Investigation of a High Efficiency U-type Two-Stage Pulse Tube Cryocooler at 20K

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ABSTRACT

With the rapid development of space application technology, the need for cold sources of liquid helium temperatures, especially for superfluid helium temperature is very urgent. At present, the Gifford-McMahon (GM) refrigerator has been used widely and maturely to precool the Joule-Thomson (J-T) refrigerator. However, the application of GM refrigerators in space is limited by their large size and heavy weight. In view of this situation, there is an urgent need to develop a smaller and lighter pulse tube cryocooler to replace the GM refrigerator and meet the demand for precooling. However, most single-stage pulse tube cryocoolers are hard pressed to reach 20 K at present.

To precool a JT refrigerator working at liquid helium temperature, a miniature U-type two-stage gas-coupled pulse tube cryocooler which can provide cooling capacity at 20 K was designed and optimized by Sage software. The simulation results show that the cryocooler has achieved the initial experimental target when the compressor swept volume is less than 10 cc with 200 W PV power input. A cooling capacity of 614 mW at 20 K and relative Carnot efficiency of 3.4% at 20 K can be reached.

INTRODUCTION

The high frequency pulse tube cryocooler (HFPTC) has the advantages of simple structure, high reliability and stability and long life due to no cryogenic displacer. The overall efficiency is also comparable to Stirling cryocoolers. The above advantages make HFPTC a research hotspot in space application cryocoolers in the last thirty years.

According to previous studies, most of single-stage HFPTCs are working between 30 K~80 K[1-8]. It is difficult to reach temperature of 20 K with single-stage HFPTC due to the heat capacity reduction of regenerative materials at low temperature and the efficiency reduction of regenerator heat transfer at the high frequency. However, the HFPTCs which work at 20K have great potential in deep space detection, cryo-pump, low temperature superconductivity (LTS), J-T cryocooler precooling etc. Thus, to obtain a HFPTC which can reach 20 K or lower temperature, multi-stage structure is generally needed[9-11]. Many efforts of improving the structure and optimizing the key parameters of components have been made. L. Yang et al. obtained a two-stage gas-coupled HFPTC, with a no-load temperature of 19.8 K which was the first time to reach a temperature below 20 K[12]. Afterwards, M. Zhao et al. optimized the parameters of a two-stage gas-coupled HFPTC, and a lowest no-load temperature of 16.1 K was obtained with 250 W electric power input[13]. Gas-coupling leads to

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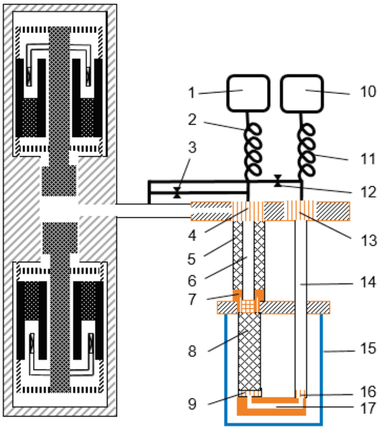

Figure 1. Schematic of the U-type two-stage gas-coupled pulse tube cryocooler: 1 1st reservoir, 2 1st inerance tube, 3 1st double-inlet, 4 1st ambient HX, 5 1st regenerator, 6 1st pulse tube, 7 1st cold HX, 8 2nd regenerator, 9 2nd cold HX I, 10 2nd reservoir, 11 2nd inerance tube, 12 2nd double-inlet, 13 2nd ambient HX, 14 2nd pulse tube, 15 radiation shield, 16 2nd cold HX II,17 cold end connecting tube.

complicated stage-coupling and instability. Therefore, there was no major progress in the two-stage gas-coupled HFPTC for a long period of time. Until 2016, to cool a single-photon quantum detector, a scheme of using a three-stage gas-coupled HFPTC to precool a J-T refrigerator was adopted by National Institute of Standards and Technology (NIST), and a cooling temperature of 2.2 K at the cold end of the J-T refrigerator was obtained, and the third stage cold end of three-stage gas-coupled HFPTC obtained the cooling performance of 6.5 mW at 10 K with 150 W electric power input. In 2017, X. Wu et al. developed a two-stage gas-coupled HFPTC which used a multi-bypass structure in first stage, and a phase shifter of cryogenic-inertance and double-inlet in second stage. A cooling performance of 600 mW at 20 K was obtained with 450 W electric power input, but the relative Carnot efficiency was 1.86% merely[14]. X. Pang et al. developed a completely coaxial two-stage gas-coupled HFPTC. The system reached 13.4 K no-load temperature and obtained 1.1 W cooling power at 20 K, but the relative Carnot efficiency was also 2.7% merely[15].

Many efforts have been made to obtain a high efficiency prototype of two-stage gas-coupled HFPTC at 20 K in this paper. Firstly, the system structure and configuration parameters have been analyzed and chosen. Secondly, the influence of operating parameters and the typical cooling performance have been simulated and discussed. Finally, some conclusions are drawn.

SYSTEM CONFIGURATION

The second stage regenerator and pulse tube of two-stage gas-coupled HFPTC mainly may have the arrangement of coaxial and U-type. Compared with the coaxial type, although the U-type is not more compact than the coaxial, but it makes the working gas possess a smoother flow path at the second stage cold end, greatly reducing the flow resistance loss and improving the cooling performance of two-stage gas-coupled HFPTC. Although the useless volume of system is increased due to the introduction of the cold head connecting tube, the flow resistance and the difficulty of processing and operating of the system are obviously reduced. Therefore, the U-type two-stage gas-coupled HFPTC is selected as the research object in this paper, as shown in Figure 1. To improve the overall performance and simplify the experimental operation, the ambient temperature inertance tube and double-inlet are used as the phase shifter for each stage. Meanwhile, a radiation shield is added over the secondary regenerator and cold head to reduce the radiant heat loss of the system.

The simulation and optimization of the cryocooler were carried out by Sage software developed by Gedeon Associates[16]. Some simulation parameters of the system are shown in Table 1. The baseline operating conditions are: average pressure of 3 MPa, ambient end of 300 K, operating

Table 1. Main structure parameters of the cryocooler

Subsystem	Components	Parameters
Compressor	Displacer	Diameter 25 mm, Length 15 mm
	Clearance	Width 15 um, Length 15 mm
	Compression volume	9.8 cc
Cold tip	1st regenerator	Outer diameter 19.5 mm, Inner diameter 9 mm, Length 44 mm, 400# stainless steel mesh
	2nd regenerator	Diameter 13 mm, Length 40 mm, 500# stainless steel mesh
	1st inerance tube	Inner diameter 2 mm+3 mm+4 mm, Total length 7.6 m
	2nd inerance tube	Inner diameter 2 mm+3 mm+4 mm, Total length 5.6 m
	1st reservoir	Volume 0.5 L
	2nd reservoir	Volume 0.3 L

frequency of 38 Hz and piston displacement of the compressor is less than 4.5 mm. In addition, the optimization target is 0.5 W at 20 K.

SIMULATION RESULTS AND DISCUSSIONS

Selection for the opening of two double-inlet valves

The double-inlet with a suitable opening is of great importance to improve the performance of PTC based on the previous studies[17]. The effects of two double-inlet valves opening (DDou) on the cryocooler are given respectively in Figure 2. However, it should be noted that when optimizing one of the two double-inlet valves, the other is at the optimum opening. Some results can be clearly obtained from the graph: there is the same trend of cooling capacity changing with double-inlet valves opening in each stage, both curves increase first and then decrease, so the optimum value can be obtained. Meanwhile, the influence of double-inlet valves opening on the second stage is stronger than the first stage, which may imply that, in the experimental study, we should use a finer double-inlet valve to control the flow. In the following simulations, we choose the valves opening of 0.34 mm and 0.46 mm at the first and second stage, respectively.

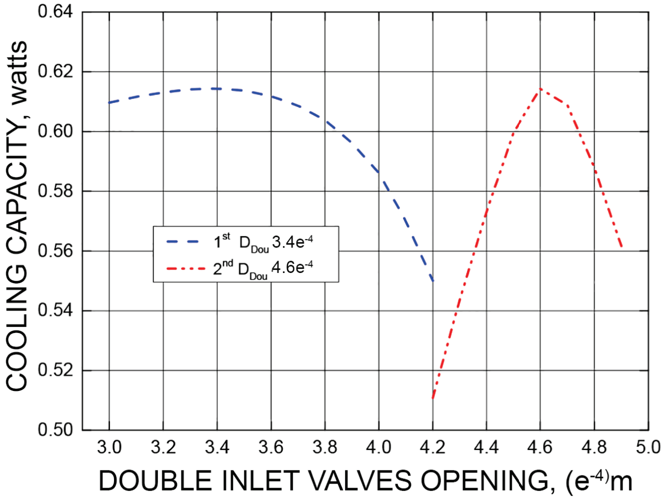

Figure 2. Dependence of the cooling capacity on the opening of double-inlet valve

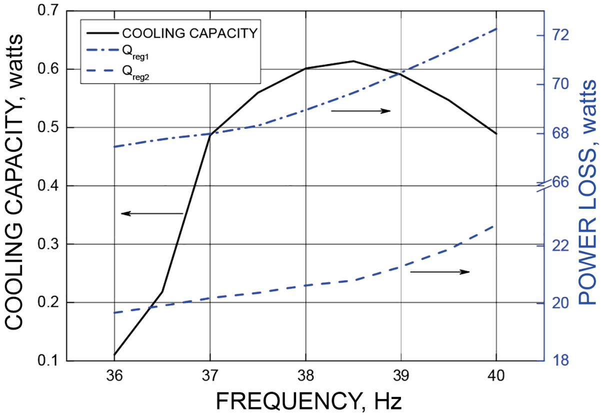

Figure 3. Dependence on operating frequency of the cooling capacity and power loss for each stage

Effects of operating frequency on cooling performance and power loss

The power loss (refers to regenerator total power loss if there are no special instructions) is vital to analyze the internal mechanism and improve the performance of PTC. Therefore, the influence of the power loss on the cryocooler has been given with the simulating operating frequency on the performance of the cryocooler as shown in Figure 3. The operating frequency has a great influence on the performance of the cryocooler, as the operating frequency increases, the cooling capacity of the cryocooler increases correspondingly, there is an optimum operating frequency of approximate 38 Hz for the cryocooler.

For convenience of analysis, we add all losses to the regenerators:

$$Q_{reg1}=Q_{fri1}+Q_{cond1}+Q_{ex1} \tag{1}$$

$$Q_{reg2}=Q_{fri2}+Q_{cond2}+Q_{ex2} \tag{2}$$

Where Q_{reg} are regenerator total power loss, Q_{fri} are regenerator friction loss, Q_{cond} are regenerator conduction loss, Q_{ex} are regenerator surface heat-exchange loss. The subscripts "1 and 2" respectively refer to the first stage and second stage.

It is found in the Figure 3 that the regenerator total loss is increasing with the increasing of the operating frequency in each stage, what's more, the Q_{reg1} is more than three times as high as Q_{reg2}, which indicates that the cryocooler's cooling performance is able to be improved if the Q_{reg1} can be effectively reduced.

Effects of average pressure on the cooling performance and power loss

Figure 4 shows the influence of the average pressure on the cooling capacity and the regenerator total power losses of the first and second stage. With the same impact trends as the operating frequency, there is an optimum average pressure of approximate 3 MPa for the cryocooler. For the regenerator total power loss, Q_{reg1} varies nearly linearly with the average pressure, Q_{reg2} varies nearly parabolically with the average pressure. The regenerator total power loss Q_{reg1} and Q_{reg2} increase to 9.66 W and 1.28 W respectively when the average pressure increases from 2.8 MPa to 3.2 MPa. Moreover, the higher the average pressure is, the lower the cooling capacity is reduced.

Typical cooling performance

In Figure 5, the cooling capacity with different given PV power of the cryocooler is simulated. For the *x* axis, Tc represents the temperature of the second stage cold end, when a heat load of 0 mW, 300 mW and 600 mW was applied to the second stage cold end successively on the condition of a 3 MPa average pressure, and a 38 Hz operating frequency. Meanwhile, as the PV power input increases, the slope increases accordingly. For instance, the cryocooler can reach a lowest no-load

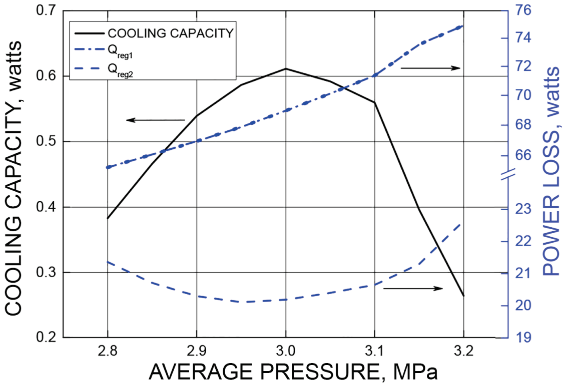

Figure 4. Dependence on average pressure of the cooling capacity and power loss for each stage

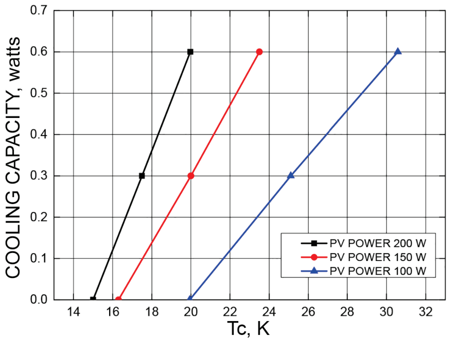

Figure 5. Typical cooling capacity of the cryocooler

temperature of 14.5 K and provide a performance of 614 mW at 20 K with 200 W PV power input. From these results, the initial target for 500 mW at 20 K has been achieved.

CONCLUSION

A high efficiency U-type two-stage gas-coupled pulse tube cryocooler driven by a linear compressor which can meet the cooling capacity target of 0.5 W at 20 K with 200 W PV power input has been designed and optimized. The optimum opening of two double-inlet valves have been found, meanwhile, the influence of the operating parameters on the cryocooler performance and regenerator power loss are simulated and discussed. Results show that the regenerator power loss will increase correspondingly when the average pressure and operating frequency are increased. Finally, the cryocooler is predicted to obtain a cooling capacity of 614 mW at 20 K, and a relative Carnot efficiency of 3.4% without a acoustic power recovery device. Assembly of the cryocooler is currently underway and some experimental results will be obtained soon.

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REFERENCES

1. Zhou, Y., Han, Y., “Pulse Tube Refrigerator Research,” 7th International Cryocooler Conference Proceedings, Air Force Phillips Laboratory Report PL-CP--93-1001, Kirtland Air Force Base, NM, April 1993, pp. 147-156.

2. Liang, J., *Development and Experimental Verification of a Theoretical Model for Pulse Tube Refrigeration*, Chinese Academy of Sciences, Beijing (1993).

3. Nguyen, T., Toma, G., Raab, J., "HEC Pulse Tube Cooler Performance Enhancement," *Cryocoolers 17*, ICC Press, Boulder, CO (2013), pp. 79-83.

4. Raab, J., Tward, E., "Northrop Grumman aerospace systems cryocooler overview," *Cryogenics,* vol. 50 (2012), pp. 572-581.

5. Wang, G.P., Cai, J.H., Li, N., et al, "Development of a 0.5 W/40 K Pulse Tube Cryocooler for an Infrared Detector," *Cryocoolers 14,* , ICC Press, Boulder, CO (2007), pp. 83-88.

6. Zhao, M.G., Liu, Y.J., Cai, J.H., et al, "Experimental Investigation of a 40 K Single-stage High Frequency Pulse Tube Cryocooler," *Cryocoolers 17,* ICC Press, Boulder, CO (2017), pp. 115-119.

7. Willems, D., Mullie, J., Groep, V., et al, "Increased capacity cryocoolers at Thales cryogenics BV," *AIP Conference Proceedings* (Vol. 1218, No. 1, pp. 719-726) (2010).

8. Groep, V., Mullie, J.C., "Development of a 15 W Coaxial Pulse Tube Cooler," *Cryocoolers 15,* ICC Press, Boulder, CO (2009), pp. 157-176.

9. Nast, T.C., Olson, J., Evtimov, B., et al, "Development of a Two-stage Pulse Tube Cryocooler for 35 K Cooling," *Cryocoolers 12,* Kluwer Academic/Plenum Publishers, New York (2003), pp. 213-218.

10. Nguyen, T., Colbert, R., Durand, D., et al, "10 K Pulse Tube Cooler," *Cryocoolers 14,* ICC Press, Boulder, CO (2006), pp. 27-31.

11. Yang, L.W., "Investigation on a thermal-coupled two-stage stirling-type pulse tube cryocooler," *Cryogenics,* vol. 48 (2008), pp. 492-496.

12. Yang, L.W., Thummes, G., "High frequency two-stage pulse tube cryocooler with base temperature below 20 K," *Cryogenics,* vol. 45 (2005), pp. 155-159.

13. Zhao, M.G., Yang, L.W., et al, "High frequency two-stage pulse tube cooler with the base temperature of 16.1 K," *Journal of Engineering Thermophysics*, vol. 28 (2007), pp. 205-207.

14. Wu, X.L., Chen, L.B., Zhu, S.X., et al, "The Study on a Gas-coupled Two-stage Stirling-type Pulse Tube Cryocooler," *IOP Conference Series: Materials Science and Engineering* (Vol. 278, No. 1). (2017), p. 012146.

15. Pang, X.M., Wang, X.T., Dai, W., et al, "Investigation on a Coaxial Two-stage Pulse Tube Cryocooler Working at Liquid Hydrogen Temperature," *Conference of Engineering Thermophysics,* (2017), p. 171284. (in Chinese)

16. Gedeon, D., *Sage User's Guide*, Gedeon Associates, Athens, OH, (2009).

17. Zhu, S., Wu, P., Chen, Z., "Double inlet pulse tube refrigerator-an important improvement," *Cryogenics*, vol. 30 (1990), pp. 514-520.