Influence of Regenerative Material on Performance of 6K Level High Frequency Pulse Tube Cryocooler

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

Introduction

Since the requirements from ultra-long wave infrared detection, superconducting devices and THz space detection are urgent, very low temperature high frequency pulse tube cryocooler has become an important direction in the field of pulse tube.

In this paper, some experiments were conducted to find the regenerative material which is suitable for 6K, besides this, methods of simulation and experiment were used to investigate the influence of stacking style for performance of 6K high frequency pulse tube cryocooler. Finally, the lowest temperature has dropped from 8.8K to 6.7K.

Simulation for filling style

Table 1 Number of different regenerative materials and different hydraulic equivalent diameters

serial number	hydraulic equivalent diameter ($\times 10^{-5}$m)	serial number	hydraulic equivalent 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	ErNi	3.3

Table 2 Filling style with same hydraulic equivalent 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)		

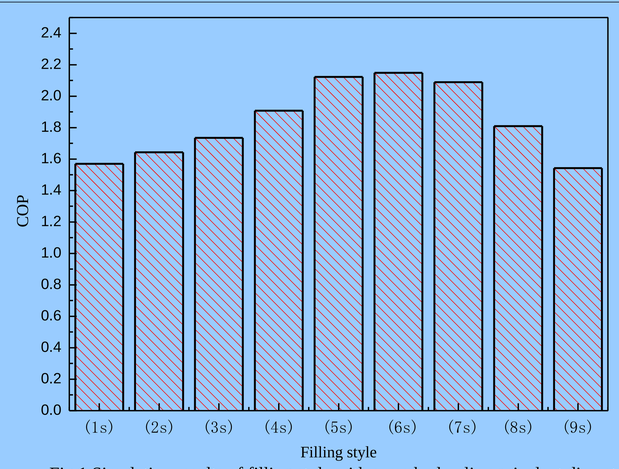

Fig.1 Simulation results of filling style with same hydraulic equivalent diameter

Table 3 Filling style with different hydraulic equivalent diameters

Serial number	Filling style	COP
Case(10s)	3/10 Er_3Ni (6)+3/10 Er_3Ni (5)+1/5 Er_3Ni (5)+1/5 Er_3Ni (5)	2.128
Case(11s)	3/10 Er_3Ni (7)+3/10 Er_3Ni (5)+1/5 Er_3Ni (5)+1/5 Er_3Ni (5)	2.119
Case(12s)	3/10 Er_3Ni (6)+3/10 Er_3Ni (6)+1/5 Er_3Ni (5)+1/5 Er_3Ni (5)	2.14
Case(13s)	3/10 Er_3Ni (6)+3/10 Er_3Ni (6)+1/5 Er_3Ni (6)+1/5 Er_3Ni (5)	2.142
Case(14s)	3/10 Er_3Ni (7)+3/10 Er_3Ni(6) +1/5 Er_3Ni (6)+1/5 Er_3Ni (6)	2.124
Case(15s)	3/10 Er_3Ni (7)+3/10 Er_3Ni (6)+1/5 Er_3Ni (6)+1/5 Er_3Ni (5)	2.162
Case(16s)	3/10 Er_3Ni (7)+3/10 Er_3Ni (7)+1/5 Er_3Ni (6)+1/5 Er_3Ni (5)	2.099
Case(17s)	3/10 Er_3Ni (7)+3/10 Er_3Ni (6)+1/5 Er_3Ni (5)+1/5 Er_3Ni (5)	2.089
Case(18s)	3/10 Er_3Ni (7)+3/10 Er_3Ni (6)+1/5 Er_3Ni (6)+1/5 Er_3Ni (7)	2.137

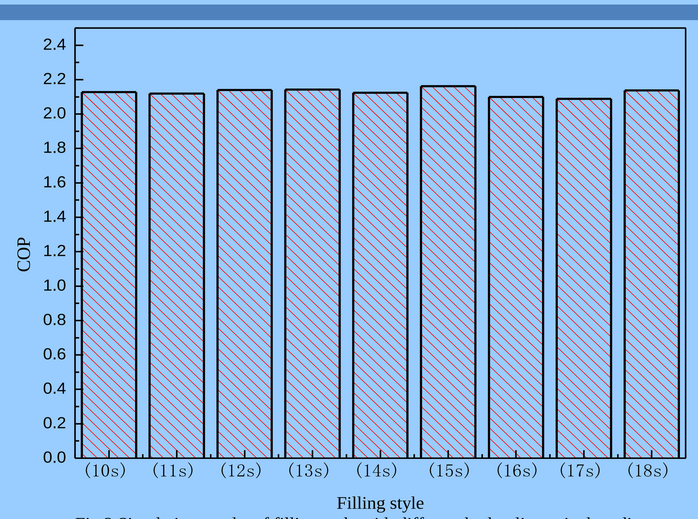

Fig.2 Simulation results of filling style with different hydraulic equivalent diameters

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

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

(2) Using multi-layer filling style (sandwich filling) will get better results at special conditions.

(3) If we use multi-layer filling style in the regenerator, the diameter of regenerative 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.

Experiment

The cryocooler used for experiment is divided into two parts: the first-stage and the second-stage . Every stage includes one compressor and one cold finger. Regenerative material in the first-stage's regenerator is stainless steel mesh. For the second-stage's regenerator, in the temperature zone above 30K, stainless steel mesh is also used as regenerative material, while the temperature is below 30K, suitable regenerative material and filling method is our study.

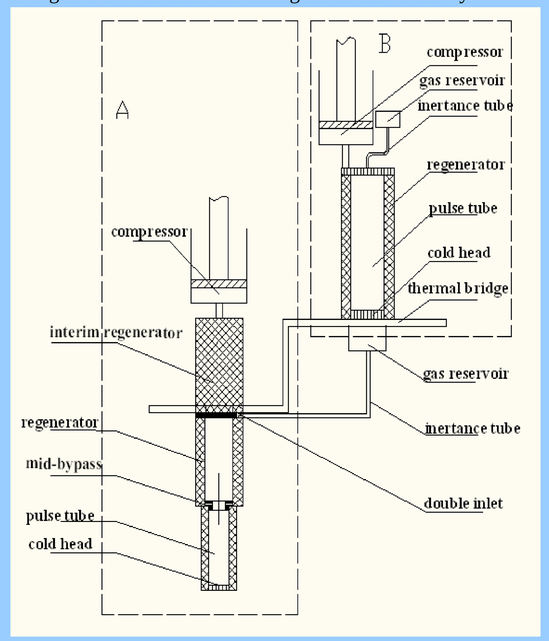

Fig.3 Schematic the two-stage pulse tube cryocooler

Table 4 Scheme of multi-layer filling style for experiment

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)

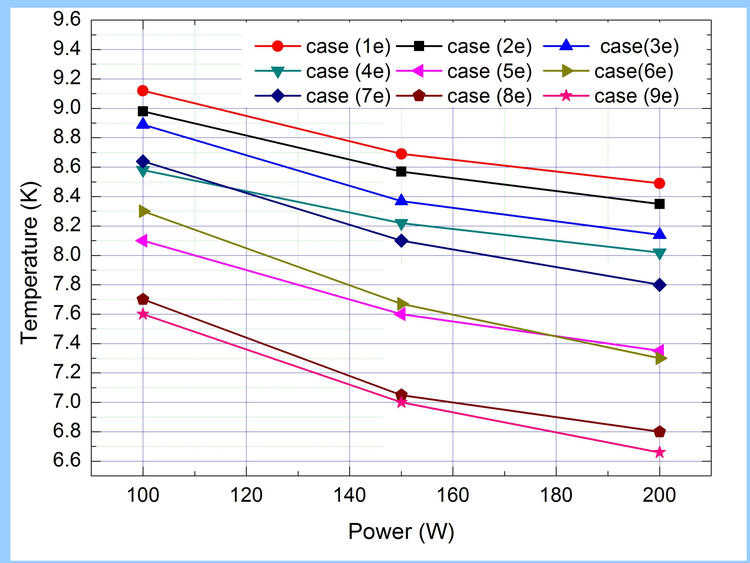

Fig. 4 Experiment results of case 1e to case 9e

For the sake of the application of sandwich filling method, the lowest temperature drops from 8.8K to 6.7K, and above 40mW cooling power can be achieved at 10K

From figure4, we get the conclusion that multi-layer filling style is beneficial to improve the performance of the cryocooler, which is 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 equivalent diameter is not fixed, while the hydraulic equivalent diameter the simulation used has fixed value. The other is that the Regen3.3 software uses laminar model which is different from the physical truth..

Conclusion

Base on the results of simulation and experiment, a conclusion that multi-layer filling method is beneficial to improve performance of cyocooler through the optimization of heat transfer coefficient and flow resistance is achieved. At the same time, there is an upper limit of hydraulic equivalent diameter, only hydraulic equivalent diameter in cold side is below the upper limit, multi-layer is useful. According this, the two-stage thermal-coupled high frequency pulse tube cryocooler was optimized, the no load temperature has decreased from 8.8K to 6.7K with 450W compressor input power. The results of the high frequency pulse tube cryocooler reach requirements of the application of NbN SIS mixers, so it paves a way for the space application of terahertz technologies.