Effect of the Charged Pressure on GM Cryocooler Performance

H. Nezuka[1], H. Nakagome[1], M. Ota[1], T. Numazawa[2], S. Masuyama[3], N. Nakashima[4] and Y. Ikeya[4]

[1]Chiba University, Chiba, Japan
[2]National Institute for Materials Science, Japan
[3]Oshima National College of Maritime Technology, Japan
[4]Sumitomo Heavy Industries, Ltd., Japan

ABSTRACT

This paper presents experimental results that show that the refrigeration efficiency of GM refrigerators can be improved by applying a charged pressure. Recently, there has been remarkable progress in superconducting systems, such as magnetic resonance imaging systems, silicon single-crystal pull-up apparatus, and cryopumps. GM cryocoolers are used to cool these systems because of their high reliability. Thus, to improve the efficiency of superconducting systems, it is important to improve the efficiency of GM cryocoolers. If the compression ratio of a GM cryocooler is reduced, its coefficient of performance (COP) will approach the Carnot COP, since the cryocooler will operate with Simon expansion. Therefore, we investigated the effect of varying the charged pressure of a cryocooler and the cycle frequency on its refrigeration efficiency. We developed a GM cryocooler that can be operated at various charged pressures and we measured its efficiency at various charged pressures and operating frequencies. The optimum charged pressure and operating frequency were determined by comparing the experimental results with numerical simulation results.

INTRODUCTION

4 K GM cryocoolers have been used in practical applications for a long time. Moreover, 20 K GM cryocoolers are also widely used throughout the world as cryopumps and in other applications. If the efficiency of GM cryocoolers can be increased, the efficiency of many applications will also increase. We attempt to increase the efficiency of the GM cryocooler by increasing the pressure difference and reducing the compression ratio. A low compression ratio and a high pressure difference were achieved by increasing the charged pressure of the GM cryocooler. The objective of this research is to assess the effect of varying the charged pressure and the operating frequency.

THEORETICAL CONSIDERATIONS

The coefficient of performance (COP) of a cryocooler can be expressed as the ratio of the work of the refrigeration output to the work of the compressor. Equation 1 shows the equation for the theoretical COP of a GM cryocooler, which is based on the ratio of the *P*-*V* work to the isothermal

Cryocoolers 16, edited by S.D. Miller and R.G. Ross, Jr.

compression work.

$$COP_{GM} = \frac{W_{PV}}{W_{iso}} = \frac{(P_h - P_l)\,V}{mRT\,\ln(P_h / P_l)} \qquad (1)$$

where W_{PV} is the P-V work per cycle, W_{iso} is the isothermal compressor work (per cycle), P_h is the intake pressure, P_l is the exhaust pressure, V is the expansion volume, m is the mass flow rate (per cycle), R is the gas constant for helium, amd T is the compression temperature. Figure 1 shows a plot obtained using Eq. (1) for a temperature of 4.2 K together with the calculated Carnot efficiency at 4.2 K. It shows that the COP of the GM cryocooler becomes asymptotic to the Carnot COP as the compression ratio decreases. Reducing the compression ratio of a real GM cryocooler confirmed this improvement in the COP which has been proved by Nakagome et al.[1]

High Pressure GM Cryocooler

A pressure-resistant cold head corresponding to a high-pressure compressor unit containing a high-pressure compressor was designed in this experiment. Figure 2 shows the cold head. The cylinder thickness is larger than that in the testing machine for the RDK-101D. To simplify the

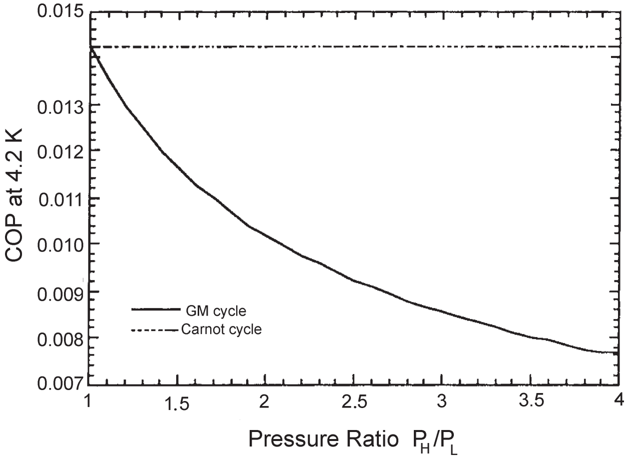
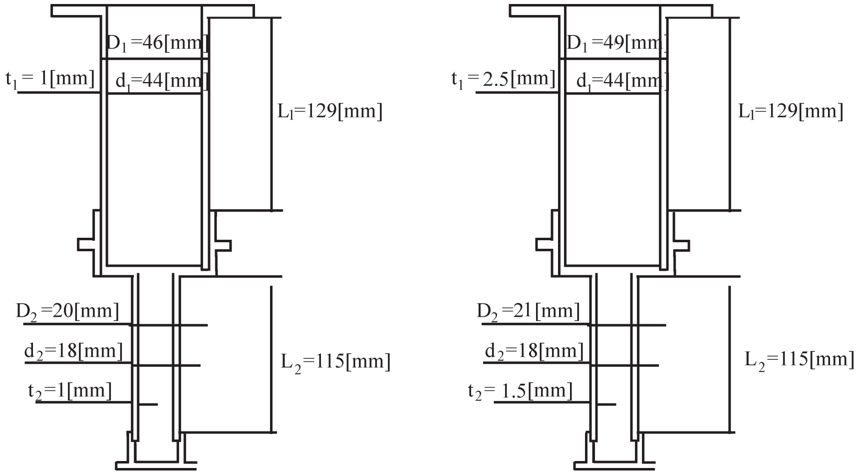


Figure 1. Pressure ratio dependences of GM and Carnot COP



(a) Conventional machine (RDK-101D) (b) Testing machine

Figure 2. Comparison of the a conventional cold head with the cold head for the testing machine.

efficiency comparison, the regenerator was evaluated for a single stage by not using two-stage in which there is no regenerator but solid bars of bakelite. The regenerator was a copper mesh. A high-pressure compressor was used, which is currently used in heat pumps (Fig. 3). This compressor was originally designed for CO_2, but it was modified to use helium. Figure 4 shows a flow chart for the pressure-resistant cold head and the high-pressure compressor.

METHODS

An experiment involving varying the operating frequency of the cryocooler was performed at rotational frequencies of 1.0, 1.8, and 2.0 Hz. Another experiment in which the charged pressure was varied was performed; in this experiment, the charged pressure of the testing machine was 2, 4, 6 MPa and that of the one-stage GM system (Sumitomo, RDK-101D) was measured to be 1.95 MPa. Each measurement compares the refrigeration capacity and efficiency with the heat load for heating inputs of 0, 3, 6, 9, 12, and 20 W. The parameter %Carnot was used to compare the cryocooler efficiencies at different refrigeration temperatures. %Carnot is the ratio of the actual COP (Eq. (2)) to the ideal COP (Eq. (1)).

$$COP_{real} = \frac{Refrigeration\ capacity}{Compressor\ electric\ power} = \frac{Q}{W} \tag{2}$$

$$\%Carnot = \frac{COP_{real}}{COP_{carnot}} \times 100 \tag{3}$$

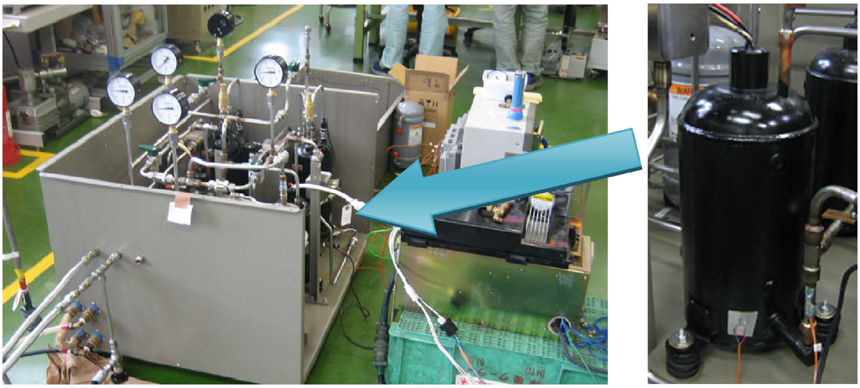


Figure 3. High pressure compressor and compressor unit

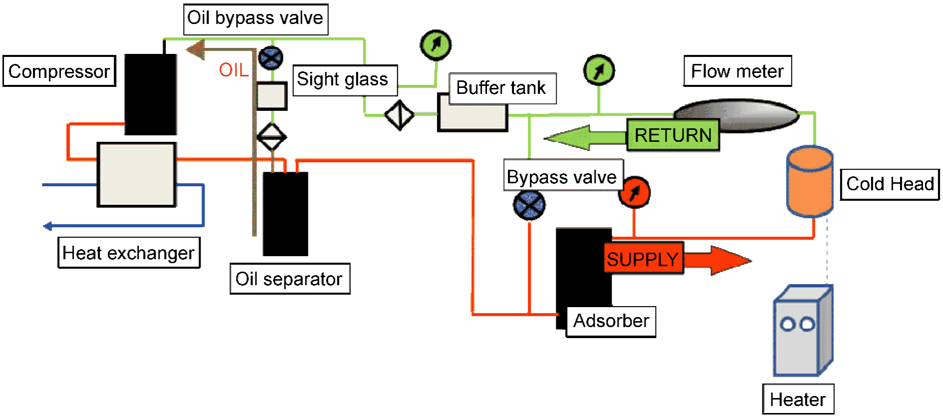


Figure 4. Flow chart of the testing machine

EXPERIMENTAL RESULTS

Figure 5 shows the refrigeration capacity for three different operating frequencies. Both the refrigeration capacity and %Carnot increase with increasing cryocooler operating frequency.

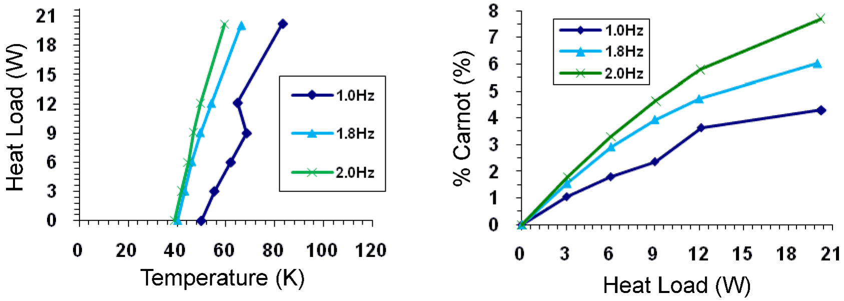
Figure 6 shows the refrigeration capacity for different charged pressures. Because of heat intrusion, the initial temperature of testing machine is higher than that of RDK-101D. When a heat load of over 12 W is input, the temperature of RDK-101D became higher than the testing machine which is caused by the high refrigeration capacity of the testing machine at a charged pressure of 4 and 6 MPa. Figure 7 shows %Carnot for different charged pressures. The %Carnot for a charged pressure of 4 MPa gave the best balance between the refrigeration capacity and power dissipation of the compressor.

Heat Intrusion

The cylinder thickness needed to be increased by a factor of 2.5 based on safety considerations to handle the high pressures used. The heat intrusion is estimated to be 7 W using the following equation:

$$Q_s = \pi D \times t\left(\Delta \int_{T_1}^{T_2} \lambda dT\right) \Big/ L \tag{4}$$

Figure 8 shows the heat intrusion as a function of refrigeration temperature. The difference heat load between testing machine and RDK-101D is considered for the difference of heat intrusion. Figure 9 shows the results of an experiment to investigate whether heat intrusion reduces the



(a) Refrigeration capacity (b) % Carnot

Figure 5. (a) Refrigeration capacity and (b) % Carnot for three operating frequencies

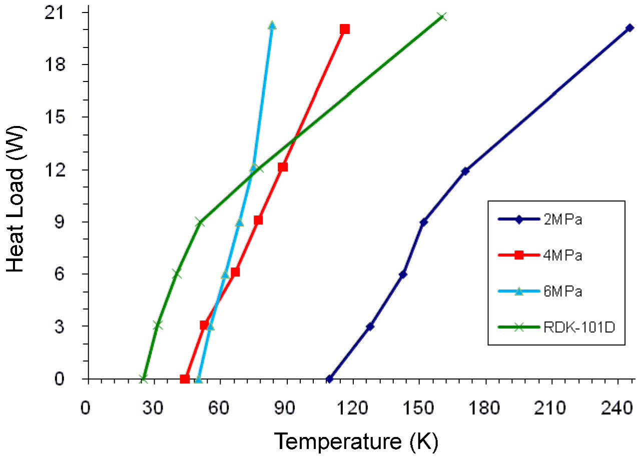


Figure 6. Refrigeration capacity for different charged pressures

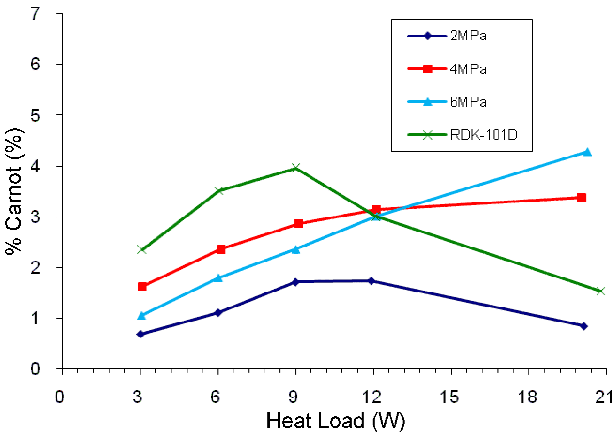


Figure 7. % Carnot for different charged pressures

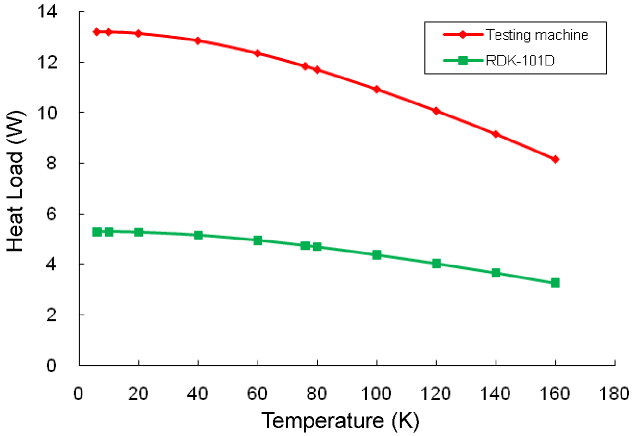


Figure 8. Heat intrusion as a function of refrigeration temperature

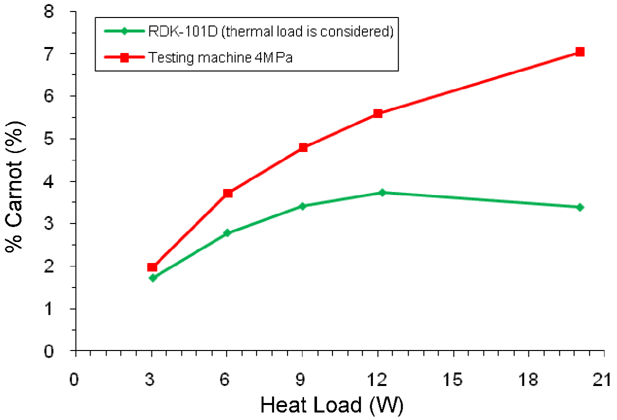


Figure 9. Effect of heat intrusion on the efficiency of the two systems

Table 2. The rates of increase of the efficiencies of RDK-101D and testing machine

Heat load [W]	%Carnot		Efficiency rate of increase
	Testing machine [%]	RDK-101D [%]	
3	1.98	1.72	15%
6	3.71	2.79	33%
9	4.79	3.41	40%
12	5.58	3.73	50%
20	7.04	3.39	107%

refrigeration capacity of the testing machine when heat intrusion of testing machine is assumed to the same heat intrusion of RDK-101D. %Carnot for the testing machine when the highest pressure (4 MPa) and heat load (7 W) were applied was compared with that of RDK-101D. Table 2 shows the rates of increase of the efficiencies of RDK-101D and the testing machine. When the heat load is taken into consideration, the testing machine is more efficient than RDK-101D. In particular, when the heat load is 20 W, the efficiency of the testing machine is twice that of RDK-101D.

SUMMARY

We have developed a high-pressure GM cryocooler that combines a high-pressure compressor (which was modified from CO_2 to helium-use) and a pressure-resistant cold head. We verified the performance of the cryocooler at high pressure. The efficiency was found to increase with increasing operating frequency. However, a high efficiency was not obtained even when a high charged pressure and a low pressure ratio were used. Since the high-pressure GM cryocooler had a thicker cylinder than conventional systems, its heat intrusion was higher. If there are no mechanical limitations, an improvement in the refrigeration efficiency of 15-107 % is expected.

ACKNOWLEDGMENT

This study is joint research with Mr. Nakajima or Mr. Iketani from Sumitomo Heavy Industries. The high-pressure GM cryocooler and RDK-101D used in this study were loaned from Sumitomo Heavy Industries. Valuable advice was received from Professor Nakagome, Dr. Numazawa, and Professor Masuyama.

REFERENCES

1. Nakagome, H., Okamura, T., and Usami, T., “Research on Improvement in the Efficiency of the GM Refrigerator,” *Cryocoolers 14*, ICC Press, Boulder, CO (2007), pp. 187-193.
2. Tsukagoshi, T., Matsumoto, K., Hashimoto, T., Kuriyama, T., Nakagome, H., "Optimum structure of multilayer regenerator with magnetic materials," *Cryogenics*, Vol. 37, Issue: 1 January 1997, pp. 11-14.