, Helium-3, Cold inertance tube, 4 K
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INTRODUCTION

Compared with Gifford MacMahon (GM)-type pulse tube cryocoolers (PTCs), which operate at frequencies of 1~2 Hz, Stirling-type PTCs operating with frequencies typically in the range of 30~60 Hz have the advantages of high efficiency, compact structure, light weight, long life and small cold end temperature oscillations. These features make them very attractive for cooling low temperature superconductors and space applications (Ross and Boyle, 2003; 2007; Ross, 2005; Ross and Johnson, 2006).

The four-stage Stirling-type PTCs developed by Lockheed Martin Advanced Technology Center are the only Stirling-type PTCs that have been capable of reaching liquid helium temperatures (Olson *et al.*, 2005; 2006; Nast *et al.*, 2006; 2007; 2008; Webber *et al.*, 2009). However, the coefficient of performance (COP) of Stirling-type PTCs working at liquid helium temperatures is still very low and the behavior of a 4 K stage regenerator in a Stirling-type PTC is not well understood from the associated publications. Real gas effects and the low volumetric specific heat capacity ratio of regenerator matrix to helium near 4 K lead to the low efficiency of a 4 K Stirling-type PTC. These problems become more serious as the operating frequency increases.

In this study, we investigated the performance of a single stage Stirling-type PTC that was precooled by a two-stage GM-type PTC (Qiu *et al.*, 2005; Gan *et al.*, 2009), and designed to operate at liquid helium temperatures (Qiu *et al.*, 2008). A systematic comparison was made between the calculated performance of the 4 K stage regenerator with helium-4 and helium-3 as the working fluids. A preliminary experimental investigation with helium-4 regarding the influence of the precooling temperature, frequency and average pressure was conducted.

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NUMERICAL SIMULATION OF REGENERATOR

The Stirling-type PTC was designed based on REGEN, a well accepted regenerator numerical simulation software developed by the National Institute of Standards and Technology (NIST) (Radebaugh *et al.*, 2002; 2008; 2009; Radebaugh and O′Gallagher, 2006; Huang *et al.*, 2006).

Fundamental equations

According to the first law of thermodynamics, the net refrigeration power in any real PTC is given as Eq.(1) (Radebaugh *et al.*, 2009) by ignoring the radiation heat leak to the cold end:

$$\dot{Q}_{\rm net} = \langle P\dot{V}\rangle_{\rm c} - \langle \dot{H}\rangle_{\rm P} - \dot{Q}_{\rm reg} - \dot{Q}_{\rm cond} - \dot{Q}_{\rm pt}, \tag{1}$$

where parameters with a dot represent time-varying parameters, $\langle PV\rangle_{\rm c}$ is the time-averaged acoustic power at the cold end, $\langle H\rangle_{\rm p}$ is the time-averaged enthalpy flow associated with the real gas effects, $Q_{\rm reg}$ is the thermal loss associated with imperfect heat transfer and limited heat capacity in the regenerator, $Q_{\rm cond}$ is the conduction heat leak through the regenerator, and $Q_{\rm pt}$ is the loss associated with an imperfect expansion process in pulse tube. By substituting $\langle PV\rangle_{\rm c}$ with $\langle PV\rangle_{\rm h}$ (the time-averaged acoustic power at the hot end of the regenerator) and assuming that the reversible expansion work at the cold end is not being fed back to the hot end of this regenerator, the COP is given as (Radebaugh *et al.*, 2008)

$$COP = \left[1 - \frac{\langle \Delta P\dot{V}\rangle_{\rm h}}{\langle P\dot{V}\rangle_{\rm h}}\right] \times \left[\frac{Z_{\rm c}T_{\rm c}}{Z_{\rm h}T_{\rm h}}\right] \times \left[1 - \frac{\langle \dot{H}\rangle_{\rm P}}{\langle P\dot{V}\rangle_{\rm c}}\right] \times \left[1 - \frac{\dot{Q}_{\rm reg}}{\dot{Q}_{\rm gross}} - \frac{\dot{Q}_{\rm cond}}{\dot{Q}_{\rm gross}} - \frac{\dot{Q}_{\rm pt}}{\dot{Q}_{\rm gross}}\right], \tag{2}$$

where $\langle \Delta PV\rangle_{\rm h}$ is the acoustic power lost at the hot end due to a pressure drop in the regenerator, $Z_{\rm c}$ is the compressibility at the cold end, $Z_{\rm h}$ is the compressibility at the hot end and $Q_{\rm gross}$ is the gross cooling power with a perfect regenerator and a perfect pulse tube which is equal to $\langle PV\rangle_{\rm c}-\langle H\rangle_{\rm p}$.

The first and fourth terms on the right hand side of Eq.(2) are both dependent on gas properties and hardware of the PTC. The second and third terms are only associated with the gas properties. Both the conduction and pressure drop are rather small for most 4 K regenerators and the relative pulse tube loss is typically from 0.2 to 0.3, so the following analysis will be focused on the relative regenerator loss $Q_{\rm reg}/Q_{\rm gross}$.

Calculated performance of 4 K stage regenerator

The efficiency of a 4 K stage regenerator is vital for the performance of the Stirling-type PTC operating at liquid helium temperatures. Helium-3 behaves closer to an ideal gas with a lower boiling point and a smaller volumetric specific heat capacity compared with helium-4. Recent experiments with 4 K GM-type PTCs (Xu *et al.*, 1999; Jiang *et al.*, 2004) and Stirling-type PTCs (Nast *et al.*, 2006; Olson *et al.*, 2006) have verified that the use of helium-3 in place of helium-4 increased the refrigeration performance. The performance of the last stage regenerator of a Stirling-type PTC working at 4 K is calculated from REGEN and a systematic comparison between helium-4 and helium-3 is made.

Table 1 lists the important parameters used for the regenerator and the operating conditions in most of the calculations with REGEN. In some calculations, these parameters were varied to determine their influence on the system performance. Mix 1 represents a multilayered mixture which is used as the regenerator matrix. The mixture is composed of stainless steel ($ErAl_2$, $ErDy_{0.8}Ni_2$, $Er_{0.9}Yb_{0.1}Ni$, and $Er_{0.6}Pr_{0.4}$). The calculation model will choose the material with the highest volumetric heat capacity at any given temperature as the regenerator matrix.

Table 1 Regenerator parameters and operating conditions in most cases of calculation with REGEN

Regenerator parameter	Value	Operating condition	Value
Diameter (mm)	12.4	Frequency (Hz)	30
Length (mm)	30	Cold end temperature (K)	4.0
Sphere diameter (μm)	100	Hot end temperature (K)	10.0
Porosity	0.38	Average pressure (MPa)	1.0
Regenerative material	Mix 1	Pressure ratio at the cold end	1.2

Influence of warm end temperature with different pressure ratios

Fig.1 compares the influence of the warm end temperature in the last stage regenerator of the Stirling-type PTC on the performance of the regenerator with helium-4 (Fig.1a) and helium-3 (Fig.1b) as the working fluid. Considering the fact that the warm end temperature is changing and the regenerator ineffectiveness loss is the main loss, we used the relative regenerator loss to evaluate the performance of the Stirling-type PTC. The upper bound of the warm end temperature in the last stage regenerator increases with the pressure ratio (P_r, maximum pressure over minimum pressure) at the cold end for both helium-4 and helium-3; the upper bound of the warm end temperature with helium-3 as the working fluid is higher than that with helium-4. With a larger warm end temperature limit, the performance of regenerator at warmer stages can be improved. However, it is difficult to achieve a large P_r at the cold end with a linear compressor because of the high density of helium at 4 K. Given that the pulse tube loss is about 20%~30% of the total gross refrigeration power, the relative regenerator loss should be less than 70% to provide any cooling power. It is impossible to reach 4 K with a P_r of 1.1 for both of the two working fluids. The maximum warm end temperature for reasonably efficient regenerator performance is about 15 K for helium-4 and 20 K for helium-3 with a P_r of 1.2, which is typically obtained at the cold end of regenerator by a linear compressor (Gan *et al.*, 2008).

Influence of frequency with different average pressures

Fig.2 shows the influence of frequency with different average pressures (P_0) on COP of the 4 K stage regenerator of the Stirling-type PTC with helium-4 (Fig.2a) and helium-3 (Fig.2b) as the working fluid. Calculation results show that the COP increases remarkably as P_0 decreases whether helium-4 or helium-3 is used as the working fluid. This may be explained by the fact that the losses associated with enthalpy flow due to the real gas effects, one of the main losses of 4 K cryocoolers, is reduced significantly as P_0 decreases. The COP with helium-3 as the

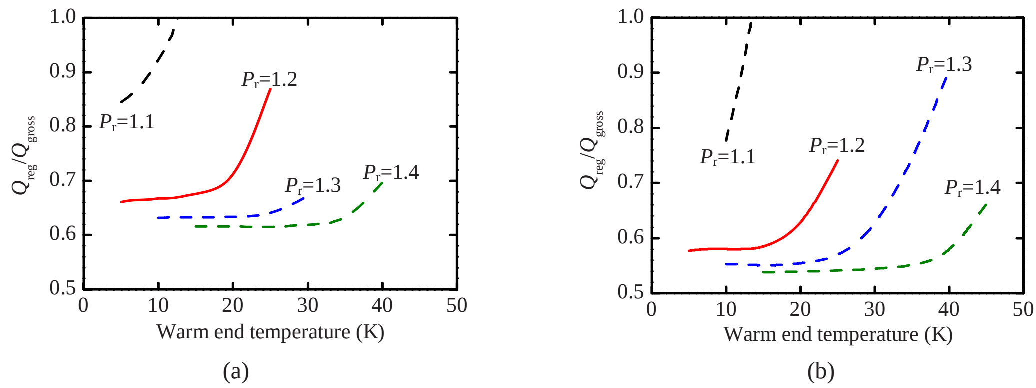

Fig.1 Influence of warm end temperature on the relative regenerator loss with (a) helium-4 and (b) helium-3 under different P_r. T_c=4.0 K (cold end temperature of regenerator), f=30 Hz, P_0=1.0 MPa

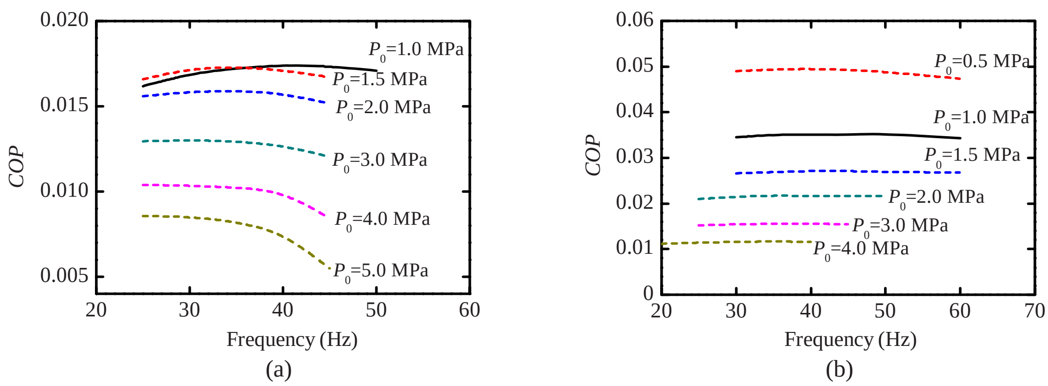

Fig.2 Influence of frequency on COP with (a) helium-4 and (b) helium-3 under different P_0. T_c=4 K (cold end temperature of regenerator), T_h=10 K (hot end temperature of regenerator)

working fluid is much higher than that with helium-4 especially for very low P_0. The COP tends to decrease when P_0 is lower than about 1.0 MPa with helium-4 while for helium-3 the benefit of using low average pressure is very obvious. And the optimal operating frequency for the Stirling-type PTC when helium-3 is used as the working fluid appears to be higher than that with helium-4 as the working fluid. This is another benefit of using helium-3 because the optimal operating frequency for most of the linear compressors is usually higher than that of 4 K Stirling-type PTCs. But the upper limit of operating frequency of 4 K Stirling-type PTC should be about 30 Hz to make sure that the heat transfer between the working fluid and the regenerator matrix is effective (Dai *et al.*, 2007).

COLD INERTANCE TUBE

The losses in the regenerator are minimized when the amplitude of the mass flow is minimized for a given acoustic power which requires that the mass flow lags the pressure by about 30° at the cold end of regenerator (Radebaugh *et al*., 2006). The inertia of a narrow and elongated inertance tube functions as the gas equivalent of an inductor in an analogous electrical system and can be configured to shift the phase angle between the pressure and mass flow at the cold end of the regenerator to the optimum value.

According to energy conservation, in order to achieve the ideal phase angle of 30° at the cold end, the mass flow should lag the pressure by about 46° at the entrance to the inertance tube for a Stirling-type PTC. However, because the acoustic power of the Stirling-type PTC used in this study is very small, the phase shift that can be produced by an inertance tube at the ambient temperature, based on our calculation, is limited to less than 10°. Therefore, we investigated the influence of the temperature of the inertance tube on the resultant phase shift. For simplification the compliance can be neglected if the reservoir of the Stirling-type PTC is large enough, and the phase shift is expressed as

$$\varphi = \arctan\frac{\omega L}{R_{\mathrm{r}}} = \arctan\frac{\rho\omega d^2}{32\mu}, \tag{3}$$

where ω is the angular frequency, L is the inductance, R_{r} is the resistance, ρ is the density of the working fluid, d is the diameter of the inertance tube, and μ is the viscosity of the working fluid. Assuming that the working fluid is an ideal gas, then ρ and μ can be written as

$$\rho = \frac{p}{RT},\quad \frac{\mu}{\mu_0} = \left(\frac{T}{T_0}\right)^n,\quad n>1,$$

where p is the average pressure, R is the gas constant, T is the temperature, and the subscript '0' represents parameters at the ambient temperature.

Substituting these expressions for ρ and μ into Eq.(3), we obtain

$$\varphi = \arctan\frac{p_0\omega d^2 T_0^n}{32R\mu_0 T^{n+1}}. \tag{4}$$

As the temperature decreases, the viscosity of the working fluid decreases and the density increases. Thus a larger phase shift is achieved and the efficiency of a Stirling-type PTC can be improved with a small acoustic power input. Therefore, a cold inertance tube is used as the phase shifter, and it is placed at the second stage thermal bridge of the Stirling-type PTC.

The designed parameters of the inertance tube used in the Stirling-type PTC at 10 and 20 K, respectively, are calculated based on transmission line theory and the results are listed in Table 2. The comparison between the results of the inertance tube at 10 and 20 K shows that the phase angle between the pressure and mass flow at the entrance to the inertance tube increases significantly as the temperature decreases and the length of the inertance tube is also greatly shortened. At 20 K, the calculated dimensions of the inertance tube can satisfy the phase shift requirement with the ideal phase angle of 30° at the cold end. However, the temperature of the inertance tube was chosen as 10 K in the experiment because the inertance tube and reservoir of the Stirling-type pulse tube cryocooler is placed at the second stage of the thermal bridge. As a result, the temperature of the inertance tube T_7 (Fig.3) is almost the same as that of the second stage precooling temperature T_5. And at present it is difficult to obtain good performance when the precooling temperature is higher than about 10 K with helium-4 as the working fluid.

Table 2 Calculation results of the cold inertance tube

Parameter	Value	
	T=10 K	T=20 K
Inner diameter (mm)	1.2	1.2
Length (m)	0.455	0.950
Phase angle (°)	59	52

EXPERIMENTAL

Based on the calculation results, a 4 K Stirling-type PTC precooled by a two-stage GM-type PTC with a cold inertance tube as the phase shifter was designed and manufactured (Qiu *et al*., 2008). The schematic graph of the Stirling-type PTC with pre-cooling is shown in Fig.3. The two-stage GM-type PTC and the Stirling-type PTC are coupled by two thermal bridges, thus they can be operated separately. The GM-type PTC is driven by a helium compressor with an input power of 7.5 kW and the Stirling-type PTC is driven by a linear compressor whose frequency can be varied from 25 to 70 Hz. The maximum input power for the linear compressor is 280 W and in the experiment the actual input power is controlled at 50 W.

The regenerator of the Stirling-type PTC is divided into three sections according to the temperature ranges shown in Fig.3. The dimension of last stage regenerator of the Stirling-type PTC is the same as that listed in Table 1 and $HoCu_2$ is used as the regenerator matrix. For regenerators working at temperatures between 10 and 300 K, stainless steel mesh and lead spheres are used as the matrix. Two thermal bridges located at the first and second stages of the GM-type PTC, respectively, are adopted to provide the required cooling power for the Stirling-type PTC. According to the simulation results, the precooling power required for the Stirling-type PTC to reach liquid helium temperature is 1.57 W at 80 K and 0.92 W at 10 K. Slot heat exchangers are used to enhance the heat transfer between the gas in the regenerator of the Stirling-type PTC and the thermal bridges. Two electrical heaters are mounted at the first and second cold ends of the GM-type PTC respectively to change the precooling temperatures. Because of the high price of helium-3, we use helium-4 as the working fluid in this experiment.

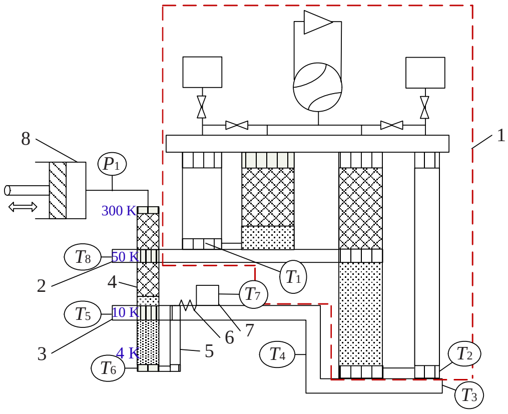

Fig.3 Schematic of Stirling-type PTC precooled by a two-stage GM-type PTC

1: two-stage GM-type PTC; 2: the 1st stage thermal bridge; 3: the 2nd stage thermal bridge; 4: regenerator of Stirling-type PTC; 5: pulse tube of Stirling type PTC; 6: cold inertance tube; 7: cold reservoir; 8: linear compressor; T_1: the first stage cold end temperature of GM-type PTC; T_2: the second stage cold end temperature of GM-type PTC; T_3: temperature at the cold end of the second stage thermal bridge; T_4: temperature at the middle of the second stage thermal bridge; T_5: temperature at the hot end of the second stage thermal bridge; T_6: temperature at the cold end of Stirling-type PTC; T_7: temperature at the reservoir of Stirling-type PTC; T_8: temperature at the first stage thermal bridge; P_1: pressure at the inlet of the regenerator of Stirling-type PTC

The distribution of thermometers is also shown in Fig.3. The refrigeration temperature of the Stirling-type PTC (T_6) is measured by a calibrated Cernox thermometer (accuracy of 0.014 K when temperature is below 10 K) and temperatures at other locations (T_1~T_5, T_7~T_8) are measured by calibrated Rh-Fe thermometers. To focus on the influence of the warm end temperature of the last stage regenerator on the performance of the Stirling-type PTC, the temperature at the first stage thermal bridge was maintained at approximately 50 K, while varying the temperature of the second stage thermal bridge. In the following discussion, the 'precooling temperature' refers to the warm end temperature of the last stage regenerator. The temperature of the inertance tube and reservoir of the Stirling-type PTC is essentially the same as this warm end temperature. The dynamic and static pressures at the inlet of the regenerator of the Stirling-type PTC (P_1) are also measured.

PRELIMINARY EXPERIMENTAL RESULTS

Influence of frequency

The influence of frequency on the refrigeration temperature (T_6) of the Stirling-type PTC with different precooling temperatures (T_5) is shown in Fig.4. The results show that the frequency has a significant influence on the performance of the Stirling-type PTC. The loss associated with the heat transfer between the gas and the regenerator matrix increases with the frequency but the efficiency of the linear compressor is very low at a low frequency. Thus the optimum frequency of the Stirling-type PTC is a compromise between the performance of the PTC and the efficiency of the linear compressor which is about 35 Hz regardless of the precooling temperature. It is worth mentioning that the refrigeration temperature exceeds the precooling temperature when the frequency is 50 Hz indicating that in this case no cooling can be obtained. As a result, the upper bound of the frequency for a Stirling-type PTC working at liquid helium temperature should be less than 50 Hz. The lower frequency limit is usually determined by the geometry of the PTC and the frequency dependence of the linear compressor's efficiency. This provides an important consideration for designing a 4 K Stirling-type PTC. The refrigeration temperature of the Stirling-type PTC decreases with the precooling temperature but the influence of the precooling temperature on the refrigeration temperature of Stirling-type PTC becomes smaller as the precooling temperature decreases.

Influence of average pressure

The influence of average pressure on the refrigeration temperature of the Stirling-type PTC at different operating frequencies with a precooling temperature being held at 10.6 K is shown in Fig.5. The results show that the performance of the Stirling-type PTC is a strong function of the average pressure and the optimum average pressure increases with frequency. The optimum pressure at 35 Hz is about 0.5 MPa, and in such conditions a temperature difference between the precooling temperature and the refrigeration temperature as large as 4.23 K can be obtained. The optimum average pressure of cryocooler may be lower than 0.4 MPa when the frequency is below 30 Hz, but it is difficult to conduct an experiment at such a low pressure, because the pistons of the linear compressor are likely to hit each other even with a very small electric power input. When no heat was applied to the second stage cold end of the GM-type PTC, the lowest no-load temperature of 4.23 K was achieved for the Stirling-type PTC with an average pressure of 0.775 MPa, a precooling temperature of 4.54 K and with an operating frequency of 40 Hz. This is the lowest temperature ever achieved for a Stirling-type PTC with helium-4 as the working fluid. According to the numerical calculation results, 4 K can be reached with the precooling temperature being 10 K. The discrepancies between the numerical results and the experiments may be explained by the fact that the numerical model REGEN 3.3 is a regenerator simulation model verified to be reasonable for 80 K Stirling-type PTCs. However, the loss

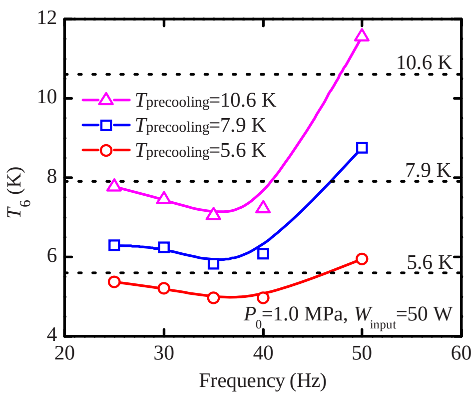

Fig.4 Influence of frequency on refrigeration temperature of a Stirling-type PTC with different precooling temperatures

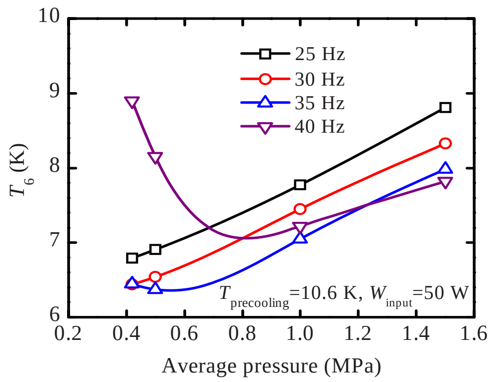

Fig.5 Influence of average pressure on refrigeration temperature of a Stirling-type PTC with different frequencies

mechanism of 4 K Stirling-type PTCs is still not well understood due to limited research and publications. Therefore, it is very likely that some losses in the regenerator are not included in this model. In addition, the rough estimate of the expansion efficiency of the pulse tube may be far away from the actual situation. The subject of this study is to know more about the losses in the 4 K Stirling-type PTCs at high frequencies. By experimental investigation we can understand the actual losses and find the way to improve the performance of a 4 K Stirling-type PTC.

CONCLUSION

In this research, a 4 K Stirling-type PTC, precooled by a two-stage GM-type PTC and utilizing a cold inertance tube and a cold reservoir as the phase shifter, was theoretically and experimentally studied. The influence of the fluid properties of helium-4 and helium-3, warm end temperature, pressure ratio, frequency and average pressure on the performance of a 4 K stage regenerator of a Stirling-type PTC is investigated based on a numerical model. A preliminary experimental investigation into the influence of precooling temperature, frequency and average pressure on the refrigeration temperature of the Stirling-type PTC was carried out. Experimental results show that the performance of the PTC is a strong function of frequency and average pressure. Performance of a 4 K Stirling-type PTC is improved by decreasing the average pressure. The lowest no-load temperature of 4.23 K was achieved with a precooling temperature of 4.54 K. However, it is very difficult to operate a Stirling-type PTC with a cold inertance tube and a cold reservoir as the phase shifter because the average helium density increases remarkably as that the temperature is decreased and large amounts of helium gas are needed to maintain the desired charge pressure during the cool down process. Additional experimental investigations will be carried out in the near future to further improve the performance of the Stirling-type PTC.

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