

Numerical Study of a 10 K Two Stage Pulse Tube Cryocooler with Precooling Inside the Pulse Tube

Xiaomin Pang^{1,2}, Xiaotao Wang^{1,*}, Wei Dai¹, Jianyin Hu¹, Ercang Luo¹

¹Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry of Chinese Academy of Sciences, China

²Graduate University of Chinese Academy of Sciences, China

Email: xtwang@mail.ipc.ac.cn, Tel: +8610-82543733

Abstract: High efficiency cryocoolers working below 10 K have many applications such as cryo-pump, superconductor cooling and cryogenic electronics. This paper presents a thermally coupled two-stage pulse tube cryocooler system and its numeric analysis. The simulation results indicate that temperature distribution in the pulse tube has a significant impact on the system performance. So a precooling heat exchanger is put inside the second stage pulse tube for a deep investigation on its influence on the system performance. The influences of operating parameters such as precooling temperature, location of the precooling heat exchanger are discussed. Comparison of energy losses apparently show the advantages of the configuration which leads to an improvement on the efficiency. Finally, the cryocooler is predicted to be able to reach a relative Carnot efficiency of 10.7% at 10 K temperature.

Key words: precooling heat exchanger; temperature distribution; precooling temperature; energy losses

1. Introduction

Pulse tube cryocoolers have the advantages of simple structure, high reliability and low mechanical vibration over traditional regenerative cryocoolers such as G-M and Stirling cryocoolers due to no moving parts in the low temperature region [1,2]. Cryocoolers around 10 K are demanded for applications of cryo-pump, superconductor cooling, cryogenic electronics and so on [3,4]. In the past decades, the pulse tube cryocooler technology has seen many improvements, especially on the phase shifters, such as orifice, double-inlet and inertance and so on [5-8]. The cooling performance of Stirling type pulse tube cryocoolers at 80 K has out-performed traditional G-M cryocoolers, but the performance at 10 K is still worse than that of G-M cryocoolers.

It is challenging for a single stage String type pulse tube cryocooler to reach 10 K below primarily due to the high losses caused by real gas effect, high operating frequency and regenerative materials. Two or more stage configurations are normally used [9-13]. L. Yang et.al in 2008 developed a thermally-coupled two stage pulse tube cooler with double inlet orifice as the phase shifter [14]. A no load temperature of 12.8 K was obtained with 400 W electric power input. J. Butterworth et.al developed a thermally-coupled two stage pulse tube cooler in 2016 [15], which used the compressor as the phase shifter of the second stage. The system reached 9.2 K no load temperature and obtained 435 mW cooling power at 15 K. Although these researches have focused on reaching lower temperature using less stage configuration, high efficiency at 10 K is still challenging to be obtained for two-stage cryocoolers.

This paper describes the design of a two-stage pulse tube cryocooler aimed for obtaining more than 1 W cooling power at 10 K. Firstly, we introduce the configuration and simulation tools. Then, the simulation results are presented, which shows the influence of precooling heat exchanger inside the pulse tube of the second stage. After this, energy losses are deeply investigated. Finally, some conclusions are drawn.

2. Geometrical and numerical model

Fig 1 illustrates the system configuration to be studied here. To ensure an easy optimization of the configuration parameters, especially of those at lowest temperature, we select thermally-coupled



configuration. For clarity, we define the pre-cooler as the first stage and the main cooler as the second stage. Two stages are connected through a copper thermal bridge. Normally, only the middle of the regenerator of the second stage is precooled. In the system to be studied here (shown in Fig 1), somewhere inside the second stage pulse tube is also precooled by the cold head of first stage.

For the first stage, we did not simulate it but assumed its cooling power at a certain precooling temperature. Considering state of the art of pulse tube cooler technology, the input power will be estimated and taken into account in the calculation of the general system efficiency.

The second stage cooler is simulated through Sage10 software [16] developed by Gedeon Associates, which can simulate and optimize a variety of thermal systems based on oscillating flow. In order to investigate the performance and some changing trends clearly, the two stage cooler is simulated separately. For conciseness, all the components mentioned later refer to those of the second stage, if not specially mentioned.

The main geometrical parameters of the system are listed in table 1. For the operating parameters, a mean pressure of 2.0 MPa and a frequency of 30 Hz are chosen. The optimization target is 2 W cooling power at 10 K temperature.

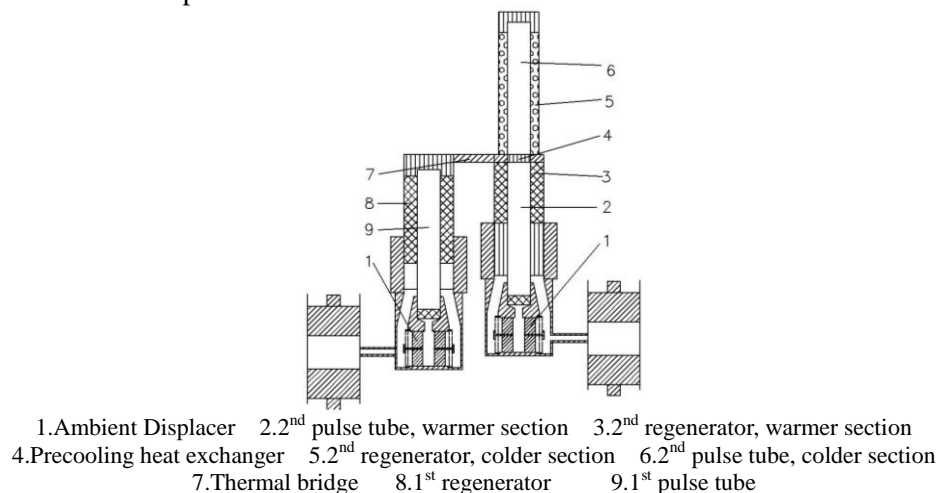


Figure 1. Schematic of the thermally-coupled two-stage pulse tube cryocooler

3. Simulation results and discussion

3.1 Effects of the precooling temperature and the location of the precooling heat exchanger

Fig 2 shows the influence of the precooling temperature and precooling location. For the x axis, L_{cold} represents the length of the colder section of the pulse tube. L represents the length of total pulse tube length (152.5 mm) which consists of 2nd stage pulse tube warmer section, middle heat exchanger and 2nd stage pulse tube colder section. With a given acoustic power, it is found that, in terms of cooling power at 10 K, the optimal range of the length of the colder section of the pulse tube is about $0.35 L$ to $0.5 L$. This is different from the paper [13] which gives an optimum value between $0.625 L$ and $0.875 L$ when only the outer surface of the second stage pulse tube was precooled at some position. If the L_{cold} is too large (especially L_{cold}/L larger than 0.6), it will need more precooling power as fig 2 shows.

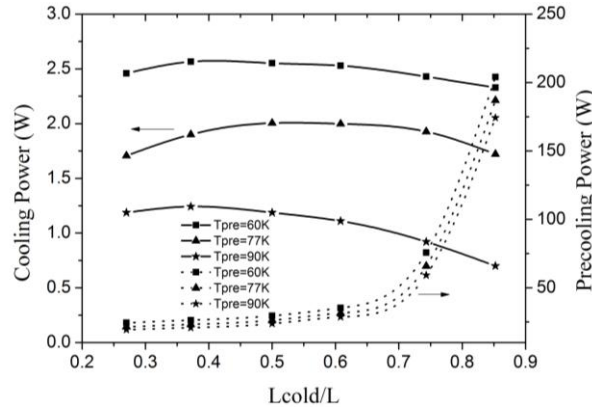


Figure 2. Precooling location vs. Cooling power & Precooling power

It can be seen in Fig 2, with lower precooling temperature, the system can obtain more cooling power, but it also needs more precooling power. For a more fair evaluation of the system performance and considering the contribution of the first stage cooler, we define a general relative Carnot efficiency of the whole system as

$$\eta = \frac{Q_c}{W + W_1} \frac{T_c}{T_0 - T_c} \quad (1)$$

where Q_c , are the cooling power and the precooling power, respectively, T_0 is the ambient temperature. W_1, W are the acoustic power input of the first stage and the second stage pulse tube cryocooler, respectively.

Here, W_1 is calculated through precooling power and an assumed relative Carnot efficiency (η_1).

$$\eta_1 = \frac{Q_{pre}}{W_1} \frac{T_{pre}}{T_0 - T_{pre}} \quad (2)$$

Considering state of the art of the cryocooler technology and most recent results on pulse tube cryocoolers with work recovery capability [17,18], we assume for the first stage a relative Carnot efficiency of around 16% at 60 K, 30% at 77 K and 35% at 90 K.

With considering the efficiency of the first stage cooler, Fig 3 shows general relative Carnot efficiency of the whole system on dependence of the precooling location. It is also seen in Fig 4 that the total system obtains a larger general relative Carnot efficiency when the precooling temperature is around 77K, in between 60 K and 90 K. The optimum simulation results indicate that the cryocooler can obtain 2.0 W cooling power at 10 K with precooling at 77 K. The input acoustic power for the 1st and 2nd stage is 251 W and 295 W, respectively. And it means a general relative Carnot efficiency can reach 10.7%.

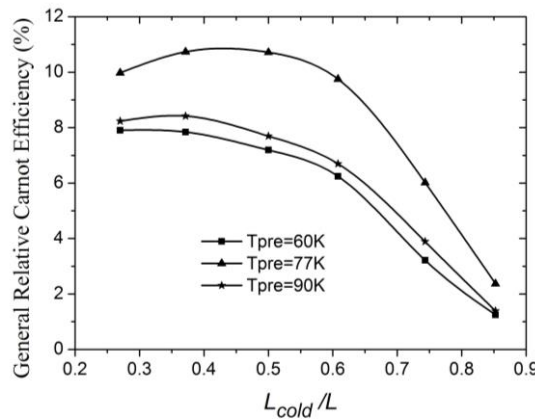
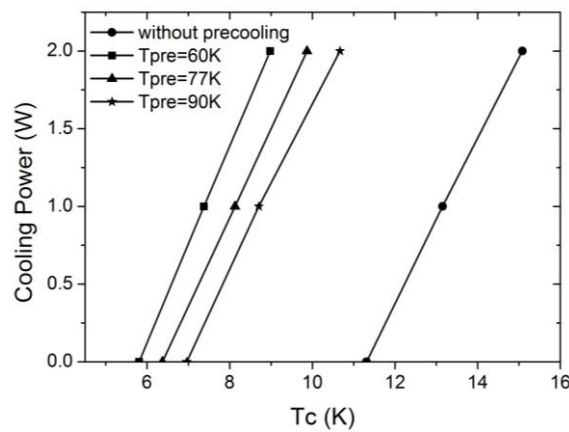


Figure 3. Precooling location vs. General relative Carnot efficiency of the whole system

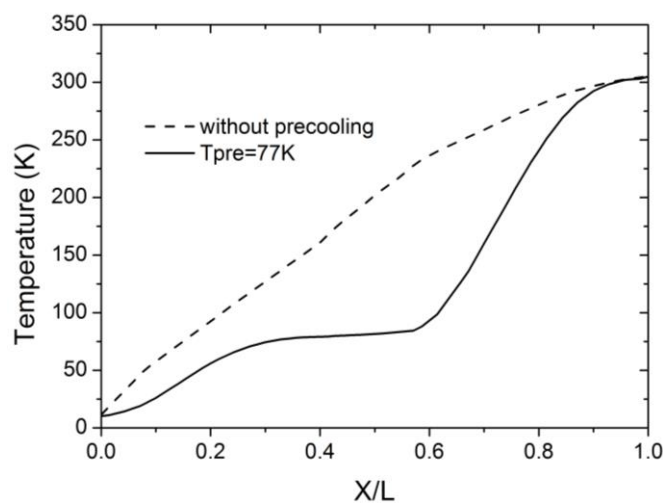
3.2 General performance

To take a deeper look into the influence of the middle heat exchanger, the following discussions take L_{cold}/L around 0.5 as a typical example. Selection of L_{cold}/L value makes it convenient to build a coaxial configuration in the future experiments. Compared with the system without precooling heat exchanger inside the pulse tube, the performance with precooled pulse tube is improved. Fig 4 shows that keeping the input acoustic power the same, lowest no-load temperatures reduce by 5.6 K, 5 K and 4.1 K when the precooling temperatures are 60 K, 77 K and 90 K, respectively. The cooling power curves shifted left-ward as the precooling temperature (T_{pre}) decreases, which mean a larger cooling power at the same temperature.

**Figure 4.** The temperature of the cold end vs. Cooling power, $L_{cold}/L=0.5$

3.3 Temperature distribution in the 2nd stage pulse tube

The temperature distributions along the second stage pulse tube are shown in Fig 5. It should be mentioned here that the middle of the regenerator is still precooled for both cases. As can be seen, the whole pulse tube gets colder if precooled. And the temperature gradient much decreases along the colder section of the 2nd stage pulse tube, which may be related to the improved performance.

**Figure 5.** Comparison of temperature distributions in the 2nd stage pulse tube between with and without precooled pulse tube

3.4 Available energy losses in the second stage pulse tube

The available energy losses in the pulse tube are also analyzed. The simulation results are shown in Fig. 6 with a given temperature and acoustic power at the cold end.

When the pulse tube is not precooled, shuttle loss and pumping loss, which is related to the temperature gradient [19,20], occupy largest fractions. Flow friction loss is the least due to an empty tube. Fig 6 indicates that about 85% of the losses locate in colder section of the pulse tube. After the pulse tube is precooled, the shuttle loss and pumping loss in the colder section of the pulse tube reduce a lot due to the decreasing temperature gradient, which contributes to the apparent decrease of the total losses in the pulse tube. In terms of entropy generation, these losses decreases the expansion efficiency of the pulse tube, which is defined as the ratio of enthalpy flow and the PV power at the cold end of the pulse tube [21]. In fact, when the pulse tube of the 2nd stage is precooled, the expansion efficiency of the 2nd stage pulse tube rises from 54.6% to 82.8%.

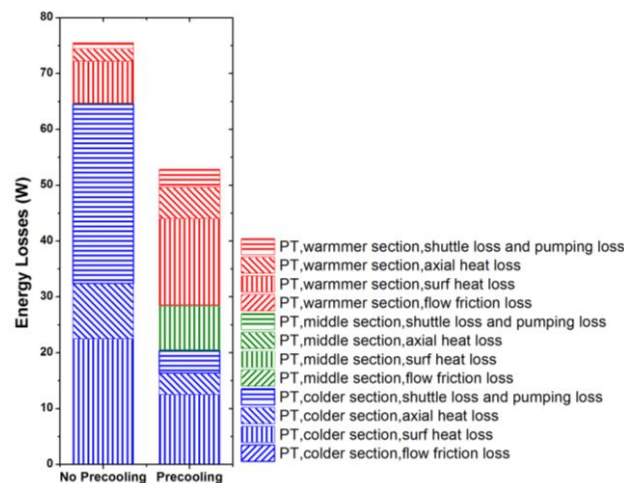


Figure 6. Comparison of energy losses in the 2nd stage pulse tube between with and without precooled pulse tube

4. Conclusion

A thermally-coupled two-stage pulse tube with a target of cooling power 1.0 W at 10 K has been designed and optimized. A precooling heat exchanger inside the 2nd stage pulse tube is introduced into the system to improve the performance. Results show that after the precooling heat exchanger is added inside the 2nd stage pulse tube, the temperature gradient of the colder section of the pulse tube much decreases and energy losses of this section also much reduce. There is an optimum precooling temperature (around 77K) and an optimum location (L_{cold}/L around 0.5) of the middle heat exchanger for a better performance of the general system. Finally, the system is predicted to obtain a relative Carnot efficiency of 10.7%. Assembling the system is currently underway and some experimental results will be acquired soon.

Acknowledgement

This work is financially supported by the Nation Natural Science Foundation of China (Contract number 5136187, 51206177). Technical support from Lihan Thermoacoustic Technologies Co.Ltd is greatly acknowledged.

Reference

- [1] Radebaugh R. The development and application of cryocoolers since 1985. In: Chen GB, Hebral B, Chen GM, editors. Proceedings of ICCR'2003. International Academic Publishers/Beijing

- World Publishing Corporation; 2003. pp.858–870.
- [2] Wang, C. Development and application of low frequency pulse tube cryocooler. In: Cryogenics and Proceedings of International Conference of Cryogenics and Refrigeration (ICCR)'2008, pp. 61-70.
 - [3] Radebaugh R. Development of the pulse tube refrigerator as an efficient and reliable cryocooler.1999. Proc. Inst. Refrigeration 96, pp.11-31.
 - [4] Ray Radebaugh.Cryocoolers :the state of the art and recent developments . J .Phys. Condents. 2009. Matter 21
 - [5] Radebaugh R, Zimmerman J, Smith D R, et al. A comparison of three types of pulse tube refrigerators: New methods for reaching 60 K[J]. Advances in Cryogenic Engineering. 1986(31).pp.779-789.
 - [6] Zhu SW, Wu PY, Chen Z. A single stage double inlet pulse tube refrigerator capable of reaching 42 K. Cryogenics 1990(30).pp.257–61.
 - [7] Kanao K, Watanabe N, Kanazawa Y. A miniature pulse tube refrigerator for temperatures below 100 K[J]. Cryogenics. 1994(34). pp.167-170.
 - [8] W.Dai,J.Hu,E.Luo.Comparison of two different ways of using inertance tube in a pulse tube cooler. Cryogenics,2006(46).pp.273-277.
 - [9] Olson J, Nast T C, Evtimov B, et al. Development of a 10 K pulse tube cryocooler for space applications[M]//Cryocoolers 12. Springer Us, 2003: 241-246.
 - [10] L.W. Yang, G. Thummes. High frequency two-stage pulse tube cryocooler with base temperature below 20K. Cryogenics,2005,45(2):pp.155-159.
 - [11] Tang K. Dietrich M. Yang L W. et al. Two-stage Stirling-type pulse tube cryocooler operating down to 13K[C].Cryogenic Engineering Conference CEC, Keystone, Colorado, 2005.
 - [12] M Dietrich, G Thummes. Two-stage high frequency pulse tube cooler for refrigeration at 25K. Cryogenics,2010,50:pp.281-286.
 - [13] L.M.Qiu, X.Q.Zhi, L.Han. Performance improvement of multi-stage pulse tube cryocoolers with a self-precooled pulse tube. Cryogenics. 2012(52). pp.575-579.
 - [14] Yang Luwei. Investigation on a thermal coupled two-stage Stirling-type pulse tube cryocooler. Cryogenics,2008,48:pp.492-496.
 - [15] J. Butterworth, Yan Pennec, Sylvain Martin, et.al. Engineering model of a high power low temperature pulse tube cryocooler for space application. ICC 19.
 - [16] Gedeon D.Sage User's Guide. Gedeon Associates. 2009.
 - [17] Xiaotao Wang, Yibing Zhang, et al. A high efficiency hybrid stirling-pulse tube cryocooler. AIP Advances 5, 037127 (2015)
 - [18] Ray Radebaugh. Cryocoolers: the state of the art and recent developments.J.Phys. Condents. Matter (21) 2009164219(9pp).
 - [19] L.W.Yang. Theoretical analysis of refrigeration and losses in a pulse tube. Advances in Cryogenics Engineering. New York: AIP Press.2000.pp.175-182.
 - [20] L.W.Yang. Shuttle losses in pulse tube. Cryocoolers 11.Kluwer Academic/Plenum Press.2001.pp.353-362.
 - [21] Radebaugh R. Thermodynamics of regenerative refrigerators[J].Generation of Low Temperature and Its Applications.2003.pp.1-20.