

Preliminary Experimental Study on a Precooled JT Cryocooler Working at 4 K - Open Cycle

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ABSTRACT

For developing a long-life precooled Joule-Thomson cryocooler (PJTC) for space use, the cold head part has been developed and tested using an open cycle. The structures and parameters of the counterflow heat exchangers and cold head heat exchanger are presented in this paper. In the testing experiment, a two-stage GM cryocooler was used as the precooler due to its sufficient and consistent cooling performance. The PJTC successfully achieved 4.4 K in the open cycle experiment. During the measurement of the cooling power, it was found that, the PJTC started to be unstable before the liquid helium was totally evaporated in the CHX. The phenomenon is described and the reasons discussed.

INTRODUCTION

The precooled Joule-Thomson cryocooler (PJTC) has become the main cooling technology at liquid helium temperatures for long-life space missions [1]. It is usually applied to directly cool the detectors or to precool other cryocoolers designed to achieve even lower temperatures. Some research institutions, companies, and space mission groups have reported their developed PJTCs [1-3]. However, few details about their designs and performance analyses have been described.

According to the analysis of Reference [4], key elements of the PJTC are the last stage recuperator, the J-T valve, and the cold head heat exchanger. These are the most important elements of the PJTC that can reflect the effects of the precooling temperature and the high pressure on cooling performance.

An open-cycle PJTC has been designed and built as part of the work reported here. For verification of the design, the PJTC was tested with a GM cryocooler as a precooler. The preliminary experimental setup is introduced in this paper. It is found from the cooling power measurement results that the PJTC went unstable before the liquid helium was totally evaporated. The reasons are discussed.

EXPERIMENT SETUP

The preliminary setup introduced here is mainly developed to verify the design of the key elements. As shown in Fig. 1, when the open cycle is operating under steadystate conditions, the helium gas discharged from the helium bottle (with reducing valve) goes through an inlet valve, a high mass flow meter (MFMh), the first counterflow heat exchanger (CFHX1), the first precooling heat exchanger (preHX1), the second counterflow heat exchanger (CFHX2), the second precooling

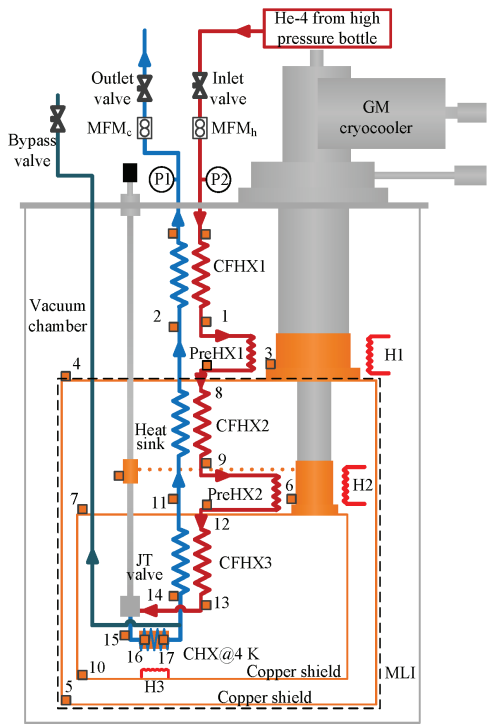


Figure 1. The open-cycle experiment setup.

heat exchanger (preHX2), and the third counterflow heat exchanger (CFHX3) before throttling to low pressure. The room temperature helium gas is precooled in these components and then goes into the two-phase region after the JT valve. The two-phase helium flow will absorb the heat load and evaporate in the cold head heat exchanger (CHX). Then the evaporated gas (or still two-phase fluid) from the CHX flows through the CFHX3, CFHX2 and CFHX1 to precool the incoming warmer helium flow. Finally it goes out to the atmosphere. The thermometers are labeled as squares numbered from 1 to 17 in Fig. 1.

For speeding up the cooling down process, a bypass line from the cold end is used. If there is no bypass, the CFHX3 and CHX will warm up the precooled gas from the preHX2 during their cooling down process. Then the warmed gas will go back to the CFHX3 and continuously consume the precooling power provided by the precooler. It will take an extremely long time to cool down the CHX to be below the inversion temperature of Helium because the effectiveness of CFHX3 is designed with a high level and the heat conductance along its length direction is small enough to be neglected. So a bypass line is shown in Fig.1, which can let the gas from the CHX flow out to the atmosphere before the CHX approaches the temperature of point 12 (below 10 K in experiment) when the outlet of the PJTC is closed by a valve.

There are two radiation shields made of copper which are cooled by the first and second stage cold heads of the GM cryocooler, respectively. MLI is used around the outside copper shield to eliminate the heat radiation. H1 and H2 are two heaters that can be adjusted to regulate the precooling temperature. H3 is another heater which is used to measure the cooling power of PJTC. The JT valve can be controlled outside the vacuum chamber which makes it easier to have the required mass flow.

The CFHX3 is a Linde type [5] heat-exchanger, also called a tube-in-tube heat exchanger, as well as CFHX1 and CFHX2. They are all made of standard stainless tubes of which the parameters are listed in Table 1. The heat exchanger model was presented in Reference [6].

The CHX is made of 1/8 inch stainless tube, which is the same as that in Table. 1. The tube is coiled and soldered around a copper cylinder. The length of the tube available for heat exchanging is about 0.6 m. The heat load can be added on the copper cylinder by an electrical resistance.

Table 1. The parameters of the CFHXs.

label	Inner tube		Outer tube		Length (m)
	Outer diameter (inch)	Wall thickness (inch)	Outer diameter (inch)	Wall thickness (inch)	
CFHX1	1/8	0.028	3/8	0.035	0.8
CFHX2	1/8	0.028	3/8	0.035	2.0
CFHX3	1/8	0.028	1/4	0.035	3.3

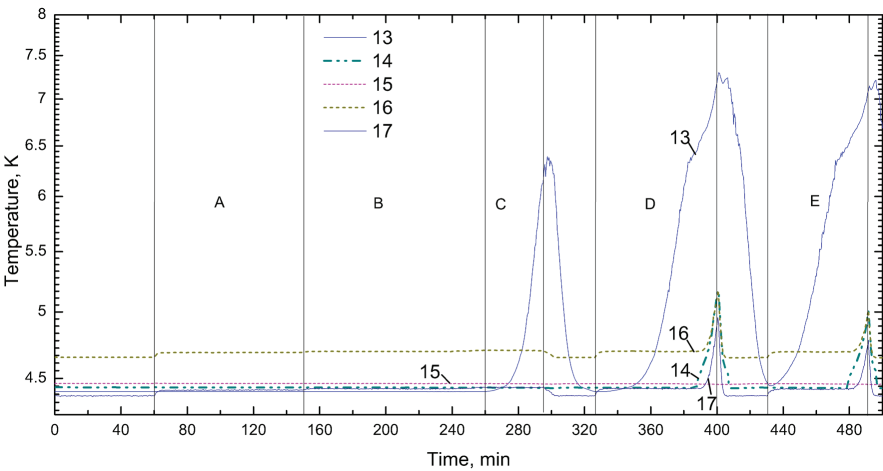


Figure 2. Cooling power

COOLING POWER MEASUREMENT

When the precooling temperature (thermometer 12) was fixed at 17.3K by controlling the H2 heater, and the high pressure was kept around 1.1 MPa, for example, the cooling power was measured. The data monitored by thermometers 13, 14, 15, 16 and 17 during cooling power measurement are plotted in Fig. 2. Thermometers 13, 14, 15 and 17 are all Cernox type while 16 is a Rhodium-iron resistance type. Thermometers 13, 14 and 15 were mounted inside small copper blocks that were soldered on the connecting tubes. Thermometers 16 and 17 were mounted inside the copper cylinder of CHX. Apiezon N grease was used to keep good thermal contact between the copper walls and the thermometers.

When there was no heat load added, temperatures 13, 14, 15 and 17 were very close to each other because they were actually all cooled by liquid helium. Thermometer 16 was a little higher than the others, but it closely followed thermometer 17, probably reflecting the higher reliability of the Cernox thermometers. So thermometer 16 will not be included in the later discussion.

When the heat load was applied, the temperature of thermometer 17 increased a little bit because the heat transfer needed to be driven by the temperature difference. For region A, B, C, D and E on Fig. 2, the heat loads are listed respectively in Table 2. The other regions with no labels are for no-load conditions.

For achieving the maximum cooling power at liquid helium temperature, the heat load was added carefully. After region B, three values of heat load were tried but all of them made the cooler

Table 2. Applied heat load for each region.

Region on Fig. 2 to 5	Heat load, mW
A	39.79
B	48.94
C	58.76
D	52.94
E	49.39

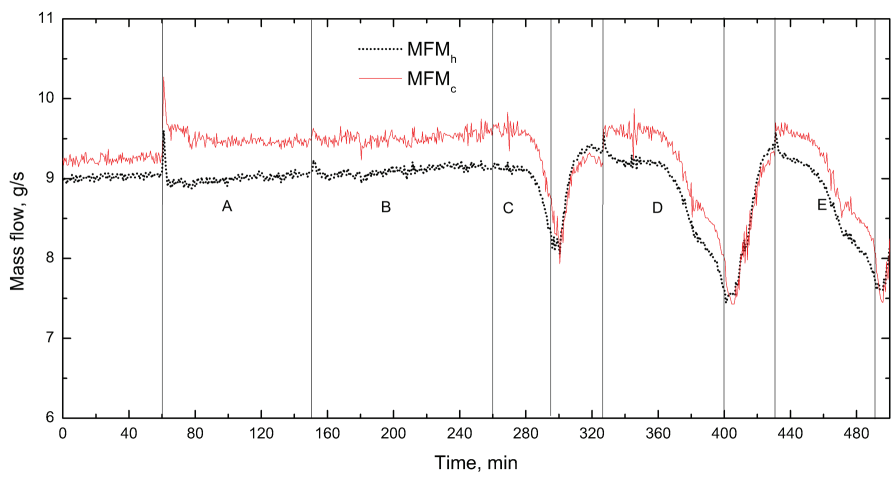


Figure 3. Mass flow

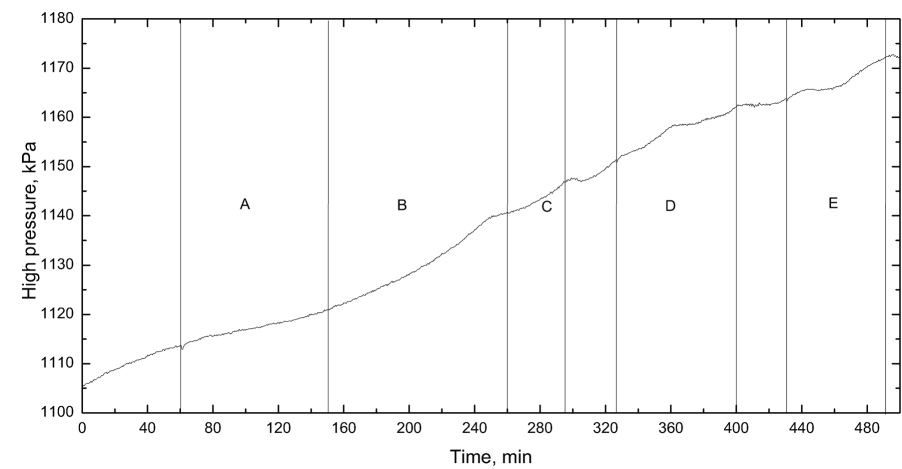


Figure 4. High pressure

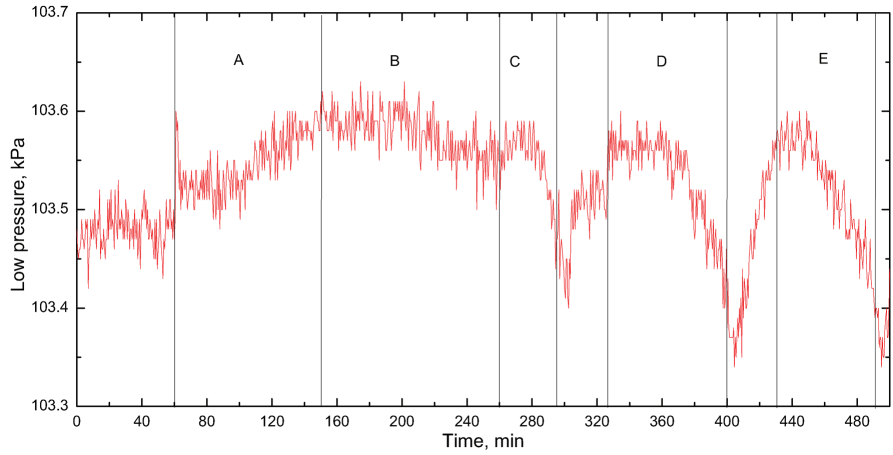


Figure 5. Low pressure

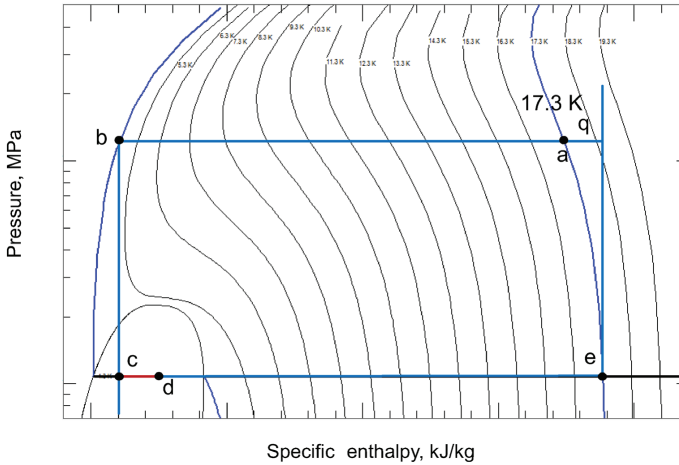


Figure 7. Maximum cooling power state

away from liquid helium temperature corresponding to the behavior of thermometer 13 in Fig. 2. The temperature of d is the second to leave the liquid helium temperature corresponding to the thermometer 14.

If the heat load was not removed, the thermometer 15 (position c) would also leave the liquid helium temperature and PJTC could never come to a steady condition. The above analysis shows how the PJTC goes unstable even without a mass flow drop. Actually the mass flow will change when the temperature before the JT valve (b) starts to rise as shown in Fig. 2 and Fig. 3. The mass flow drop will accelerate the process of the PJTC becoming unstable because the maximum cooling power will decrease.

Mass Flow Drop

Figures 2 and 3 show that when the temperature of 13 increased, the mass flow decreased dramatically. Here this phenomena will be discussed qualitatively.

Usually a PJTC working at liquid helium temperature has a pressure ratio larger than the critical pressure ratio about 2 for choked flow [5]. For an ideal gas, the molar mass flux in choked flow conditions is defined as

$$\dot{n}A = \kappa^{1/2} \left(\frac{2}{1+\kappa} \right)^{\frac{\kappa+1}{2(\kappa-1)}} \frac{P_0}{\sqrt{MRT_0}} \quad (1)$$

where A is the minimum cross section area of the passageway, κ is the adiabatic exponent, p_0 is the high pressure, T_0 is the temperature of the high pressure flow. M is the molecular mass. R is the ideal gas constant. It is shown that the mass flow is decided by the p_0 and T_0 . In our experiment, the p_0 can be treated as constant. T_0 is corresponding to the temperature monitored by the thermometer 13. The tendency of the mass flow changing as the T_0 showed in Fig. 2 and Fig. 3 is consistent with Equation (1).

However, the condition in the experiment is for real fluids including subcooled liquid or supercritical state at the inlet and the two-phase condition at the outlet of the JT valve. Reference [7] measured the mass flow of helium for T_0 between 4 and 20 K when p_0 was 1 MPa. The mass flow at 4 K was more than 3 times of that at 20 K with which similar phenomena was found in our experiment.

Up to now, the characteristic of choked flow is supposed to be the main factor to cause the mass flow drop detected during our experiment. Theoretical or numerical methods may help to make it clear; this will be left to future work.

CONCLUSIONS

The open-cycle PJTC setup was built and tested. The PJTC successfully achieved the cooling power of 48.94 mW at liquid helium temperature. The reason to cause the unstable condition can be explained by the p-h map analysis. The mass flow drop accompanying the unstable condition is likely related to the characteristic of choked flow, which needs further quantitative analysis.

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