Process analysis and experimental verification of compact JT cryocooler at liquid helium temperature region

Z.J.Zhou [1,2], Y.J.Liu[1], J.Wang[1], J.G.Li[1], J.Quan[1,2], J.T.Liang[1]

[1] Key Laboratory of Space Energy Conversion Technologies, Technical Institute of Physics and Chemistry, CAS, Beijing 100190, China

[2] State Key Laboratory of Technologies in Space Cryogenic Propellants, Beijing 100028, China

z_zhenjun@yeah.net

Abstract: A compact ^{4}He Joule-Thomson(JT) cryocooler using two-stage Gifford-McMahon(GM) cooler as pre-cooling stages has been successfully designed and developed. The GM refrigerator cools the incoming helium gas to 91K at the first stage and 14K at the second stage. The JT system consists of three tube-in-tube heat exchangers(HEX), two spiral heat exchangers and a JT orifice. Experiments discussed in this paper are carried out in the two styles of open loop and closed cycle. A new JT compressor with single cylinder and check valves is used in the closed cycle to provide high pressure gas. The curves of throttling are given and the cooling power is measured. In open loop the no-load temperature of 3.4K and the cooling power of 30mW@4.5K are obtained, while in closed cycle 4.27K and 5mW@4.5K are obtained respectively. The optimum operating frequency of JT compressor is also investigated. The heat exchanger is verified to be efficient when the temperature at second stage of GM refrigerator is changed to 20K.

Key words: ^{4}He JT; cryocooler; heat exchanger; compressor

1. Introduction

In the fields of astronomy and atmospheric science, some electronic detectors should be cooled to 4K level to improve its sensitivity and reduce the background noise [1-3]. Mechanical cryocooler is a very important technology for the future space science missions, and compact cryocooler relying on the expansion of helium gas through a fixed orifice has some advantages such as no moving parts at low temperature and the cooling power can be transmitted to several meters away [4-6]. In some developed countries, the technology utilizing expansion of helium gas producing JT effect to obtain low-temperature has already been mature and applied to the fields of aerospace[7-8], our research on this area has just started facing the growing demands on this technology, so a JT cryocooler that can achieve 4K level and produce 30mW at 4.5K has been designed and tested in this article.

In order to reach the liquid helium temperature region, helium gas is used as the refrigerant. The transition temperature of helium gas is about 40K, only below that temperature can the helium gas produce positive JT effect[9-10]. A GM cryocooler is chosen as pre-cooler to provide cooling power to the incoming helium gas at present. In order to achieve the characters of miniaturization and compactification of the JT cryocooler, the GM pre-cooler will be replaced by pulse tube cryocooler in near future. This paper shows the no-load temperature and cooling capacity in open loop and closed cycle respectively, and a new compressor is introduced and discussed.

2. System flow diagram

The helium gas flow diagram of the cryogenic system is shown in Figure 1.The major components of JT system are JT compressor, gas filter, heat exchangers, evaporator and a JT orifice. Besides offering cooling power to the incoming gas, the GM cryocooler cools two shields which reduce heat radiation to the JT system.

The high pressure gas flows through filter and three tube-in-tube heat exchangers before expansion at JT orifice. The filter can absorb impurities in the gas flow in order that the JT orifice is not blocked. The first is HEX1 where the high pressure gas is cooled from the room temperature to about 90K by the returning low pressure gas. This is followed by a heat exchanger at the first stage of the GM pre-cooler. The second heat exchanger (HEX2) cools the high pressure gas from 90K to about 14K. This is also followed by the third heat exchanger (HEX3) where the high pressure gas is cooled to the low temperature before JT orifice by the returning gas. Then high pressure gas cooled by the preceding three heat exchangers expands at JT orifice to become saturated helium.

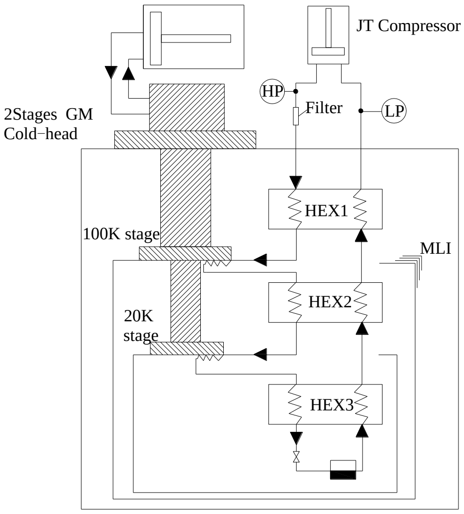


FIGURE 1. System flow of ^{4}He J-T cooler

FIGURE 2. Inner structure of4He J-T cooler

3. Design of cryogenic JT system

3.1 JT compressor

In the JT system, a new compressor with single cylinder is selected, which consumes less power than that has two pistons. The compressor is improved based on the model that has two opposite pistons mounted on a drive shaft linearly, suction and exhaust valves are mounted at the front of the piston to provide a one-way flow of helium gas, gas storages at inlet and outlet of the compressor are used to obtain stable flow. Figure 3 shows the prototype compressor. The gas from the low pressure gas storage flows into the compressor through the suction valve when the piston moves backwards, and then the gas is compressed when the piston moves towards outside, and at last the compressed helium gas exhausted to the high pressure gas storage through exhaust valve.

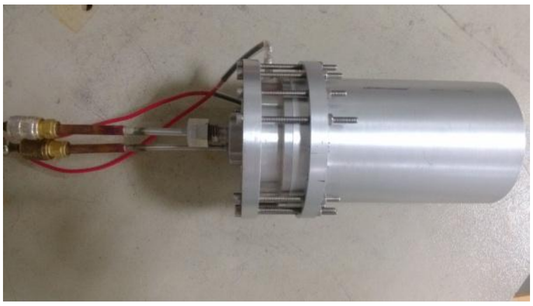


FIGURE 3. Prototype of J-T compressor

3.2 Heat exchangers

Heat exchangers are very important parts of the system and there are two types of heat exchanger in the JT cooler. The first type is tube-in-tube heat exchanger that includes HEX1, HEX2 and HEX3.The three heat exchangers apply the type of resembling hampson heat exchanger, which features large heat transfer area and effectiveness. The high pressure gas flows in the inner tube while the returning low pressure gas flows in the opposite direction in the space between the two tubes to cool the incoming gas. The diameters of the inner tube are 1mm and 2mm respectively, the inner diameter of the outer tube is 3.5mm, as the designed efficiency of the heat exchanger is 97%, the length of the three heat exchangers are 0.75m, 1.3m and 1.0m respectively. The second type of heat exchanger is coil type that attached spirally on the two cold stages of the GM cooler, the material is copper and the inner diameter is 1mm, its role is to transfer cooling power from the pre-cooler to the incoming helium gas.

3.3 Design Specifications of the Joule-Thomson Cooler

Based on above analysis and the cooling capacity of the pre-cooler in the laboratory, the design scheme is given in Table 1. The total heat load at 90K and 15K mainly brought by incoming helium gas and radiation to the shields is 3.1W and 122mW respectively.

TABLE(1). Design Specifications of the Joule-Thomson Cooler

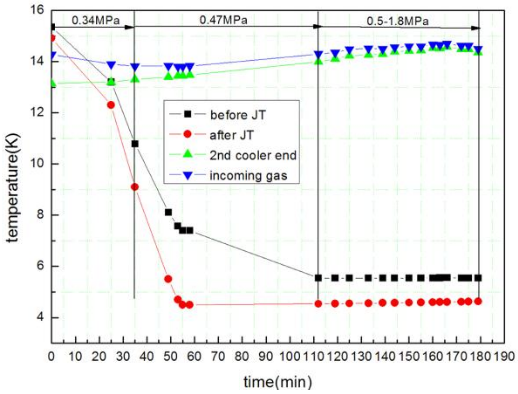
Items	Specifications
Cooling capacity	30mW@4.5K
Helium gas flow rate	Approx. 6mg/s
High pressure	1.6MPa
Low pressure	0.1MPa
Pre-cooler	
The first cooler end	3.1W
The second cooler end	122mW
JT compressor	
Configuration	Single stage
Compression ration	Approx.6
Heat exchanger	tube-in-tube heat exchanger,97%
Orifice	Approx. 25μm

4. Experiments and discussions

In this part, the experiments of open loop and closed cycle are carried out. The JT system we designed is verified to be effective in the open loop experiment, and then the JT compressor is added to the system to build a complete closed cyrocooler. The closed cycle system is tested and some preliminary valuable results are obtained.

4.1 Open loop experimernt

In the open loop JT system, the high pressure helium gas is provided by gas cylinder. The whole pre-cooling process lasts about 12 hours when the incoming helium gas at the inlet of HEX3 is precooled to 14K by a GM cooler, and simultaneously the temperatures before and after JT orifice are precooled to about 16K from room temperature. Then the charging pressure is adjusted to an appropriate value to generate significant throttling effect. Figure 4 shows the temperature curves when the returning helium gas flows directly to the atmosphere, while Figure 5 shows the temperatures change at different charging pressures when the returning helium gas is pumped by vacuum pump. The liquid helium temperature region can be reached when the high pressure is adjusted to 0.47MPa, and the temperature after JT orifice drops to 3.4K when the vacuum pump works. It can be seen from the both pictures that the temperature after JT orifice rises with the increasing of the charging pressure, which is caused by the rising of the corresponding pressure to the temperature after JT orifice.



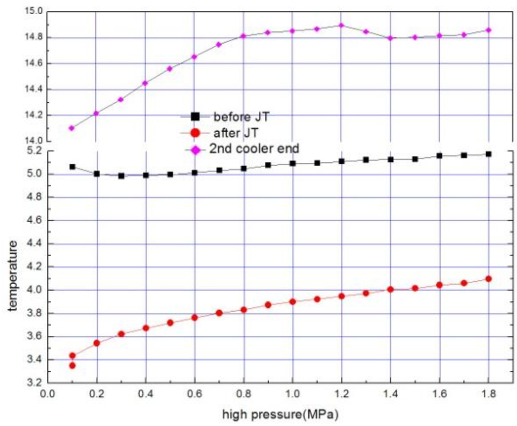


FIGURE 4. Cool-down of ^{4}He J-T cooler in open loop **FIGURE 5.** JT effect at different charging pressures

The reason can be illustrated from Figure 6, where *P1* is the saturation pressure corresponding with the temperature, *P* is the pressure at inlet of the vacuum pump, and *ΔP* is the pressure drop caused by the resistance along the returning path, it follows the equation

$$\mathrm{P1} = P + \Delta P \tag{3}$$

The increasing of the charging pressure leads to the increase of the flow rate *m*, which causes the increase of *ΔP* directly, and eventually *P1* rises.

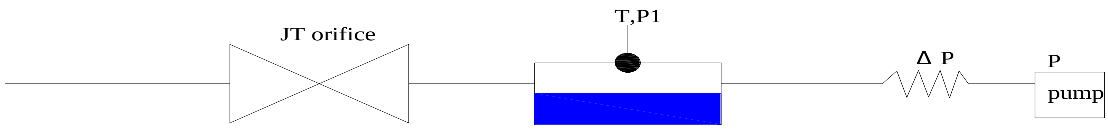


FIGURE 6. Pressure distribution along gas returning pipe

Then the second stage of the pre-cooler is heated to 20K to test the efficiency of HEX3, as seen in Figure 7, the temperature after JT orifice drops to 16K from 21K when the charging pressure is 0.6MPa, and the no-load temperature of the JT cooler reaches 4K when the charging pressure is adjusted to 1.22MPa, which illustrates the tube-in-tube heat exchanger is efficient.

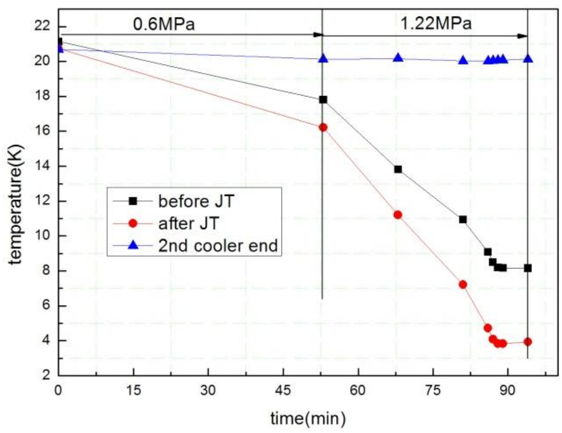


FIGURE 7. Cool-down when the temperature of 2nd stage of pre-cooler is 20K

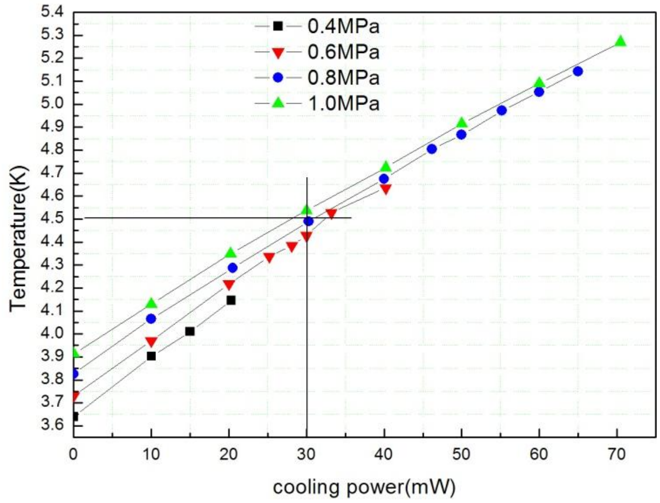


FIGURE 8. Cooling capacity at different charging pressures

Figure 8 shows that the maximum cooling capacity of the JT cooler becomes larger with the increase of the charging pressure. 30mW@4.5K is obtained at different high pressure, and 70mW@5.3K can be achieved when the high pressure is 1.0MPa.

4.2 Closed cycle experiment

As the closed cycle JT system is shown in Figure 9, the gas cylinder is replaced by a new JT compressor with single cylinder and check valves. A gas filter is introduced in the system to remove the impurities in the helium gas to avoid blocking the JT orifice. Figure 10 shows the cool-down of ^{4}He J-T cooler. When HEX3 is pre-cooled to about 15K, the charging pressure of JT compressor is adjusted to 0.3MPa, and then we start the JT compressor. The power consumed by the JT compressor is 36W at beginning, the high pressure and the low pressure are 0.6MPa and 0.02MPa respectively. While the temperatures before and after JT orifice decrease continuously, the compressor power drops to 20W. As shown in Figure 10, the no-load temperature reaches 4.27K finally when the frequency of the compressor is 50Hz.

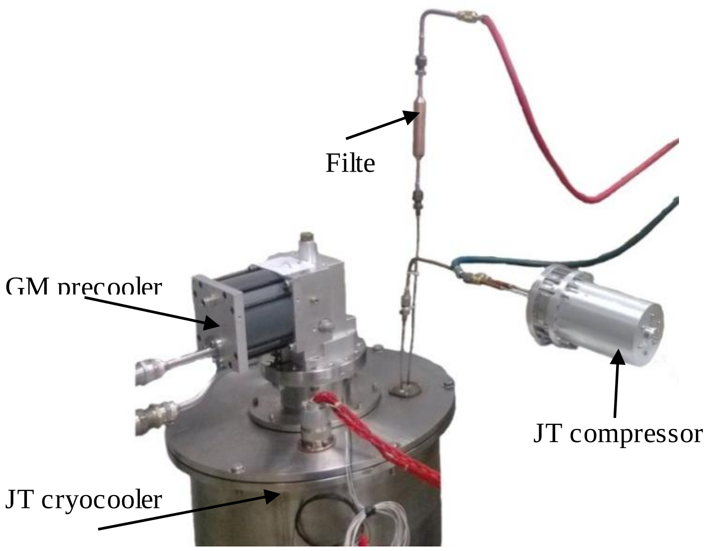


FIGURE 9. ^{4}He J-T cooler of closed cycle

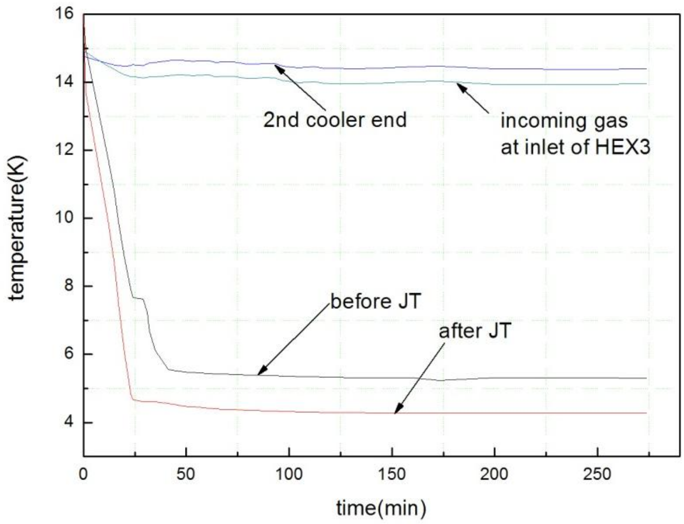


FIGURE 10. Cool-down of ^{4}He J-T cooler in closed cycle

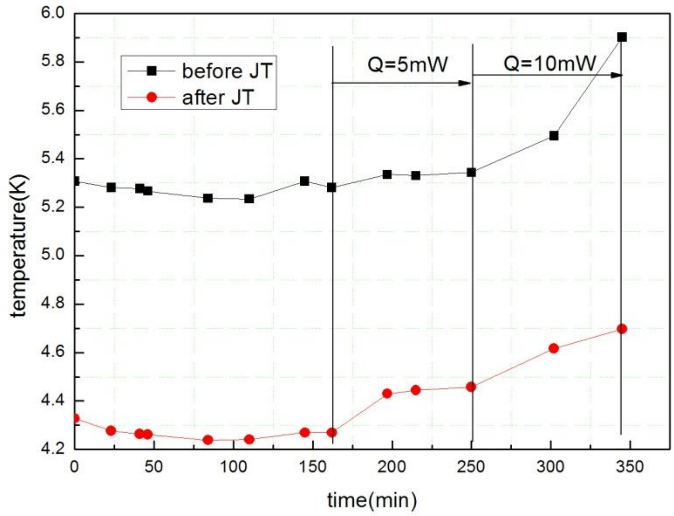
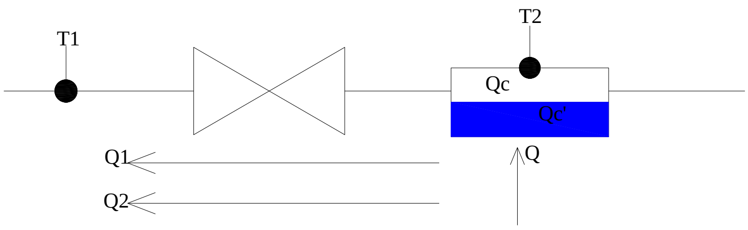


FIGURE11. Cooling capacity in closed cycle

The cooling capacity of the JT cryocooler of closed cycle is shown in Figure 11. The power of JT compressor is 19W, and the high and low pressure of the JT compressor are 0.35MPa and 0.1MPa respectively when the no-load temperature is 4.2K. The compressor power increases slightly when the evaporator is heated, which is caused by the evaporation of the liquid helium. The cooling capacity of 5mW@4.5K and 10mW@4.7K are obtained.

The process that the liquid helium is heated until evaporating into helium gas can be illustrated as follows. As seen in Figure 12, besides pre-cooled by returning helium gas in HEX3, the helium gas before JT orifice is also pre-cooled by the liquid helium through conduction, similarly it is also heated by current heating through heat conduction. Therefore the following situations are observed in the experiment.



1,Q—current heating;2,Qc—cooling capacity; 3,Qc′—useful cooling power;

4,Q1—cooling conduction; 5,Q2—heat conduction;

FIGURE12. Distribution of heat in the evaporator

(a) There is no current heating ,Q=0;the useful cooling power is

$$Qc' = Qc - Q1 \tag{4}$$

(b) When the evaporator is heated, $Q \neq 0$, $Qc' > (Q - Q2)$,the whole cooling power follows the equation

$$Qc = Q1 + [Qc' - (Q - Q2)] \tag{5}$$

(c) If we continue to increase the current heating, $Q1 < Q2$, $Qc' < (Q - Q2)$, in this situation the current heating is greater than the useful cooling power, and the temperature after JT orifice will rise rapidly when the liquid helium evaporates completely.

5.Conclusion

A prototype of ^{4}He JT cryocooler has been successfully designed, assembled and tested, which is the first compact Joule-Thomson cryocooler at helium temperature region reported in china so far with ^{4}He. Experiments are carried out in the forms of open loop and closed cycle, respectively. In the experiment of open loop, the no-load temperatures at different charging pressures are tested. The no-load temperature is 3.4K when the charging pressure is 0.1MPa, and it rises when we increase the charging pressure. About 30mW@4.5K is obtained at various charging pressures. It proved that the designed heat exchanger is efficient when the temperature of second stage of pre-cooler is raised to 20K.

In the closed cycle experiment, a new JT compressor improved based on the model that has two opposite pistons in our lab is introduced to provide high and low pressures helium gas for the JT cycle. The no-load temperature of 4.2K and the cooling capacity of 5mW@4.5K is obtained. At last the optimum operating frequency of JT compressor is tested and it comes to a conclusion that the no-load temperature is lower when the JT compressor operates at 50Hz than at other frequencies.

The compact J-T cryocooler at liquid helium temperature region has achieved preliminary results, a ^{4}He JT cryocooler of closed cycle with two stages JT compressor improved based on the existing system is under assembled and tested which could provide greater cooling power. Compact cryocoolers utilizing the throttling effect of ^{4}He at low temperature could offer reliable low temperature environment and greater cooling power for the electronic devices on future astronomy science and space exploration missions.

6.Acknowledgments

This work is supported by the Strategic Pioneer Program on Space Science, Chinese Academy of Sciences, Grant No.XDA04074100.

References

1.K.Shinozaki,H.Sugita,Y.Sato,K.Mitsuda,T.Nakagawa,R.Fujimoto,K.Narasaki,K.Kanao,S.Tsunematsu,K.Otsuka, Developments of 1-4 K Class Space Mechanical Coolers for New Generation Satellite Missions in JAXA, Cryocoolers11,pp.1~8.,2011.

2.J.Inatani,T.Noguchi,S.C.Shi,K.Miyazawa,H.Masuko,S.Ochiai,Y.Irimajiri,M.Kyoya,K.Narasaki,S.Tsunematsu,M.Murakami,andD.Okamoto,A Submillimeter SIS Receiver Cooled by a Compact Stirling-JT Refrigerator, Eighth International Symposium on Space Terahertz Technology, pp.273-280, 1997.

3. K.C.Ng, H.Xue, J.B Wang, Experimental and numerical study on a miniature Joule-Thomson cooler for steady-state characteristics, Int. J. of Heat and Mass Transfer, Vol. 45, pp. 609–618, 2002.
4. J. lnatani, K.Narasaki, S.Tsunematsu, M.Kyoya, T.Manabe, M.Seta, T.lida and R. Satoh, Mechanical Cooler and Cryostat for Submillimeter SIS Mixer Receiver in Space,Proceedings of SPIE, Vol. 4540, September 2001.
5. Orlowska A H, Bradshaw T W, Closed cycle coolers for space applications[J].Space Science Reviews,1992,61: 233-240.
6. Bruce Swinyard,Takao Nakagawa. The space infrared telescope for cosmology and astrophysics: SPICA A joint mission between JAXA and ESA[J].Exp Astron ,2009, 23:193–219.
7. Takao Nakagawa and SPICA team,The next-generation infrared space mission: spica.EDP Sciences, 2009.
8. Glaister D S, Gully W J, Wright G P, Simmons D W, Tomlinson B J,A 10 K Cryocooler for Space Applications.Cryocoolers,2001,11:505~511.
9. Ross R G Jr. A Study of the Use of 6K ACTDP Cryocoolers for the MIRI Instrument on JWST[J].Cryocooler, 2004, 13:15~24.
10. Ross R G Jr,Boylet R F,Key R W and Coulter D R.NASA advanced cryocooler technology development program[M].International Society of Optical Engineering (SPIE) Conference,2002.