A 70 K J-T cryocooler based on the fractional mixed-refrigerant cycle*

Gong M.Q., Wu J.F.

Technical Institute of Physics and Chemistry, Chinese Academy of Sciences
P.O. Box 2711, Beijing, 100080, China

An effort was made in this paper to reach about 65 to 70 K temperature range by using a mixed-gases Joule-Thomson system. A special cycle configuration was disclosed utilizing a new developed fractional phase-separator with inner heat and mass transfer. This separator avoids cold clogging essentially. An optimal mixture was used to improve the system performance. A stable coldest temperature of 65 K and a cooling capacity of 1.06 W at 70 K were achieved driven by a commercial single-stage hermetic compressor with a nominal input power of 500 W. The detailed analysis of mixture properties and cycle configuration are also presented in this paper.

INTRODUCTION

The last two to three decades has seen a remarkable development of the mixed-gases Joule-Thomson refrigerator (MJTR). Driven by an oil-lubricated commercial compressor makes the MJTR more competitive with other type coolers. This new revival refrigeration method with multi-component mixture has demonstrated high performance in the cooling temperature range from 80 K to 230 K in many applications, such as cooling infrared sensors, gas chiller or liquefaction, cryosurgery, cryo-preservation, water vapor cryo-trapping, etc. The merits of mixed-gases refrigeration is obvious such as low cost, high reliability, high efficiency, and easily to be produced in industry scale, etc. However, for applications of cooling high temperature superconductivity devices, the appropriate temperature should be lower than 80 K. That is, providing cooling capacity at 70 K is accepted for commercialized applications. Difficulties are brought by using high-boiling point components and oil lubricant in the system in the traditional MJTR system because of the coldest clogging and low efficiency. The detailed information of the thermodynamic consideration of mixed-refrigerant and design of cycle configuration for reaching 70 K are presented in this paper.

THERMODYNAMIC DESIGN

For properly operating at low temperature range, a careful thermodynamic design was made from two aspects of gas properties and cycle configuration, which were discussed in the following.

Properties of the cryogenic gases for low temperature refrigeration

For operating at 70 K temperature range, two kind of properties of cryogenic gases are most important.

* This work is financially supported by the National Natural Sciences Foundation of China under the contract number of 50206024.

One is the liquid-solid (L-S) equilibrium characteristics which essentially influence the reliability of the refrigeration system, the other is the Joule-Thomson effect which represents the thermodynamic performance of the system. For most substances, low boiling temperature component has low freezing point. A list of the solubility limits for different substance is shown in Table 1 [1].

Table 1 Solubility limit for some hydrocarbon substances at low temperature range [1]

Temperature /K	Solubility limits (mole fraction)				
	CH_4	C_2H_6	C_3H_8	iC_4H_{10}	iC_5H_{12}
65	0.62	0.23	0.21	0.03	0.01
70	0.70	0.33	0.33	0.05	0.02
75	0.78	0.47	0.50	0.08	0.04
80	0.85	0.62	0.71	0.13	0.07
85	0.92	0.80	0.97	0.20	0.10
90	0.99	1	1	0.29	0.16

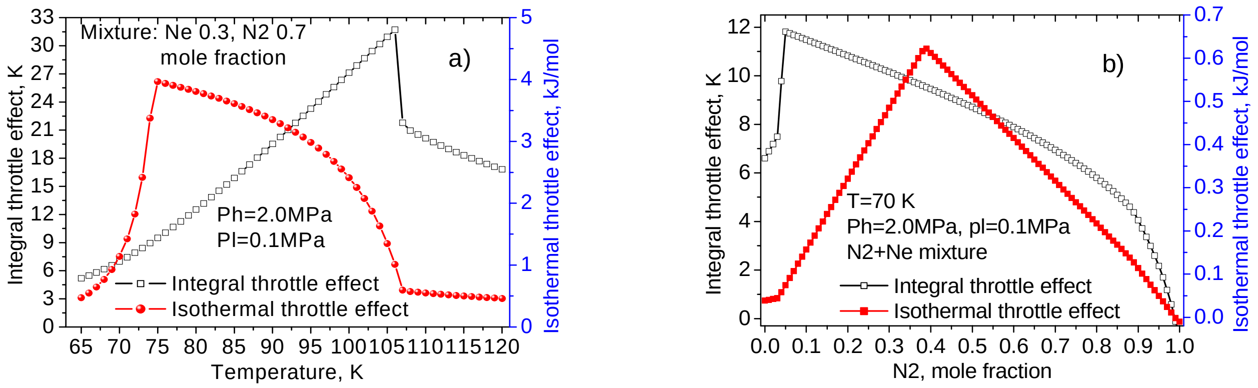


Figure 1 Throttle effects of a mixture at low temperature, a) influence of temperature, b) influence of mole concentration

From Table 1, it can be found that there is an acceptable solubility limit for the most used substance in the low temperature. For most mixtures used in this temperature range, the mole fractions of those substances are far less than this solubility limit because of the phase separation in the cycle configuration which will be discussed later. So a high reliability of the refrigeration system can be reached.

Joule-Thomson effects, especially the isothermal Joule-Thomson are important parameters in the design of the throttle refrigeration system. In the 70 K temperature range, the candidate gases are still nitrogen and neon. The isothermal effect Δh_T and integral throttling effect ΔT_h can be obtained with the following equations [2]:

$$\Delta T_h = \int \mu dp = \int \left(\frac{\partial T}{\partial P} \right)_h dp = T_0 - T_1 \tag{1}$$

$$\Delta h_T = h_0 - h_1 \tag{2}$$

where T_0 ,T_1 are the temperatures of the gas before and after the throttling, h_0 is the enthalpy of the gas before being compressed, and h_1 is the enthalpy of the gas after being isothermally compressed, μ is the differential throttle effect, and p is pressure. Figure 1 shows the calculation results of the throttle effects of nitrogen and neon mixture at different conditions, in which p_h and p_l denote the high and low pressures, respectively. Figure 1 a**)** gives an suggestion that the separation temperature in the refrigeration cycle should be better in the range from 100 K to 120 K, and Figure 1 b) shows that the mixture composition after separation should be better that the mole fraction of nitrogen is about 0.4 in the mixture, and the rest component is neon.

The optimization of the multicomponent mixture is another very important thing in the design of the 70 K refrigeration system. The normal boiling point and freezing point should be considered while optimizing the mixtures. From the discussion of the properties of mixture in the above section, an optimal mixture was used in this refrigeration system. Indeed, for different refrigeration temperature ranges the mixture component candidates are different. For the 70 K temperature range of this cryocooler, seven component mixtures are adopted, which consists of hydrocarbons, fluorinated hydrocarbons, nitrogen and neon. The optimized mixture is designed to minimize the irreversibility losses of the heat exchanger over the operating temperature range, and to be compatible with the compressor lubricating oil and the materials of construction of the refrigeration system.

Design of the refrigeration cycle configuration

The schematic diagram of the refrigeration system for operating at 70 K temperature range is shown in Figure 2 [3]. The refrigeration system consists of two separate modules: the compressor unit and the cryostat, which are connected by gas lines. The compressor unit consists of a compressor, an air-cooled condenser or so-called after cooler, and an oil pre-removal unit. The compressor is a hermetic single stage oil-lubricated air-conditioning compressor with a nominal input power of 0.5 kW. The disadvantage is the oil contamination in the refrigeration stream. If the oil contamination in the mixture exceeds compatible quantities, this would result in clogging in the cold end at low temperature. Having a good oil removal unit is much more important in the low temperature refrigeration system. However, it is not enough just using an oil removal unit in the system. So special phase separators are used in the design of such cycle configuration for low temperature refrigeration. Special structures have been incorporated in the phase separator, which is known as the reflux heat exchanger, also called the dephlegmation separator, instead of the traditional liquid vapor separator to ensure the liquid and vapor separation. Two dephlegmation separators are used in this cycle to ensure that there will be no solid generated in the coldest section of the system. One separator is set at ambient temperature, and the other is near 110 K temperature. The separation temperature is determined by the recuperative heat exchanger size.

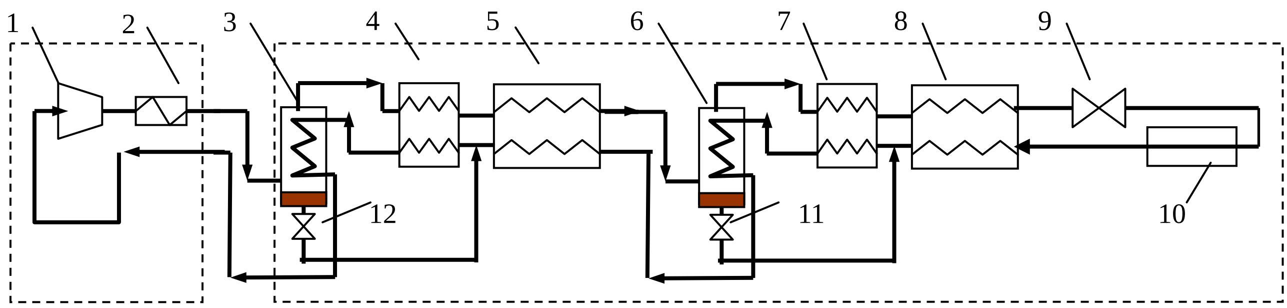


Figure 2 Schematic diagram of the refrigeration cycle configuration with a dephlegmation separator, 1: compressor 2: after cooler 3,6: simplified dephlegmation separator 4,5,7,8: heat exchanger 9,11,12: throttle valve10: evaporator

EXPERIMENTAL RESULTS

Experimental rig

Based on above considerations, an experimental setup was built and tested. The features of experimental setup were listed in Table 2.

Experimental results

Extensive experimental test were carried out with the setup described above. Figure 3 shows the typical cooling down curves of the temperatures and pressures of the refrigerator. Figure 4 shows the flow rate variation in the cool-down process. The diagram of cooling capacity vs. refrigeration temperature is shown in Figure 5. From those figures, it can be found that a lowest stable refrigeration temperature of 66K and 1.06 W cooling power at 70 K were achieved. From Figure 3, the cool-down process is a little bit long because of the large heat capacity of the cryostat and poor vacuum isolation. This can be improved by a future design of the cryostat especially the recuperative heat exchanger and improvement of the vacuum system.

Table 2 Specifications of the experimental rig

Components	Number	Features
Compressor	1	Single-stage; oil-lubricated; hermetic; 0.5 kW input power
Heat exchanger	4	7 inner tubes: inner/outer diameter: 1.8/3 mm; outer tube inner/outer diameter: 10/12 mm
JT valve	3	Capillary tube
Mixed-refrigerant	/	Seven components of light hydrocarbons form C1 to C5; nitrogen; neon

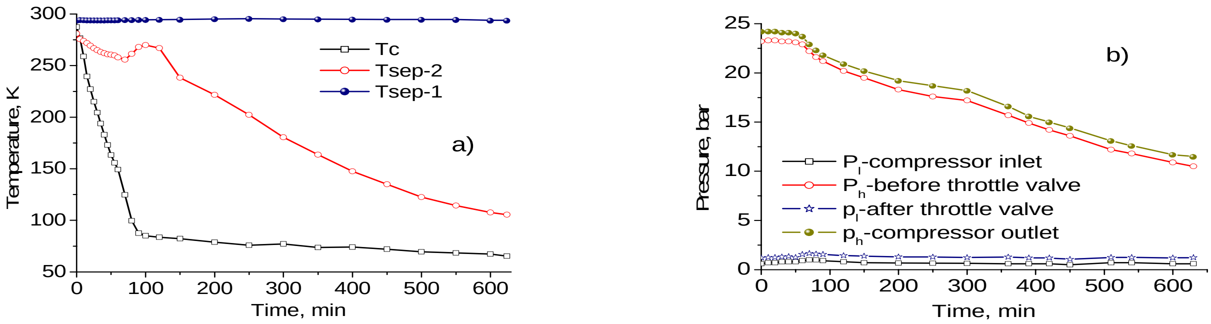
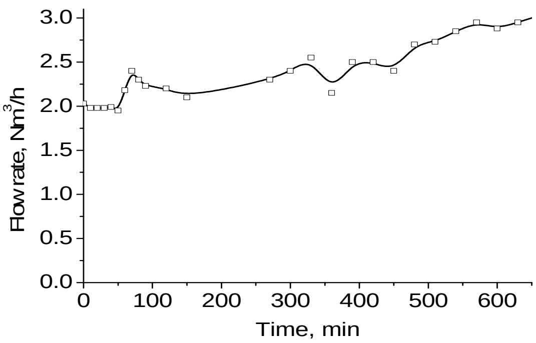


Figure 3 cooling down curve, a) temperature, b) pressure



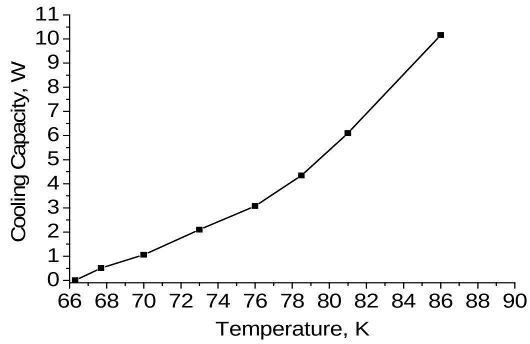


Figure 4 Flow rate variation curve

Figure 5 Cooling capacity vs. temperature

SUMMARY

A mixed-refrigerant Joule-Thomson refrigeration system is developed, built, and tested in our experiment for operating at 70 K temperature range. A stable lowest temperature at 66 K and 1.06 W cooling capacities at 70 K were achieved with an input power of 0.5 kW. The results obtained in this investigation shows that with optimal mixed-refrigerant and cycle configuration, the mixed-refrigerant J-T cryocooler can provide refrigeration at 70 K temperature properly. This provides a low cost, high reliability refrigerator for 70 K temperature range application, especially for cooling high temperature superconductivity devices.

REFERENCES

1. Luo E.C. Study on mixed-refrigerant Joule-Thomson cryocoolers in liquid nitrogen temperature range, in Ph.D. thesis, Beijing, (1997)
2. Cravalho E. G., Smit J. L., in Engineering thermodynamics, Pitman, Boston, (1981)
3. Wu, J.F., Gong, M.Q., et al, A new type mixture auto-cascade refrigeration cycle with a partial condensation and separation reflux exchanger and its preliminary experimental test, in Adv. in Cryo. Eng. (2002) 47 887-892