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THEORETICAL AND EXPERIMENTAL INVESTIGATION OF A 4 K SINGLE-STAGE STIRLING TYPE PULSE TUBE CRYOCOOLER WITH PRECOOLING

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ABSTRACT

The efficiency of 4 K Stirling type pulse tube cryocoolers (SPTC) is rather low compared with that of 80 K SPTCs. Real gas effects and low specific heat capacity ratio of regenerator matrix to helium near 4 K are the main reasons that lead to the low efficiency of 4 K Stirling type PT. A single-stage Stirling type PTC precooled by a two-stage G-M type PTC is developed to study the performance of 4 K Stirling type PTC with a focus on the performance of the regenerator working at 4 K-10 K. In order to reduce loss associated with real gas effects, relatively low average pressure was used. In order to reduce the regenerator loss caused by ineffective heat transfer between regenerator matrix and helium, Gd_2O_2S (GOS) was used as regenerator matrix to replace $HoCu_2$ around 4 K. A systematic comparison between the two types of regenerator matrix was made theoretically and experimentally including effect of frequency, average pressure and precooling temperature. Performance of the linear compressor is also presented in this paper.

KEYWORDS: Regenerator, Pulse tube, Cryocooler, 4 K, Stirling, GOS, precooling

INTRODUCTION

The application of low temperature superconductors requires the use of 4 K cryocoolers. GM cryocoolers and GM type pulse tube cryocoolers (PTC) operating at frequencies of 1 Hz-2 Hz are the typical 4 K cryocoolers. Stirling type pulse tube cryocoolers (SPTC) operating at frequencies of 30 Hz-60 Hz have the advantages of compact structure, light weight and long life compared with the above cryocoolers. As a

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result, research on SPTC working at 4 K is of great significance especially for military and space application.

Great efforts are being made in developing SPTC working around liquid helium temperature both theoretically and experimentally [1-3]. Two four-stage Stirling type PTCs developed by Lockheed Martin Advanced Technology Center have been the only Stirling type PTC capable of reaching liquid helium temperatures [1, 2]. However, the behavior of a 4 K stage regenerator in a Stirling type PTC is not well understood from the associated publications and the efficiency of 4 K SPTC is still very low. In this paper, a single-stage SPTC precooled by a two-stage GM type PTC was developed to get more understanding of the 4 K PTC characteristic at high frequency with a focus on the performance of the regenerator working at 4 K-10 K[4-6]. In order to improve the performance of the 4 K SPTC, regenerator matrix ($HoCu_2$ and Gd_2O_2S), and operating parameters such as operating frequency, average pressure and pressure ratios were optimized. However, the performance is still not good enough compared with the calculation results by REGEN3.3 [7]. The purpose of this paper is to point out the difference between the existing theory and the actual experimental results regarding 4 K SPTC and provide some guidance for the design of 4 K SPTC.

EXPERIMENTAL SETUP

The Stirling type PTC was designed based on a practical regenerator simulator known as REGEN 3.3 developed at NIST. The schematic of the Stirling type PTC with precooling is shown in FIGURE 1 [8]. The GM type PTC is driven by a Helium compressor with a rated input power of 7.5 KW and the Stirling type PTC is driven by a linear compressor with a maximum electric input power of 280 W. The operating frequency of the linear compressor can be varied from 25 Hz to 70 Hz. The regenerator of the Stirling type PTC consists of three sections (Ⅰ,Ⅱ and Ⅲ) according to the designed temperature ranges as shown in FIGURE 1. The Stirling type PTC works in the inertance mode. Cold inertance tube and reservoir were designed as the phase shifter of the Stirling type PTC for better phase relationship between the pressure and mass flow, which are placed at the second stage thermal bridge. Two thermal bridges located at the first stage cold end and the second stage cold end of the GM type PTC, respectively, are adopted to provide the required precooling for the Stirling type PTC at the joint positions of regenerator sections. The arrangement of thermometers is also shown in FIGURE 1. The temperature at the cold end of the Stirling type PTC (T4) is measured by a calibrated Cernox thermometer (accuracy of 0.014 K when temperature is below 10 K) and five calibrated Rh-Fe resistance thermometers (accuracy of 0.1 K) are used to measure temperatures at other locations (T1-T3, T5-T6). Two electrical heaters are mounted at the first stage and the second stage cold end of the G-M type PTC respectively to adjust the precooling temperatures. The static and dynamic pressure at the inlet of the regenerator of the Stirling type PTC (P1) is also measured as shown in FIGURE 1. Helium 4 is used as the working fluid.

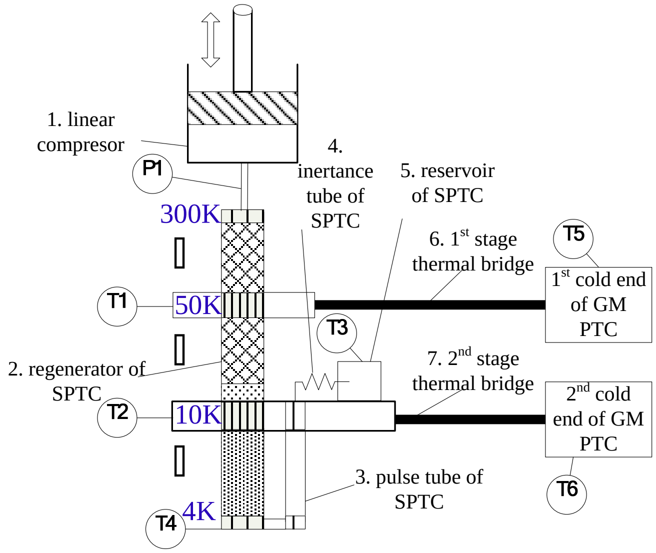

FIGURE 1. Schematic of single-stage SPTC with precooling

REGENERATOR MATRIX

Regenerator is the key component of all regenerative cryocoolers. The efficiency of the regenerator working at 4 K (part III, 4 K-10 K) is vital for the performance of the Stirling type PTC operating at liquid helium temperature. Previously we have done some calculation on the performance of 4 K regenerator [5, 6]. The volumetric specific heat capacity of the regenerator matrix should be much larger than that of the working fluid for effective heat transfer between them. FIGURE 2 shows the volumetric specific heat capacity of the typical regenerator matrix used below 20 K. The specific heat capacity of typical matrix materials is rather small around 4 K and the specific heat capacity of helium increases as the temperature decreases. As a result, the regenerator matrix of the last stage has a significant effect on the performance of the Stirling type PTC.

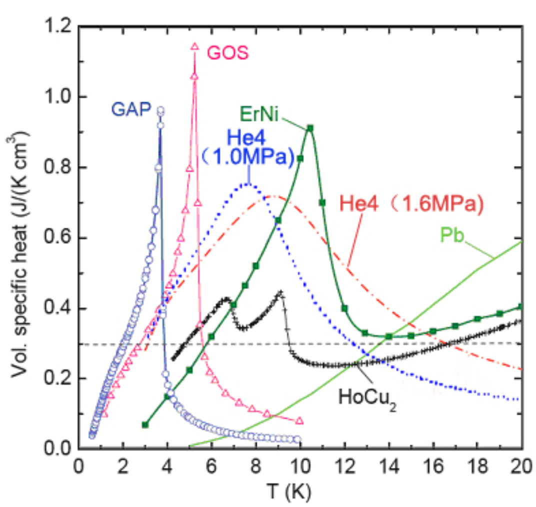

FIGURE 2. Volumetric specific heat capacity of regenerator matrix below 20 K

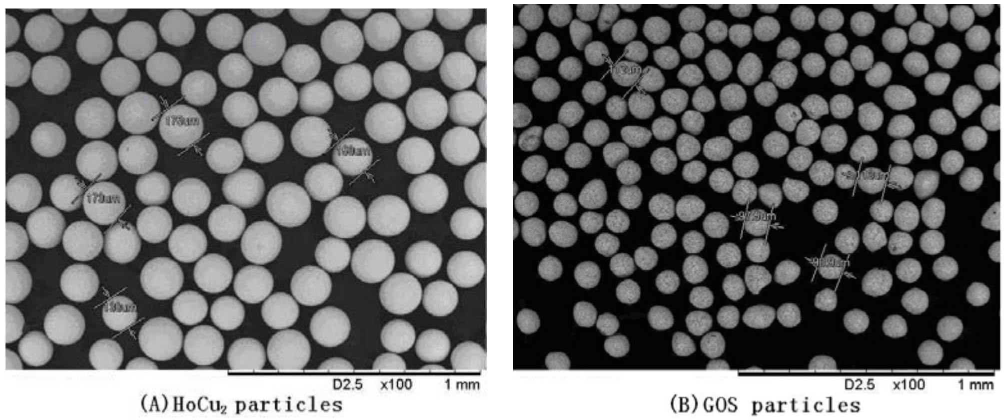

FIGURE 3. Photo of regenerator matrix particles used in experiment under a microscope

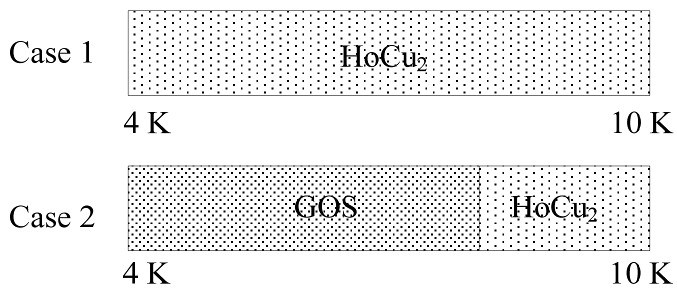

FIGURE 4. Composition of regenerator matrix of part III regenerator

In order to investigate the effect of regenerator matrix on performance of 4 K regenerator at high frequency, comparison was made between two kinds of regenerator matrix ($HoCu_2$ and GOS [9]) both theoretically and experimentally in this paper. FIGURE 3 shows the photo of the regenerator matrix particles $HoCu_2$ of and GOS under a microscope. FIGURE 4 shows the composition of the two different cases of the regenerator matrix compared in the calculation and in the experiment.

CALCULATED PERFORMANCE OF SPTC WITH HOCU$_2$ AND GOS

Calculations are carried out on the performance of part III of the regenerator based on REGEN3.3. FIGURE 5 shows the effect of ratio of regenerator gas volume to swept volume at the cold end on COP and relative regenerator loss (regenerator loss/ gross cooling capacity) of 4 K SPTC. The results show that with the use of GOS at temperature around 4 K, COP increases by almost 100% due to reduction in the enthalpy flow associated with imperfect heat transfer between regenerator matrix and helium in the regenerator. And the optimal ratio of gas volume in the regenerator to swept volume at the cold end is about 16 for both of the two cases. Given the fact that when the volume ratio is too large the loss in the warmer regenerator will be greatly increased due to imperfect phase angle between the mass flow and the pressure, a value of about 12 is used in our experiment.

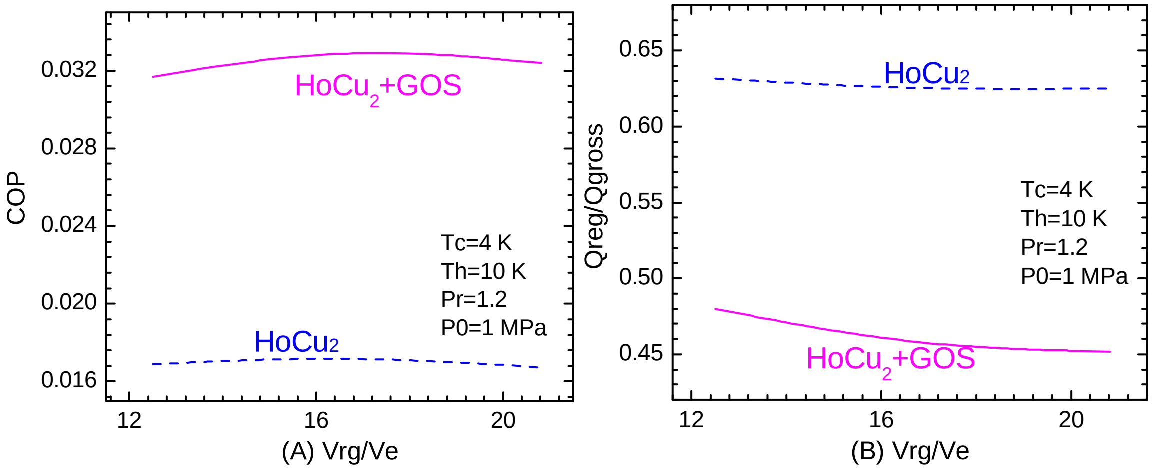

FIGURE 5. Effect of ratio of regenerator gas volume to swept volume at the cold end on COP and relative regenerator loss

PERFORMANCE OF LINEAR COMPRESSOR

Effect of frequency on power factor of linear compressor

FIGURE 6 shows the effect of frequency on the power factor (effective power/electric power) under different average pressures. The results show that the optimal frequency for the linear compressor increased with the average pressure. And the efficiency of the linear compressor decreased as the average pressure increased. FIGURE 7 shows the effect of input power on the power factor of the linear compressor. The power factor of the linear compressor decreased significantly as the input electric power increased.

Effect of frequency on pressure ratio of linear compressor

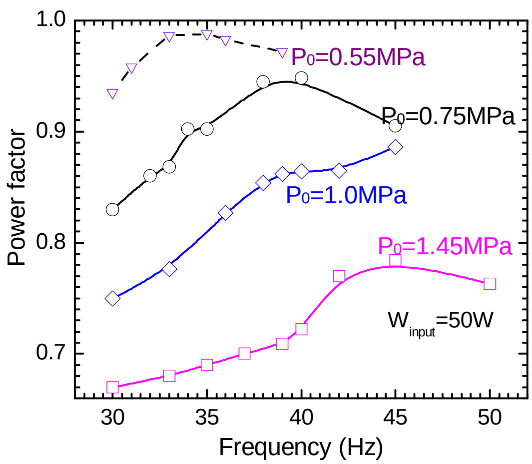

FIGURE 6. Effect of frequency on power factor of linear compressor under different average pressures

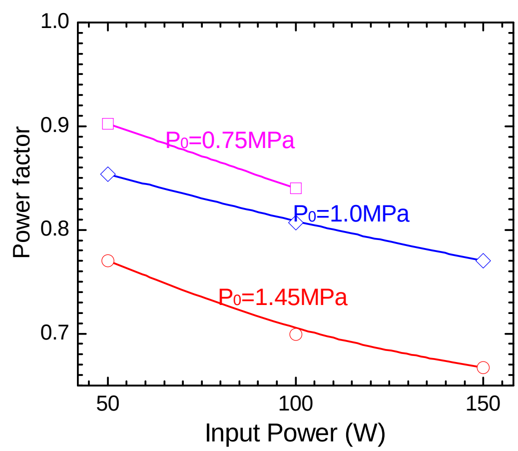

FIGURE 7. Effect of input power on power factor of linear compressor under different average pressures

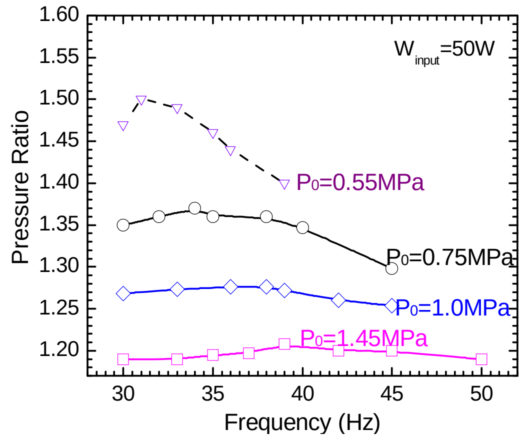

FIGURE 8. Effect of frequency on pressure ratio of linear compressor under different average pressures

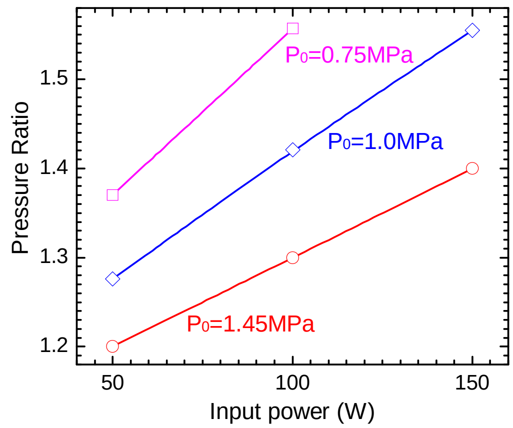

FIGURE 9. Effect of input power on pressure ratio of linear compressor under different average pressures

FIGURE 8 shows the effect of frequency on pressure ratio of linear compressor under different average pressures with the input electric power of 50 W. The optimum frequency at a constant pressure decreased as the average pressure increased. FIGURE 9 shows the pressure ratio of the linear compressor as a function of input power. The pressure ratio increased almost linearly with the input power.

EXPERIMENTAL RESULTS OF 4 K SPTC

The performance of the section III of the regenerator is vital for the efficiency of the Stirling type PTC. As a result, the influence of the second stage thermal bridge temperature (T2, see FIGURE 1) on the refrigeration temperature of the Stirling type PTC (T4) was experimentally investigated, while the temperature of the first stage thermal bridge (T1) was kept almost constant at about 50 K in the preliminary stage. In the following discussion, the ‘precooling temperature’ refers to the temperature of the second stage thermal bridge T2.

Effect of frequency with different precooling temperature

FIGURE 10 shows the experimental results of the influence of frequency on the refrigeration temperature of the Stirling type PTC with different precooling temperatures (T2) with $HoCu_2$ (case 1) and both $HoCu_2$ and GOS (case 2) as the regenerator matrix, respectively. In the experiment the precooling temperature (T2) was fixed at 10.6 K, 7.9 K and 5.6 K respectively. The average pressure was kept constant at 1.0 MPa. With the use of GOS the performance of the 4 K SPTC is improved when the precooling temperature is 5.6 K. The lowest temperature achieved is 4.7 K for case 2 while the lowest temperature is about 5 K for case 1. When the precooling temperature is higher, such as 7.9 K and 10.6 K, the performance of 4 K SPTC with case 2 is not as well as that of case 1. The main reason may be that the pulse tube expansion efficiency is much lower than 80%，the assumed

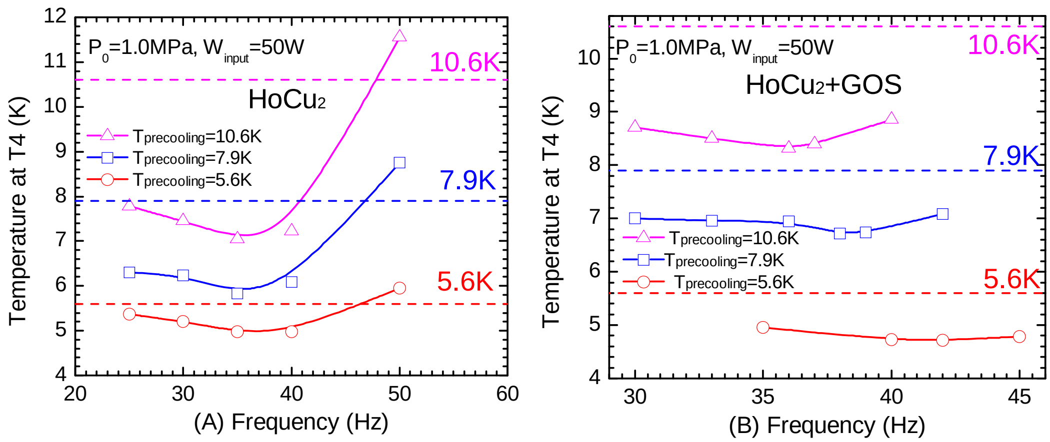

FIGURE 10. Effect of frequency on T4 with different precooling temperature T2

value in the calculation. The pulse tube is working at very low temperature (4 K-10 K). Most of the volume in the pulse tube is filled with helium with large density behaving very close to liquid helium. As a result, the effective volume of the pulse tube is much smaller than 3-5 times the swept volume at the cold end. The refrigeration temperature of SPTC can't reach the temperature region around 5.2 K where the heat capacity of GOS is large.

Effect of frequency with different average pressures

Experiment of the effect of frequency on T4 with different average pressures when T2 is 5.6 K was carried out and the results are shown in FIGURE 11. The optimal frequency increased as the average pressure for both the two cases. But for case 1 when only $HoCu_2$ is used as the matrix the frequency has a significant effect on refrigeration temperature of SPTC. When the frequency is 35 Hz the refrigeration temperature exceeds the precooling temperature at 0.55 MPa. This is because the losses associated with imperfect heat transfer in the regenerator increased as the frequency. The lowest temperature for case 1 and case 2 is 4.65 K and 4.49 K, respectively.

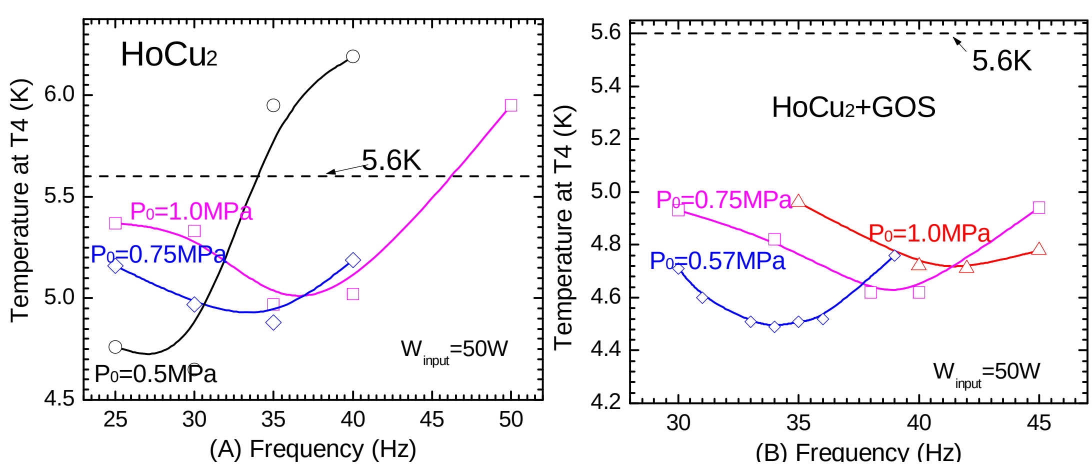

FIGURE 11. Effect of frequency on T4 with different average pressures when T2 is 5.6 K

CONCLUSIONS

Theoretical and experimental investigation was carried out on a Stirling type PTC with precooling working at 4 K. In order to reduce regenerator loss associated with imperfect heat transfer, a ceramic material GOS was used as the matrix near 4 K. Experimental results showed that with the use of GOS the performance of the 4 K SPTC is improved when the precooling temperature is low. And the optimal frequency for the SPTC increased as the average pressure. Effect of pulse tube on performance of the 4 K SPTC will be carried out in the near future.

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