Experimental Investigation of Regenerative Material on Performance of a 10 K Multi-Stage High Frequency Pulse Tube Cryocooler

Jia Quan[1,2], Yanjie Liu[1], Jingtao Liang[1], Juan Wang[1]

[1] Key Laboratory of Space Energy Conversion Technologies
Technical Institute of Physics and Chemistry CAS, Beijing, 100190, China
[2] Graduate University of Chinese Academy of Sciences, Beijing 100190, China

ABSTRACT

A multi-stage high frequency pulse tube cryocooler is a way to meet the thermal requirements of infrared detectors, superconducting devices, and equipment for deep space exploration. As thermally-coupled cryocooler's mass flows are easier to control, and energy flows are more readily monitored than gas flows, we have designed a 10 K thermally-coupled two-stage pulse tube cryocooler for use with different kinds of regenerative material in a variety of experiments. In this paper we describe the newly-designed two-stage pulse tube cryocooler and present the experimental results. A key focus was identifying regenerative materials that are optimal for use around 10 K and analyzing the influence of the different regenerative materials and fill styles on the performance of the cryocooler. The experimental results show that Er_3Ni is a good regenerative material for use in a 10K high frequency pulse tube cryocooler. The results provide a technical foundation for the design of future multi-stage 10 K high frequency pulse tube cryocoolers.

INTRODUCTION

At present, the lowest refrigeration temperature that can be achieved by a single-stage Stirling-type pulse tube is above 20 K. Thus, it is indispensable to develop high frequency multi-stage pulse tube cryocoolers for use at lower temperatures, such as 10 K. This has been an important direction in the research field of pulse tube cryocoolers. Depending on the type of thermal coupling between stages, multi-stage pulse tube cryocoolers can be divided into two types: thermally-coupled and gas-coupled. As thermally-coupled cryocooler's mass flows are easier to control, and energy flows are more readily monitored than gas flows, thermally-coupled cryocoolers have been the focal point of many research institutes. Lockheed Martin's Advanced Technology Center (LMATC), Northrop Grumman Space Technology (NGST), and the Institute of Refrigeration and Cryogenics at Zhejiang University have all developed different kinds of thermally coupled pulse tube coolers [1-8].

One of the primary challenges in achieving an efficient 10 K Stirling-type pulse tube cryocooler is finding a regenerative material that has a high capability for regeneration in this extremely low temperature environment. At this time, the common regenerative materials for high frequency pulse tubes working below 30 K are Er_3Ni, $HoCu_2$ and GOS. As GOS is expensive and difficult to acquire, $HoCu_2$ and Er_3Ni were selected for the experiments described here.

Cryocoolers 17, edited by S.D. Miller and R.G. Ross, Jr.

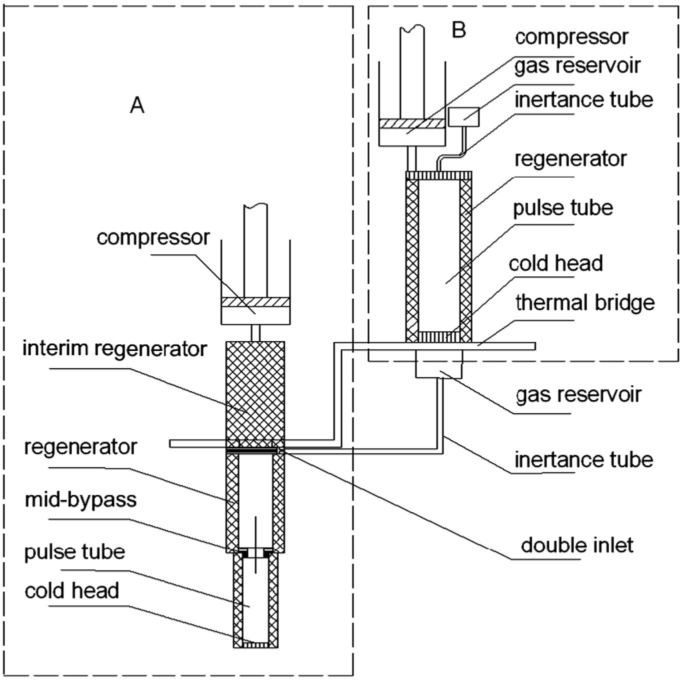

Figure 1. Schematic of the two-stage high frequency pulse tube cryocooler

STRUCTURE OF A TWO-STAGE HIGH FREQUENCY PULSE TUBE CRYOCOOLER

The structure of the newly-designed two-stage high frequency pulse tube cryocooler is shown in Figure 1. The system is made of two parts: the compressor assembly and the pulse tube expander assembly. The compressor assembly includes two compressors that are used to provide pressure waves for the first-stage (precooler) and the second-stage (cryogenic cryocooler). The pulse tube expander includes two pulse tube cold heads, one each for the first and second stages. Both of the two pulse tube expanders are of the coaxial type construction.

Figure 2 describes the thermal performance of the first stage when tested as a stand-alone cooler. As shown, it provides a cooling capacity of 6.4 W @ 80 K when driven with a compressor input electric power of 170 W. In terms of phase control, the precooler uses an inertance tube and gas reservoir as its phase shifter. The first-stage cold head is thermally coupled to the second-stage heat sink using a thermal bridge made of copper foil. The thermal resistance is 2 K/W.

The PT expander for the second stage is of stainless steel construction. A cold inertance tube, cold gas reservoir, cold double inlet, and cold mid-bypass are used as the phase shifter. Both the regenerator and the pulse tube have variable cross sections.

According to the variation of temperature in different regenerator sections, different regenerative materials are filled in the second-stage regenerator. In the temperature zone above 80 K, the volumetric heat capacity of stainless steel mesh is much higher than helium gas, and the hydraulic equivalent diameter of stainless steel screen is much less than its thermal penetration depth. Thus, stainless steel mesh is a good regenerative material in this temperature range.

In the zone of 30-80 K, considering the volumetric heat capacities of materials, lead regenerative material is a good choice. But according to the research of Yang Lu-Wei, high thermal conductivity, low heat exchange and low thermal penetration depth suggest that lead spheres are not suitable for high frequency pulse tube cryocoolers [9]. As a result, stainless steel mesh is also used as the regenerative material in the 30-80 K temperature range. It is filled into the regenerator between the heat sink of the second-stage and the mid-bypass.

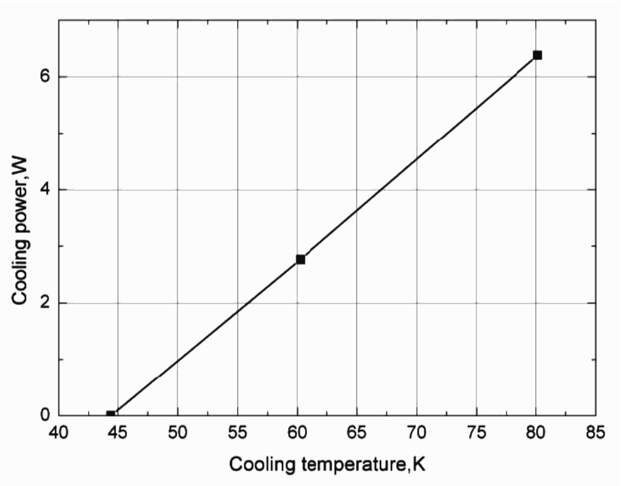

Figure 2. Performance of first-stage pulse tube cryocooler.

When the temperature is below 30 K, the volumetric heat capacity of stainless steel is close to that of helium gas, and it can't meet the requirements of a good regenerative material. Here we selected Er_3Ni and $HoCu_2$ as candidate regenerative materials for improved performance.

EXPERIMENTAL INVESTIGATION

In exploring a suitable regenerator material for the second stage, we used Er_3Ni and $HoCu_2$ with the same particle diameter and multi-layer filling style. The materials were filled in the regenerator between the mid-bypass and the cold head of the second-stage. Figure 3 describes the various particle sizes and filling styles used in the eight test cases examined.

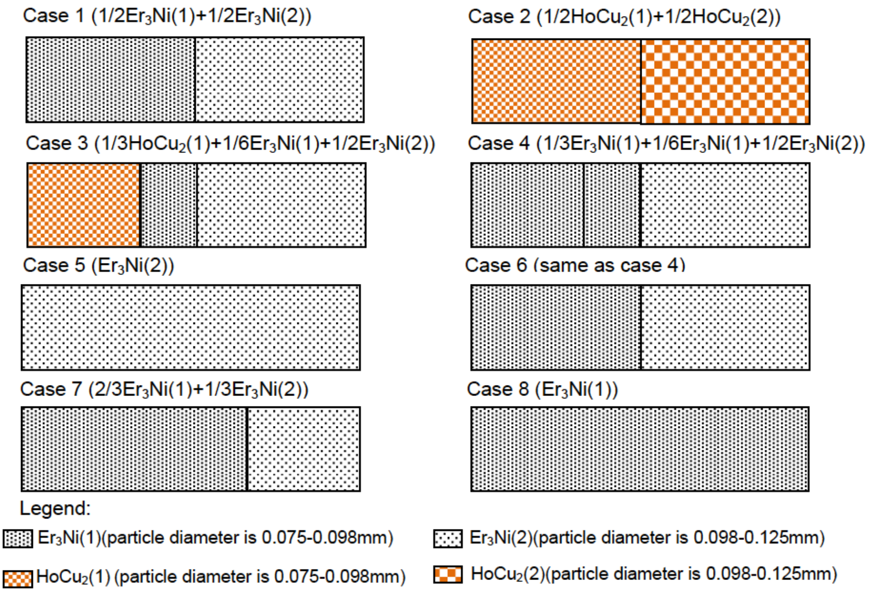

Figure 3. The design of multi-layer filled style

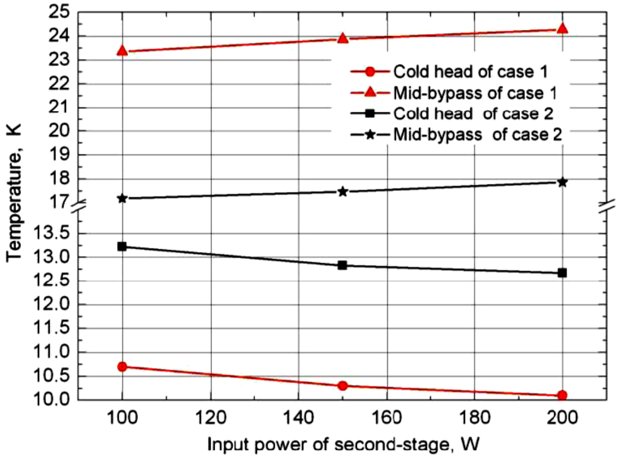

Figure 4. Experimental results for case 1 and case 2.

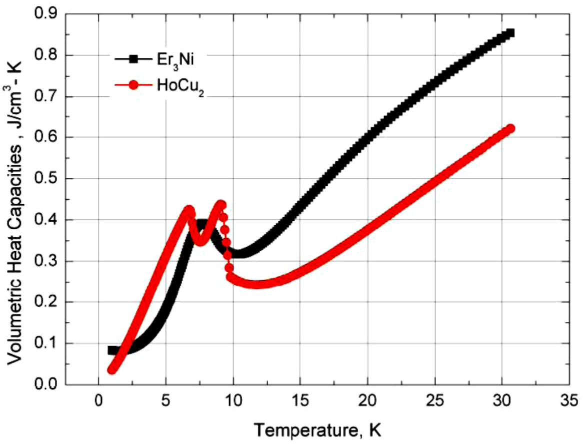

Figure 5. Volumetric heat capacities of Er3Ni and HoCu2.

Figure 4 presents the results of achieved no-load temperatures for the first two cases. For these tests the first-stage input power was 170 W, and the second-stage input power was 100 W, 150 W, and 200 W, respectively, .

From the results shown in Figure 4, though the temperature of the mid-bypass is lower with $HoCu_2$ as the regenerative material, the no-load cooling temperature of the second-stage is lowest when Er_3Ni is used as regenerative material. According to data on volumetric heat capacities supplied by NIST and shown in Figure 5 [10], the volumetric heat capacity of Er_3Ni is higher than that of $HoCu_2$ in the temperature zone immediately above 10 K. Thus, the cooling temperature of the second-stage was lowest when the regenerative material was Er_3Ni.

As the temperature of the regenerator and pulse tube between mid-bypass and the cold head of the second-stage is higher when $HoCu_2$ is used as regenerative material, the pressure of the working fluid is higher, and the distribution of the working fluid changes. More mass flux flows into the pulse tube from the mid-bypass, which results in the temperature of the mid-bypass being lower when the regenerative material is $HoCu_2$.

After optimizing the design of the regenerator of the second-stage, the cooling temperature of second-stage was below 9K, so a new multi-layer filling style was designed to make the most of the

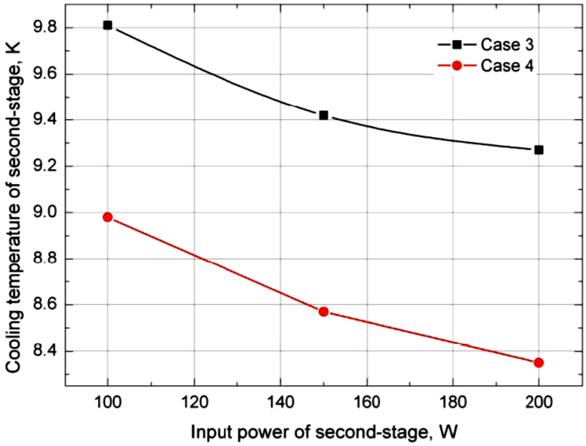

Figure 6. Experiment results of case 3 and case 4.

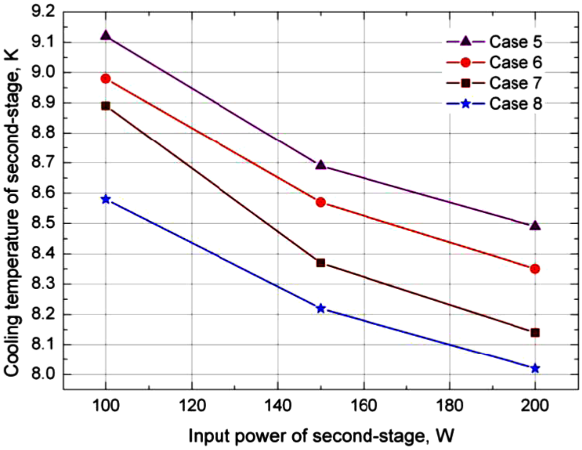

Figure 7. Experiment results of case 5 to case 8.

peak of volumetric heat capacity of $HoCu_2$ around 9 K. This filling style is defined in Figure 3 as cases 3 and 4. For this set of experiments, 250 W of electric power was supplied for the first-stage compressor, while second-stage input powers were 100 W, 150 W, and 200 W, respectively.

Based on the results shown in Figure 6, using Er_3Ni achieved the lowest cooling temperature. With further analysis, it appears the $HoCu_2$ peak is too narrow, and the average value of volumetric heat capacity of Er_3Ni is higher than that of $HoCu_2$ in this temperature zone. The experimental results shown above established that Er_3Ni was the preferred regenerative material for cases 3 and 4. However, previous experience suggested that a multi-layer filling style can often achieve a better cooling temperature. As a result we tested an additional four filling styles defined in Figure 3 as cases 5 to 8.

Figure 7 shows the results of these experiments. As before, 250 W of electric power was supplied for the first-stage compressor, and the second-stage input power was 100 W, 150 W, and 200 W, respectively. Based on the results, when the regenerator was filled with Er_3Ni whose particle diameter is between 0.075 mm and 0.098 mm, the lowest temperature of the multi-stage high frequency pulse tube cryocooler reaches 8 K. This is the lowest temperature for this kind of cryocooler reported in the world so far. However, this result does not conform to our previous experience with respect to multi-layer filling, and we feel that multi-layer filling can not be ruled out as a suitable style in the future. The most likely theory is that the particle diameter of the regenerative material has an upper limit; namely, the volumetric porosity in the regenerator has an upper limit. Only when particle diameter or volumetric porosity is less than some corresponding value, will the multi-layer-fill style provide better performance in the cryocooler. More data on these porosity dependencies are needed to further clarify the experimental results.

CONCLUSION

In this study, a new type multi-stage high frequency pulse tube cryocooler was used to experiment with regenerator materials suitable for cooling to 10 K. With the best performing Er_3Ni regenerator material, the cooler reached a no-load temperature of 8 K; this is the lowest temperature for this kind of cryocooler reported in the world so far. Er_3Ni was established as the most suitable regenerative material in this temperature range. For multi-layer filling to show an advantage, it appears that the particle size must be less than some upper limit. The test results should prove useful for the design of multi-stage high frequency 10 K pulse tube cryocoolers.

REFERENCES

1. Nast, T., Olsen, J., Champagne, P., Mix, J., Etvimov, B., Roth, E., and Collaco, A., "Development of 4.5 K Pulse Tube Crycooler for Superconducting Electronics," *Adv. in Cryogenic Engineering*, Vol. 53, Amer. Institute of Physics, Melville, NY (2008), pp. 881-886.

2. Webber, R. J., Dotsenko, V.V., De lmas, J., Kadin, A.M., and Track, E.K., "Evaluation of a 4 K 4-stage pulse tube cryocooler for superconducting electronics," *Cryocoolers 15*, Springer Science and Business Media, New York, NY (2009), pp. 657-664.

3. V.V. Dotsenko, J. Delmas, R.J. Webber., "Integration of a 4-Stage 4 K Pulse Tube Cryocooler Prototype with a Superconducting Integrated Circuit," *IEEE Transactions on Applied Superconductivity*, 19 (2009), pp. 1003-1007.

4. Nguyen T., Colbert, R., Durand, D., Jaco, C., Michaelian, M. and Tward E., "10K Pulse Tube Cooler," *Cryocoolers14*, New York, Kluwer Academic/Plenum Publishers, New York (2007), pp. 27-31.

5. Jaco, C., Nguyen, T., Colbert, R., Raab, J., "10 K EM Pulse Tube Cooler," *Adv. in Cryogenic Engineering,* Vol. 53, Amer. Institute of Physics, Melville, NY (2008), pp. 659-664.

6. Jaco, C., Nguyen, T., Colbert, R., Raab, J., "10 K Pulse Tube Cooler Performance Data," *Cryocoolers 15*, Kluwer Academic/Plenum Publishers, New York (2009), pp. 1-6.

7. Raab, J., Tward, E., "Northrop Grumman Aerospace Systems Cryocooler Overview," *Cryogenics,* 50, pp. 572-581.

8. Zhi Xiaoqin, Qiu Limin, Gan Zhihua, Cao Qiang, Liu Yang, "Investigate the performance of 5K level three-stage stirling pulse tube cryocooler," *Conference of Engineering Thermophysics,* (2011).

9. Y. Lu-Wei, M. Dietrich, G. Thummes, "Research of Two-stage High Frequency Pulse Tube Cooler Using Lead Regenerative Materials," *Journal of Engineering Thermophysics*, 28 (2007), pp. 33-36.

10. http://cryogenics.nist.gov/MPropsMAY/material%20properties.htm