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Influence of Regenerator Material on Performance of a 6K High Frequency Pulse Tube Cryocooler

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Abstract. As very low temperature high frequency pulse tube cryocooler has been a hot topic in the field of pulse tube cryocooler, improving the cryocooler's performance is a common goal of researchers. By integrating the former results, we found that regenerator material is a key factor for the improvement of pulse tube cryocooler's efficiency. In this paper, methods of simulation and experiment were used to investigate the influence of stacking style on performance of 6K high frequency pulse tube cryocooler. Finally, the lowest temperature has dropped from 8.8K to 6.7K and more than 10mW of cooling power is achieved at 8K with a two-stage thermally coupled high frequency pulse tube cryocooler. The results make the space application of NbN terahertz detectors possible.

1. Introduction

Since the need for ultra-long wavelength infrared detection, superconducting devices and THz space detection are increasing, very low temperature high frequency pulse tube cryocooler has become important. Even though G-M pulse tube has met the requirements in temperature, it can't meet the demands of space because of its size. Lockheed Martin's Advanced Technology Center (LMATC), Northrop Grumman Space Technology (NGST) and the Institute of Refrigeration and Cryogenics in Zhejiang University have been working on multi-stage high frequency pulse tube cryocooler to get to very low temperatures [1-5].

In the research of high frequency pulse tube cryocooler, the key factor in its performance is the regenerator. When the temperature is below 30K, volumetric heat capacities of common regenerator materials are lower than helium, so heat exchanging effect deteriorates below 30K. Lead is suitable for low frequency cryocooler, but it can't improve the performance of high frequency pulse tube cryocoolers[6]. In view of this situation, suitable regenerator materials for very low temperatures and the influence of filling method of the regenerator are investigated in this paper.

2. Simulation for filling style

At the 17th International Cryocooler Conference (ICC), the present authors did some preliminarily research on the regenerator materials and filling style of a 10K high frequency pulse tube cryocooler. In the article, the authors found that Er_3Ni was better than $HoCu_2$ as a 10K regenerator material, and proposed a concept of upper limit of volumetric porosity [7]. In a follow-up study, the authors found that the volumetric porosity changed relatively little as the diameter of the particles changed. In order

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to find out how particle diameters influence the performance of cryocooler, regen3.3 was used to make a simulation for the stacking style in a regenerator. In the simulation, working temperature was set up between 6K and 30K and operating frequency was 23Hz. The operation parameters were close to the conditions of experiments so as to compare results.

As many kinds of particle diameters were used in the simulation and experiments, we converted them into hydraulic diameters for simulation and numbered hydraulic diameters as shown in Table 1. The stacking style in regenerator are shown in Table 2 and Table 3 and the simulation results of coefficient of performance (COP) are shown in Figure1 and Figure2

Table 1 Number of different regenerator materials and different hydraulic diameters

serial number	hydraulic diameter ($\times 10^{-5}$m)	serial number	hydraulic diameter ($\times 10^{-5}$m)
Er_3Ni(1)	2.15	Er_3Ni(6)	3.7
Er_3Ni(2)	2.3	Er_3Ni(7)	4.0
Er_3Ni(3)	2.5	Er_3Ni(8)	4.4
Er_3Ni(4)	3.0	Er_3Ni(9)	4.7
Er_3Ni(5)	3.3		

Table 2 Filling style with the same hydraulic diameter

Serial number	Filling style	Serial number	Filling style
Case(1s)	Er_3Ni (1)	Case(6s)	Er_3Ni (6)
Case(2s)	Er_3Ni (2)	Case(7s)	Er_3Ni (7)
Case(3s)	Er_3Ni (3)	Case(8s)	Er_3Ni (8)
Case(4s)	Er_3Ni (4)	Case(9s)	Er_3Ni (9)
Case(5s)	Er_3Ni (5)		

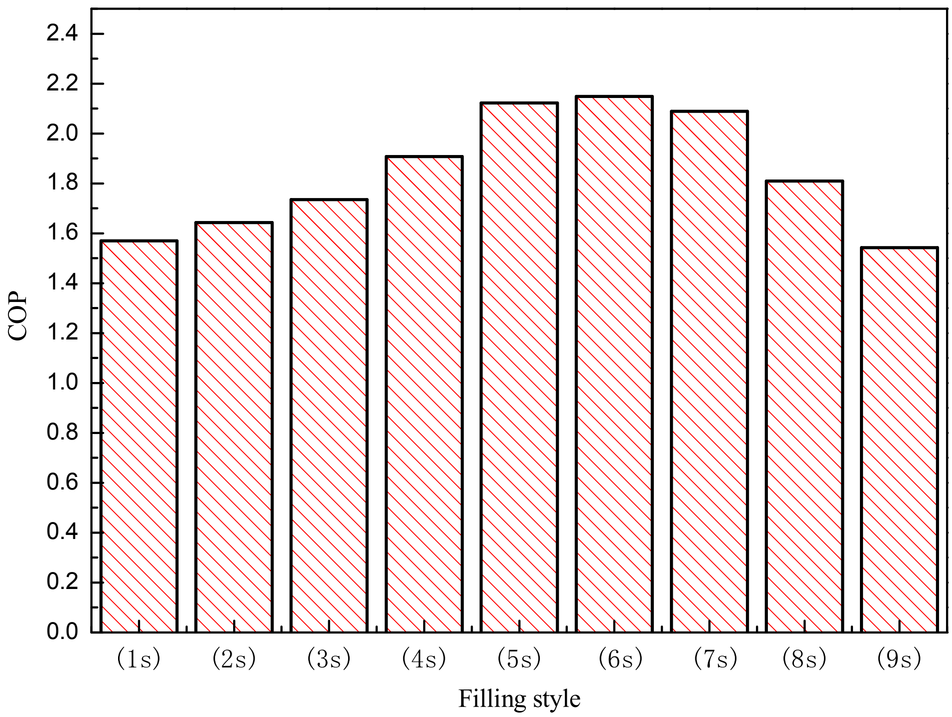

Fig.1 Simulation results of filling style with same hydraulic diameter

Table 3 Filling style with different hydraulic diameters

Serial number	Filling style
Case(10s)	3/10 Er_3Ni (6)+3/10 Er_3Ni (5)+1/5 Er_3Ni (5)+1/5 Er_3Ni (5)
Case(11s)	3/10 Er_3Ni (7)+3/10 Er_3Ni (5)+1/5 Er_3Ni (5)+1/5 Er_3Ni (5)
Case(12s)	3/10 Er_3Ni (6)+3/10 Er_3Ni (6)+1/5 Er_3Ni (5)+1/5 Er_3Ni (5)
Case(13s)	3/10 Er_3Ni (6)+3/10 Er_3Ni (6)+1/5 Er_3Ni (6)+1/5 Er_3Ni (5)
Case(14s)	3/10 Er_3Ni (7)+3/10 Er_3Ni(6) +1/5 Er_3Ni (6)+1/5 Er_3Ni (6)
Case(15s)	3/10 Er_3Ni (7)+3/10 Er_3Ni (6)+1/5 Er_3Ni (6)+1/5 Er_3Ni (5)
Case(16s)	3/10 Er_3Ni (7)+3/10 Er_3Ni (7)+1/5 Er_3Ni (6)+1/5 Er_3Ni (5)
Case(17s)	3/10 Er_3Ni (7)+3/10 Er_3Ni (6)+1/5 Er_3Ni (5)+1/5 Er_3Ni (5)
Case(18s)	3/10 Er_3Ni (7)+3/10 Er_3Ni (6)+1/5 Er_3Ni (6)+1/5 Er_3Ni (7)

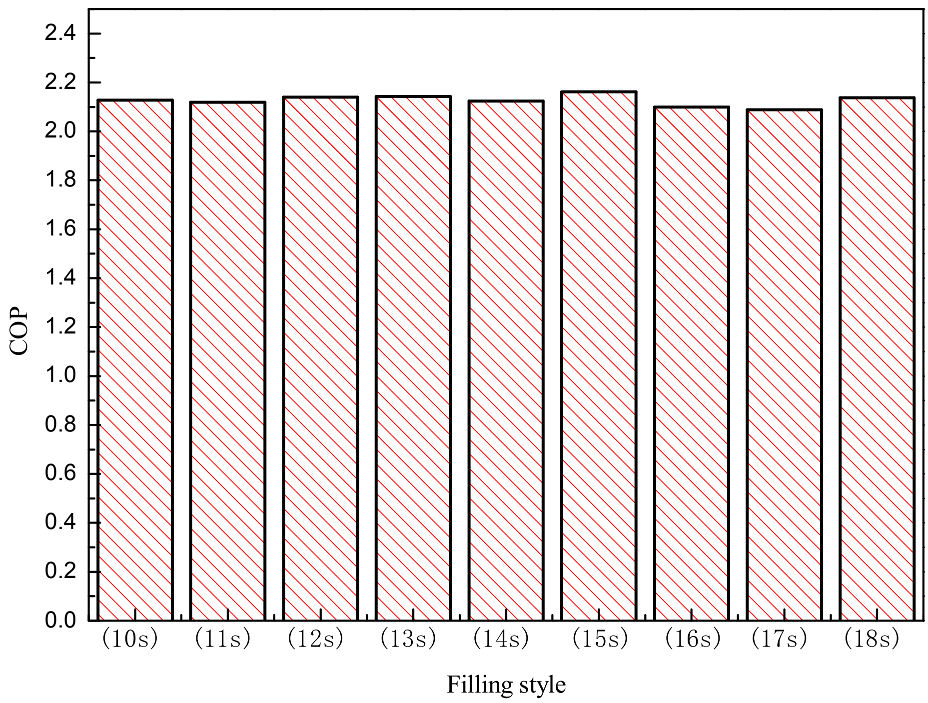

Fig.2 Simulation results of filling style with different hydraulic diameters

The fraction is the filled length ratio of the regenerator material with a specific hydraulic diameter in the regenerator. For example: 3/10 Er_3Ni (6) means that the filled length of Er_3Ni with 3.7×10^{-5}m hydraulic diameters is 3/10 of the total regenerator length. If the ratio is 1, the number will be omitted.

From the results of simulation, we get some guesses which should be verified by experiment.

(1) When we use a single diameter regenerator material filling in the regenerator, there is an optimum value for the diameter. If the value of diameter is below or above it, the COP of cryocooler will decrease.

(2) Using a specific combination of materials we get better results.

(3) If we use multi-layer filling style in the regenerator, the diameter of the regenerator material filled in the cold side should be less than the best value of diameter mentioned above, or the cryocooler may not achieve the best performance.

In view of the simulation results, we consider that heat capacity of regenerator matrix and pressure drop in regenerator are main factors that affect the COP of regenerator. If smaller diameter regenerator material is used, heat transfer will be improved due to the increase in the heat transfer area, but the flow resistance becomes larger as a result of the decrease in the hydraulic diameter. Using suitable multi-layer filling method would enhance heat transfer coefficient, and flow resistance wouldn't change drastically, so the COP gets larger.

3. Experiment

3.1. Experimental apparatus

A two-stage high frequency thermally coupled pulse tube cryocooler designed by Key Laboratory of Space Energy Conversion Technologies (SECT), Technical Institute of Physics and Chemistry (TIPC), Chinese Academy of Sciences (CAS), is used to conduct the experiments. The schematic of the cryocooler is shown in Figure3. The cryocooler is divided into two parts: the first-stage (pre-cooler) and the second-stage (cryogenic-stage). Every stage includes one compressor and one cold finger. Regenerator material in the first-stage regenerator is stainless steel mesh. For the second-stage regenerator, above 30K, stainless steel mesh is used, while below 30K, a suitable regenerator material and filling method studied.

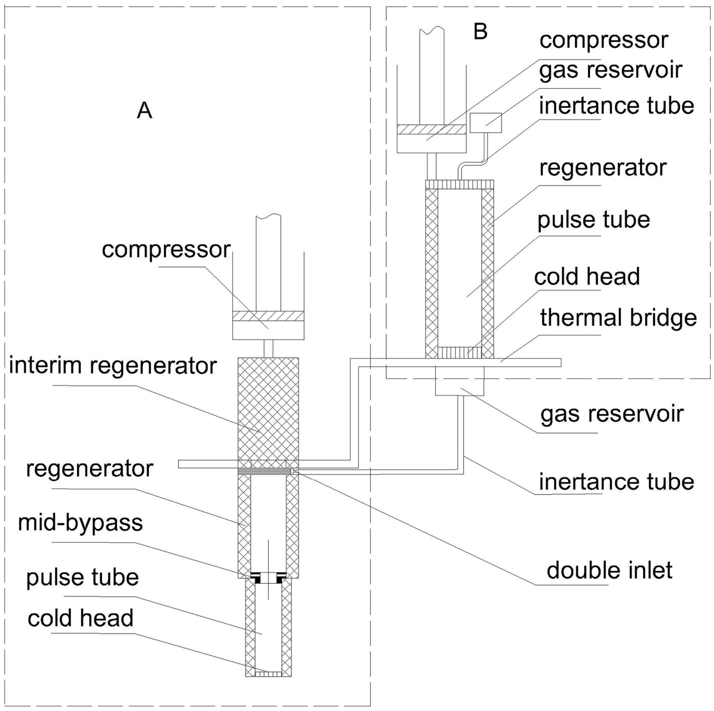

Fig.3 Schematic the two-stage pulse tube cryocooler

3.2. Experimental results

In view of the conclusion that Er_3Ni is appropriate for regenerator material for 8K operations, which is presented in the article "Experimental Investigation of Regenerator Material on Performance of Multi-stage High Frequency Pulse Tube Cryocooler"[7], we used Er_3Ni as the regenerator material and designed a series of experiments to search for a reasonable filling method. The stacking styles are shown in Table 4, and the experimental data is shown in Figure 4. For the stacks filling method, the lowest temperature has dropped from 8.8K to 6.7K, and more than 40mW of cooling power is achieved at 10K which is shown in Figure 5. The results meet the requirements of the application of NbN Superconductor-Insulator-Superconductor (SIS) mixers used for terahertz detection.

Table 4 Scheme of multi-layer filling style for experiments

Serial number	Filling style
Case(1e)	Er_3Ni (8)
Case(2e)	1/4 Er_3Ni (5)+1/4 Er_3Ni (5)+1/4 Er_3Ni (8)+1/4 Er_3Ni (8)
Case(3e)	2/3 Er_3Ni (5)+1/3 Er_3Ni (8)
Case(4e)	Er_3Ni (5)
Case(5e)	3/10 Er_3Ni (4)+3/10 Er_3Ni (4)+1/5 Er_3Ni (5)+1/5 Er_3Ni (5)
Case(6e)	3/10 Er_3Ni (4)+3/10 Er_3Ni (4)+1/5 Er_3Ni (4)+1/5 Er_3Ni (5)
Case(7e)	Er_3Ni (4)
Case(8e)	3/10 Er_3Ni (3)+3/10 Er_3Ni (3)+1/5 Er_3Ni (5)+1/5 Er_3Ni (5)
Case(9e)	3/10 Er_3Ni (3)+3/10 Er_3Ni (4)+1/5 Er_3Ni (5)+1/5 Er_3Ni (5)

From Figure4, we can conclude that multi-layer filling style is beneficial to improve the performance of the cryocooler, which is the same as the simulation results, however, the best diameter and the best filling style is different from the simulation. We analyse that two causes lead to this difference. One is that the material used in the experiment is irregular, hydraulic diameter is not fixed, while the hydraulic diameter in the simulation used has fixed value. The other is that the Regen3.3 software uses laminar model which is different from the physical situation.

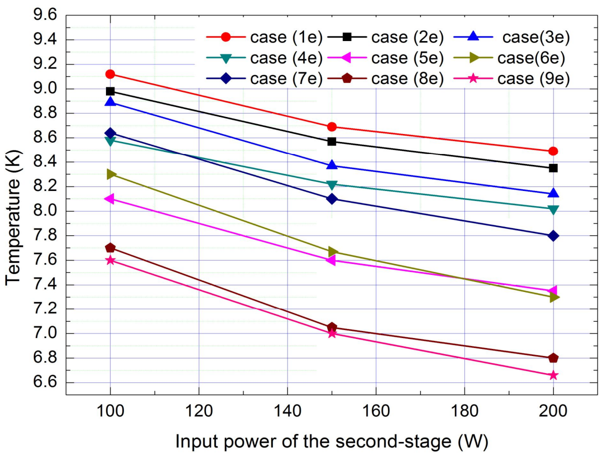

Fig. 4 Experiment results of case 1e to case 9e

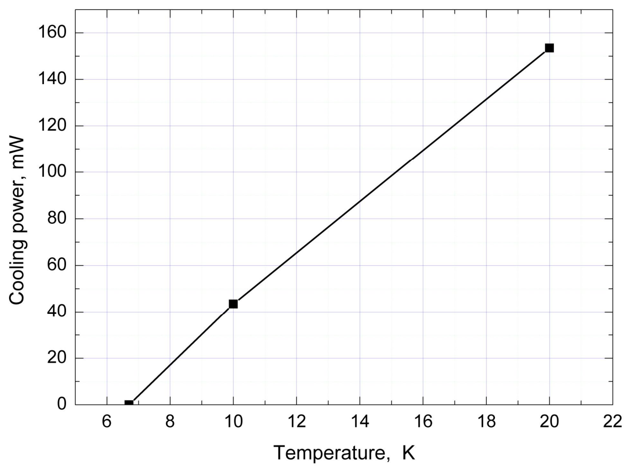

Fig. 5 Cooling capacity of the cryocooler

4. Conclusions

Based on the results of our simulations and experiments, we conclude that the multi-layer filling method can improve the performance of a cyocooler through the optimization of heat transfer and flow resistance. At the same time, there is an upper limit of hydraulic diameter. Only hydraulic diameter in the cold side is below the upper limit, multi-layer filling method is useful. A two-stage thermally coupled high frequency pulse tube cryocooler was optimized based on this approach, the no load temperature has decreased from 8.8K to 6.7K with a 450W compressor input power. The results of the high frequency pulse tube cryocooler achieve the requirements of the application of NbN SIS mixers, so it paves a way for the space application of terahertz technologies.

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