Performance optimization of a 4K hybrid JT cooler for space application

Yuexue Ma[1], Ziyao Liu[1*], Jia Quan[1], Jianguo Li[1], Yanjie Liu[1], Juan Wang[1], Jingtao Liang[1,2]

[1] State Key Laboratory of Cryogenic Science and Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China
[2] University of Chinese Academy of Sciences, Beijing, China.

[*]E-mail: liuziyao@mail.ipc.ac.cn

Abstract. A 4K hybrid JT cooler is developed to precool the adiabatic demagnetization refrigerator (ADR) for the Hot Universe Baryon Surveyor (HUBS) mission, which is proposed to study "missing" baryons in the universe. The 4K hybrid JT cooler is composed of a 4He JT cooler precooled by a two-stage thermally coupled pulse tube cooler. Recently, the two-stage pulse tube cooler is optimized to provide more precooling power for the JT loop. The performance of the hybrid JT cooler has been improved and special efforts have been made to optimize the compression system of the JT loop. Eventually, cooling power of 100mW is achieved at 4K which is able to meet the requirements of the ADR of HUBS.

1. Introduction

Space cryogenic technology is a key technology in enabling scientific exploration in space. Space cryocoolers have made significant advancements in the past few decades. Many electronic detectors need to be cooled to liquid helium temperature level to improve their sensitivity and reduce the background noise [1], so miniature liquid helium temperature cryocooler for space application has become a key field for cryogenic research at National Aeronautics and Space Administration (NASA), Japan Aerospace Exploration Agency (JAXA) and European Space Agency (ESA). Hybrid JT cryocoolers are widely used in space detectors working at 4K in view of their flexibility and relatively higher efficiency. In fact, nearly all the space applications of mechanical cryocoolers working at liquid helium temperature having been launched or under development are hybrid JT cryocoolers. For instance, the cryocooler used in JWST is a 4He JT cooler precooled by a three-stage pulse tube cryocooler [2]. In SMILES and SPICA, two-stage Stirling coolers are used to provide precooling power for JT coolers [3,4]. Athena, the mission under development by ESA, plans to use a hybrid J-T cooler to precool hybrid sorption/ADR cooler[5].

Furthermore, there is an increasing demand for cryocoolers which can provide much greater cooling power at 4.5K. Both THz detectors, BIB detectors and space adiabatic demagnetization refrigerator (ADR) require space hybrid JT coolers to provide cooling power exceeding 100 milliwatts.

The Key Laboratory of Space Energy Conversion Technologies (SECT) of the Technical Institute of Physics and Chemistry (TIPC), Chinese Academy of Sciences (CAS) has previously reported a space 5 K JT cryocooler precooled by GM cooler[6]. Based on this cooler, a 100mW@4.5K JT cooler precooled by a two-stage pulse tube cooler is developed.

2. System description of the hybrid JT cooler

The hybrid JT cooler is illustrated as Figure 1. It is composed of two thermally coupled parts: the two-stage pulse tube cryocooler and the JT loop. The two-stage pulse tube cooler, providing precooling power for the JT loop at 80K and 15K, is also thermally coupled. The JT loop consists of compressors, counter-flow heat exchangers, precooling exchangers, JT valve and evaporator. Besides, filters are also indispensable components of the JT loop. Both the pulse tube cooler and the JT loop are driven by oil-free linear compressors. Helium-4 is the working medium of the pulse tube cooler and the JT cooler. High pressure ^{4}He passes through the inner tube of the counter-flow heat exchangers where it is cooled by the low pressure returning gas. The high pressure helium will also be precooled in the precooling heat exchangers at 80K and 15K. Eventually, the high pressure helium gas goes through the JT orifice where it will be expanded to about 4K through the JT effect.

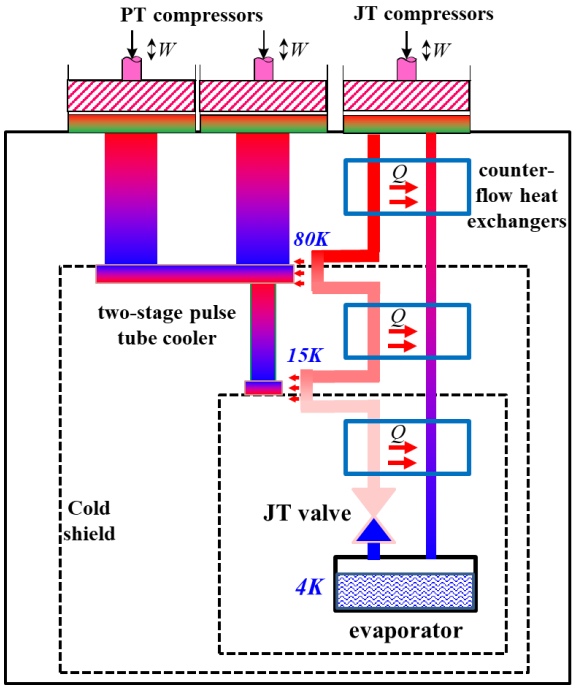

Figure 1. Schematic of the hybrid JT cooler.

2.1 Performance of the two-stage pulse tube cooler

A two-stage high frequency pulse tube cooler developed by our laboratory is used to precool the JT loop. Optimizations are conducted on the two-stage thermally coupled pulse tube refrigerators to improve their cooling power at 80K and 15K. The performance of the first stage pulse tube cooler is illustrated in Figure 2. Cooling power of about 10W@80K can be achieved when input power is 250W. The performance of the second stage pulse tube cooler is also improved through the optimization of phase shifter and regenerative materials. Eventually, the second-stage pulse tube cooler is able to achieve cooling power of 780mW at 20K, when total power consumption is about 400W. The two-stage pulse tube cooler can fulfill the precooling requirements of the JT cooler.

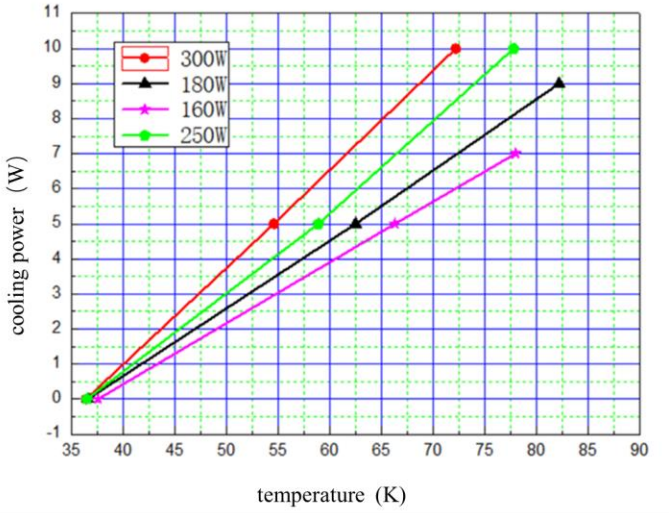

Figure 2. Cooling power of the first stage pulse tube cooler.

2.2 JT compressors

The development of the JT compressor suitable for space applications is one of the main challenges in the development of the space 4.5K JT cooler. A new four-stage compression system is developed, as shown in Figure 3. It consists of two compressors which are connected in tandem. Both of the compressors are dual two-stage designs. The pistons are supported by diaphragm springs so the JT compressors are completely oil free by use of clearance seal between the piston and cylinder. The compression system is able to provide a pressure ratio of more than 20 which means supply pressure of more than 2MPa can be achieved when suction pressure is 0.1MPa. The operating frequencies of the two JT compressors is 80Hz and 90Hz, respectively. This four-stage JT compressor system is used to drive the JT loop in the following closed loop experimental study.

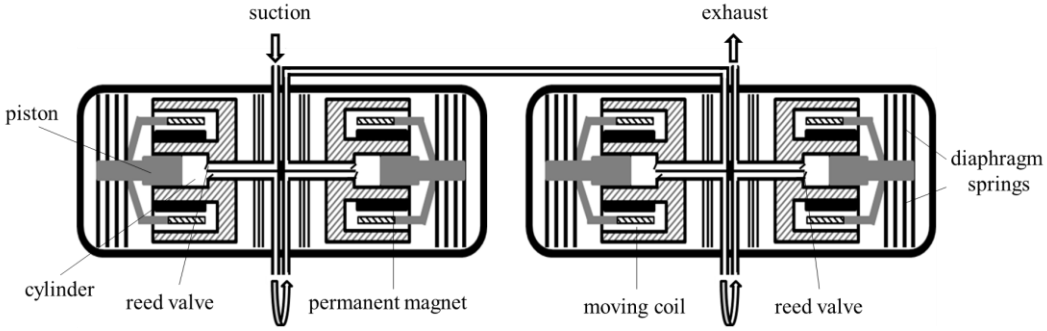

Figure 3. Schematic of the four-stage compression system.

3. Experimental study of the hybrid JT cooler

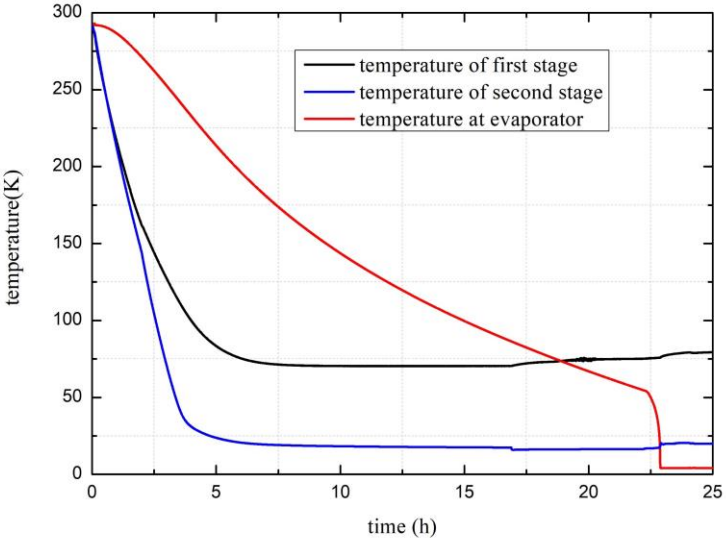

Figure 4. The cooling down curve of the hybrid JT cooler.

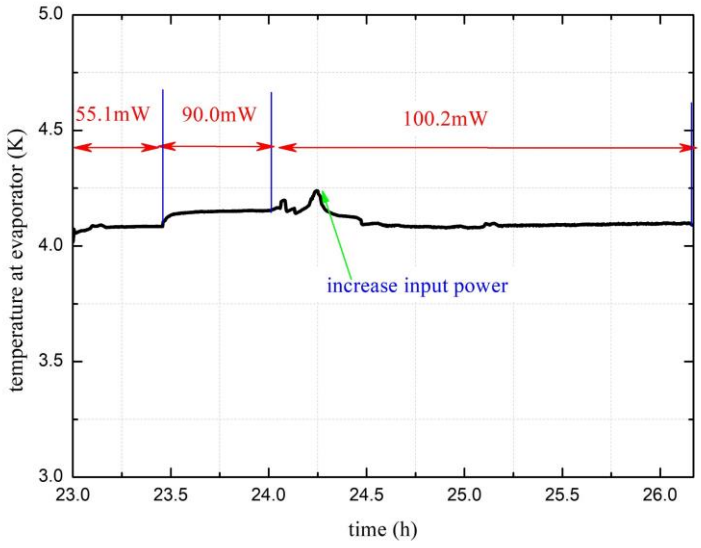

Figure 5. Performance of the hybrid JT cooler.

A hybrid JT cooler is developed and experimentally tested. The cooling down curve is presented in Figure 4. Firstly, the pulse tube cooler is turned on to provide precooling for the JT cycle. The JT compressors are turned on when the temperature before JT valve drops below the inversion

temperature of helium. Then, the temperature of the evaporator drops rapidly to about 4K. The temperature of the first and second cold stage of the pulse tube cooler will increase slightly due to the increase of flow mass rate in the JT cycle. The total cooling down time is about 23h.

The performance of the hybrid JT cooler is given in Figure 5. The temperature at the evaporator will rise slightly when the heat load on the evaporator increases gradually. The hybrid JT cooler operates stably when the heat load on the evaporator is 55.1mW or 90.0mW. However, the temperature at the evaporator fluctuates violently and then rises rapidly when the heat load reaches 100mW. The temperature fluctuations is due to the fact that the heat load exceeds the cooling capacity of the refrigerator at this time. Then, we increase the input power of the hybrid JT cooler. Then, the temperature tends to be stable and the hybrid JT cooler continues to operate stably. Eventually, cooling power of 100.2mW@4.1K is achieved when the supply pressure is 2.28MPa. The power consumption of the JT cooler and the pulse tube cooler are 134.2W and 365.9W, respectively. The comparison of the performance of the 4K hybrid JT cooler is presented in Table 1.

Table 1. The comparison of the performance of the 4K hybrid JT cooler.

	Type of cryocooler	Cooling capacity	Input power
JWST	3-stage pulse tube cooler + JT	75mW@6.2K	400W
SPICA	2-stage Stirling cooler + JT	50.1mW@4.42K	145.1W
TIPC	2-stage pulse tube cooler + JT	100.2mW@4.1K	490.1W

4. Conclusion

A space hybrid JT cooler, which is able to provide 100mW cooling power at liquid helium temperature, is developed and experimentally tested. The JT cycle is precooled by a two-stage high-frequency pulse tube cooler. A four-stage compression system composed of two oil-free linear compressors is developed to drive the JT loop. The two-stage thermally coupled pulse tube designed to precool the JT loop is able to provide cooling capacity of 780mW@20K. Finally, cooling power of 100.2mW@4.1K is achieved when the supply pressure is 2.28MPa. The power consumption of the JT loop and the pulse tube cooler are 134.2W and 365.9W, respectively. This hybrid JT cooler will not only serve as the precooler of the ADR of HUBS, but also become the excellent choice of other space missions. space qualification. The space qualification of the hybrid JT cooler will proceed as planned.

Acknowledgments

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