Research on Improvement in the Efficiency of the GM Refrigerator

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ABSTRACT

In moving toward a hydrogen energy society, a key focus of research has been on the development of fuel-cell electric vehicles. As the volume and weight density of liquid hydrogen are large, liquid hydrogen is seen as the preferred storage method over gaseous hydrogen. However, in order to store liquid hydrogen stably over a long period of time with minimal loss of energy, it becomes important to develop an efficient small cryocooler. In contrast, progress toward superconducting systems in recent years has been remarkable. Therefore, improvement in the refrigeration efficiency of 4 K cryocoolers desirves increased consideration.

This paper reports on research aimed at improving the refrigeration efficiency of a two-stage GM cryocooler. Because a GM cryocooler operates using Simon expansion, its coefficient of performance (COP) approaches that of the ideal Carnot cycle as the compression ratio is lowered. When investigated with this viewpoint, we have verified that GM refrigeration efficiency rises with reduction of the compression ratio. If the compression ratio is further lowered, refrigeration efficiency will fall rapidly. Thus, by optimization of the compression ratio of a GM cryocooler, it has been verified that refrigeration efficiency can be improved significantly. Application of the results of this research have the potential of sharply reducing the energy consumption of liquid hydrogen and superconducting systems.

INTRODUCTION

4 K GM refrigerators have been used in practice for a long time. Moreover, 20 K GM refrigerators are widely used in the world's cryopumping market and in many other applications. However, within the past ten years, little progress in improving the efficiency of GM refrigerators is apparent. In order for the superconductivity and liquid hydrogen markets to develop greatly from now on, extensive improvement of cryocooler efficiency will be indispensable.

We first observe that a GM refrigerator operates using the Simon expansion process, which is an irreversible cycle. Therefore, the efficiency of a GM refrigerator is lower than that of a Stirling refrigerator. However, since the thermal losses in a small refrigerator are large, the superiority or inferiority of the efficiency of an actual refrigerator does not necessarily correspond with the theoretical

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efficiency. We report here on experimental research to improve the efficiency of the GM refrigerator by lowering the compression ratio. Since many methods for improvement in the efficiency of small refrigerators are available, there are numerous opportunities for innovative research.

THEORETICAL CONSIDERATIONS

The coefficient of performance (COP) of a refrigerator can be expressed as the ratio of refrigeration output work to input compressor work. The theoretical coefficient of performance of a GM refrigerator using P-V work and isothermal compression work is shown in Equation 1.

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

where:
W_{PV} = P-V work (per cycle)
W_{iso} = Isothermal compressor work (per cycle)
P_h = Intake pressure
P_l = Exhaust pressure
V = Expansion volume
m = Mass flow rate (per cycle)
R = Gas constant of helium
T = Compression temperature

In Eq. (1) the intake pressure (P_h) and the exhaust pressure (P_l) serve as the principal parameters. Using Eq. (1) to calculate the COP for a temperature of 4.2 K gives the results shown in Figure 1. Also shown in Fig. 1 is the computed Carnot efficiency for 4.2 K. The figure shows that the COP of the GM refrigerator approaches the ideal Carnot COP as the compression ratio falls. To verify that this improvement of COP with decreasing pressure ratio also occurs in an actual GM refrigerator, we conducted an experimental investigation.

EXPERIMENTAL PROCEDURE

The experimental device and measurement points are shown in Fig. 2; Table 1 summarizes the cold head specifications. The compression ratio was changed by adjusting a bypass valve, and the isothermal work of the compressor was computed by measuring high pressure, low pressure, and mass flow rate.

Experiments at coldend temperatures of 4.2 K and 20 K were conducted using cylinders of three sizes. The regenerator materials that were used are shown in Table 2. The first regenerator used a hybrid construction of copper mesh and lead spheres. In contrast, the second regenerator used a three-layer structure of lead, Er_3Ni, and $HoCu_2$.

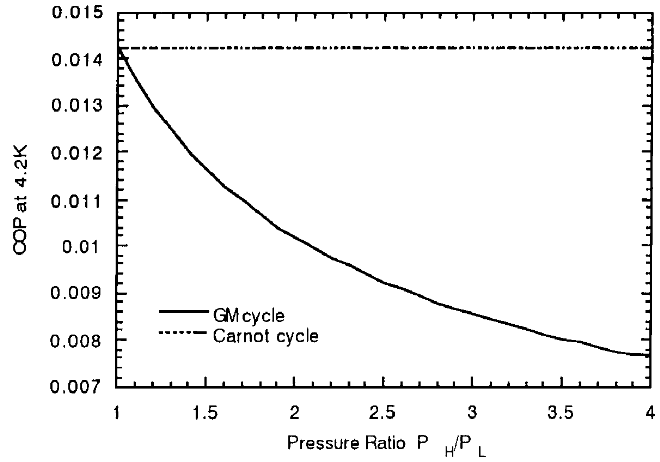

Figure 1. Pressure ratio dependence on COP_{GM} and COP_{Carnot}.

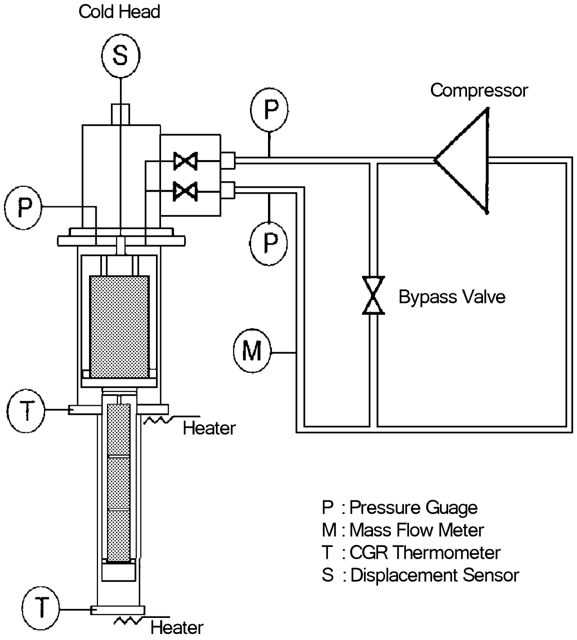

Figure 2. Flow diagram of GM refrigerator.

Table 1. Detailed dimensions of cold heads.

Cold head	1st Cylinder		2nd Cylinder		Stroke of Displacer (mm)
	Diameter (mm)	Length (mm)	Diameter (mm)	Length (mm)	
32/70	70	220	32	252	20
40/80	80	260	40	252	32
56/90	90	260	56	252	32

Table 2. Regenerator composition.

Cold head	1st regenerator			2nd regenerator		
	Internal diameter (mm)	Internal length (mm)	Regenerative materials (volumetric ratio)	Internal diameter (mm)	Internal length (mm)	Regenerative materials (volumetric ratio)
32/70	50	160	Cu mesh +Pb (80:20)	28	160	Pb+Er_3Ni+$HoCu_2$ (45:35:20)
40/80	55	210	Cu mesh +Pb (75:25)	35	160	Pb+Er_3Ni+$HoCu_2$ (45:20:35)
56/90	64	210	Cu mesh +Pb (75:25)	50	160	Pb+Er_3Ni+$HoCu_2$ (45:20:35)

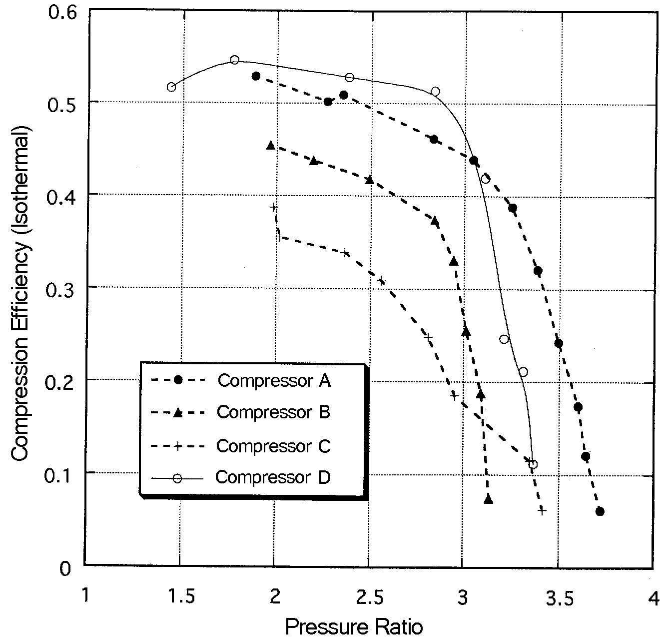

Figure 3. Measured value of compression efficiency.

In order to estimate the actual input electric power from the measured isothermal work of the compressor, a representative efficiency of the compressor was determined. The efficiencies of four kinds of compressors against compression ratio are shown in Fig. 3. From these results, we chose to model compressor efficiency as a constant value of 0.48 for all compression ratios.

EXPERIMENTAL RESULTS

When beginning an experiment from the state where the bypass is closed, opening the bypass valve causes the compression ratio to fall. The experimental results for the 4K level are shown in Fig. 4 for the 40/80 cold head. With the fall of the compression ratio, refrigeration capacity de-

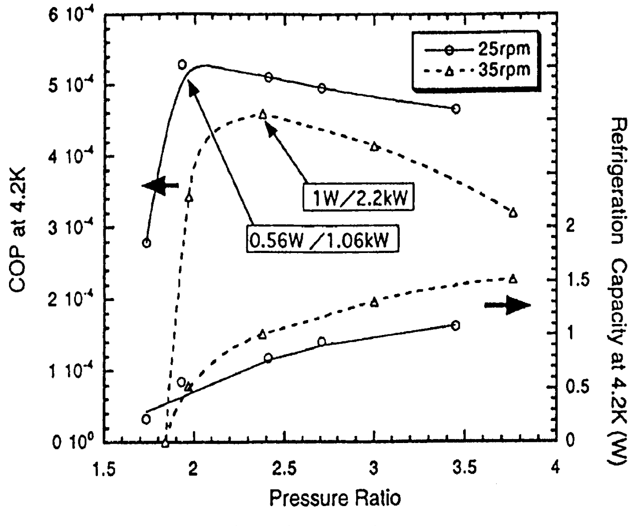

Figure 4. COP and Refrigeration capacity at 4.2K.(40/80 Cold Head).

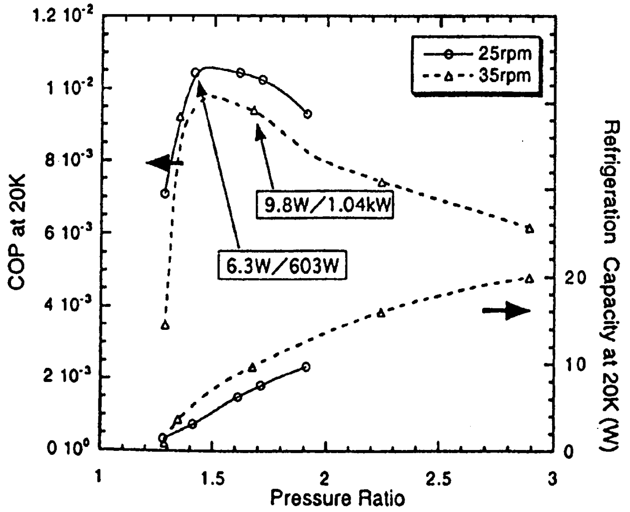

Figure 5. COP and refrigeration capacity at 20K (40/80 cold head).

creases monotonically. On the other hand, COP increases gradually compared with the state of a high compression ratio. At a compression ratio of 2 -2.5, the COP shows a peak; then it decreases rapidly. The peak value of COP corresponds to a refrigeration capacity of 1 W (reciprocating speed: 35 rpm) and an input electric power to the compressor of 2.2 kW. Moreover, when the reciprocating speed was 35 rpm, 0.56 W (4.2K) refrigeration capacity was achieved for 1.06 kW of compressor electric power. Although Fig. 5 shows the experimental results for a temperature of 20 K, the observed trend was also the same at 4 K.

Table 3 shows typical values from all of the data, including the results shown in Figs. 4 and 5. The compressor electric power required for a refrigeration capacity of 0.5W at 4 K is about 1 kW, and about 2 kW of electric power is needed to achieve 1 W at 4.2 K. Compared with the work of H.J.M.ter Brake et al.[6], the value of %Carnot improves about 4 times. On the other hand, at 20 K about 10 W of refrigeration capacity was achieved with 1 kW of compressor electric power. In the case of the same compressor electric power, the refrigerating capacity at 20K was about 10 times

Table 3. Arrangement of refrigeration performance for 4.2 K and 20 K.

4.2K Refrigerator

	Refrigeration Power	Input Power	COP	%Carnot
Cold head	W	W	$(\times 10^{-4})$	%
32/ 70	0.34	780	4.3	3.1
40/ 80	1	2200	4.8	3.4
	0.563	1064	5.3	3.8
56/ 90	2	3340	5.95	4.25

20K Refrigerator

	Refrigeration Power	Input Power	COP	%Carnot
Cold head	W	W	$(\times 10^{-3})$	%
40/ 80	6.3	603	10.4	14.6
	9.8	1040	9.5	13.4

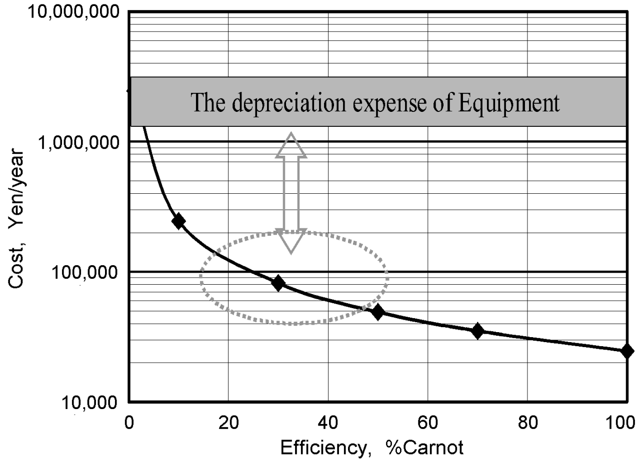

Figure 6. Annual electricity cost versus %Carnot (1$: 110Yen) .

that at 4 K. Moreover, this result was 2 to 3 times the efficiency at 20 K (5%Carnot) of a conventional refrigerator. Next, we examine these result from the viewpoint of economic efficiency.

ECONOMIC EFFICIENCY ESTIMATION

Here, we consider a liquid hydrogen station for supplying liquid hydrogen to a fuel-cell electric vehicle. Beneath the ground of a station there is a large liquid hydrogen tank, and the boil off of hydrogen is prevented using a 20 K GM refrigerator. Therefore, the GM refrigerator will be in continuous operation throughout the year. Figure 6 compares the annual electric cost of the GM refrigerator with the depreciation expense of the equipment. Usually, the depreciation expense of the equipment occupies a large portion (for example, ten percent or more) of the annual required cost. From the figure, when the efficiency of a refrigerator reaches 20-40% Carnot, it turns out that it becomes a sufficiently low rate. With this experimental result, since efficiency was about 14%Carnot, there is still value in further efficiency improvement.

In the case of the 4 K refrigerator, it is more difficult to find the conditions of economical efficiency. For example, in the case of a superconductive MRI, since it is an instrument that needs electric power like a power supply in addition to a refrigerator, there is a view that a compressor electric power of 10 kW or less seldom poses a problem.

Figure 7 summarizes the amount of the electric power used by a room air conditioner. The amount of electric power used also increases as the floor space (m^2) of the room increases. Typically, with a 120 V line voltage, the maximum appliance load is a little over a 1000 W; for larger loads, the appliance will use 240 V. Although a room air conditioner is a home electronics product that draws a substantial amount of electric power, the maximum for home use is probably about 2500-3000 W. Therefore, if the operating power of a 4 K refrigerator is roughly the same as a room air conditioner, it will be a system that is easy to use under most service conditions. When considered from such a viewpoint, being able to operate a 4 K GM refrigerator with an input power of 1000-2000 W is quite enabling.

CONCLUSIONS

It has been shown that, by lowering the compression ratio of a GM refrigerator, the efficiency at a coldend temperature of either 4.2 K or 20 K can be improved. As a result, a refrigeration capacity of 1 W at 4.2 K can be obtained with a 1 kW compressor, and about 10 W capacity can be expected at 20 K. It was also shown that this improvement in efficiency (%Carnot) of a 20 K GM refrigerator is quite valuable in terms of the econmomics of use in consumer markets. With respect to a 4 K GM

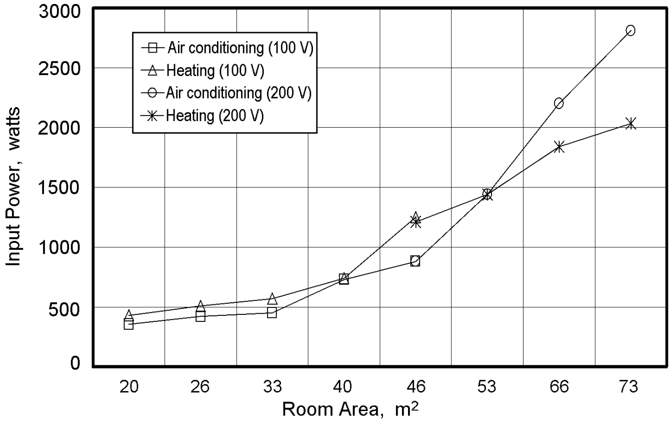

Figure 7. Power consumption of a room air conditioner.

refrigerator, an important consideration is achieving an input electric power in the 1-2 kW level. At this level, it too will be in a range where its electricity usage is comparable to other common home electronics. Improving refrigeration efficiency in the future is highly desirable for the birth and further expansion of important consumer markets.

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