BNL-66747

Presented at Cryogenic Engineering Conference and International Cryogenic Materials Conference
July 12~16, 1999, Montreal, Canada

STUDY ON THE VOLUMETRIC RATIO OF THE HYBRID GM REGENERATOR OVER THE COLD CHAMBER WORKING AT 4K

L. Wang,[1] X. D. Xu,[2] L. Fang,[2] L. Zhang,[2]

[1]Brookhaven National Laboratory
Upton, NY 11973, USA
[2]Cryogenic Laboratory, Chinese Academy of Sciences
Beijing 100080, China

ABSTRACT

This paper presents a computational analysis on the hybrid GM regenerator at liquid helium region. The effects of the ratio of the regenerator volume over the cold chamber volume on cooling performance were simulated numerically. The results show that there exits a minimum ratio of the regenerator volume over the cold chamber volume for a G-M cryocooler at 4K. The cooling capacity of the refrigerator drops sharply with smaller regenerator, and rises slowly with larger regenerator. The effects of the material combinations of the hybrid regenerator on the volumetric ratio were also studied. The design principle of the geometry size of the regenerator working at 4K was discussed.

NOMENCLATURE

A	Heat transfer area
C	Volumetric specific heat
h	Specific enthalpy of fluid
m	Mass of control volume
$\dot{m}$	Mass flow
P	Pressure
Q	Heat exchange
T	Temperature
t	Time
V	Volume

Greek letters

α	Heat transfer coefficient

Subscripts

i	The i-th control volume
w	Matrix of control volume
f	Boundary of control volume, or gas flow

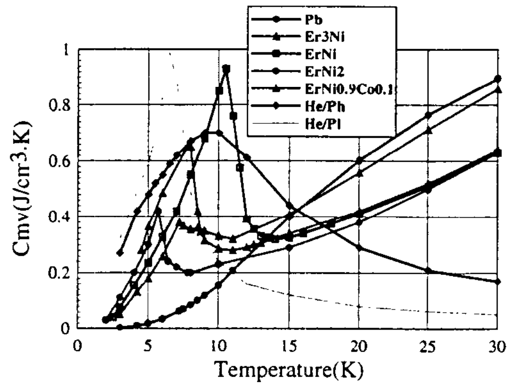

Figure 1. Volumetric specific heat of the regenerator materials[1]

INTRODUCTION

The heat of compression of helium gas causes the major loss on cooling capacity of the 4K GM cryocooler, because of the non-ideal physical properties of helium and the low specific heat of the regenerator materials near 4K region. The specific heat of matrix at the cold end of the regenerator is the key factor for further improving refrigerator performance[2][3][4]. At present, to obtain larger cooling capacity and increase regenerator efficiency, hybrid regenerators are greatly developed[5][6]to compensate the narrow peak of the specific heat of a single magnetic material, as shown in Figure 1. It has been realized through early numerical analyses[7] and experimental investigations[8][9] that the combinations for currently used materials and the ratio for the materials packed in the low temperature regenerator have larger effects on the cooling performance.

In this paper, we mainly studied the effects of the ratio of the volume of the regenerator with multi-layered materials over the cold chamber volume on cooling performance by numerical method. The effects of different combinations of materials on the volumetric ratio are also analyzed in detail. The design principle of the geometry size of the regenerator working at 4K was discussed.

NUMERICAL SIMULATION

The physical model is shown in Figure 2, including the regenerator with multi-layered hybrid materials, the cold end heat exchanger and cold chamber. The right hand side is the surface of the imaginary piston. The regenerator was assumed stationary. At the left hand side, pressure oscillation[2] is given in Figure 3. The basic assumptions in the model are: one-dimensional flow of gas, negligible heat conduction and axial pressure drop, and constant wall temperature of the cold chamber. The fundamental equations are as follows:

The mass equation for gas flow:

$$\frac{\partial m_i}{\partial t} = \dot{m}_{f_{i+1}} - \dot{m}_{f_i} \qquad (1)$$

The energy equation for gas:

$$\frac{\partial(mh-PV)_i}{\partial t} = (\dot{m}h)_{f_i} - (\dot{m}h)_{f_{i+1}} + \frac{\delta Q}{dt} - P_i \frac{dV_i}{dt} \quad (2)$$

Where $\delta Q = \alpha_i \cdot A_i \cdot (T_{wi} - T_i) \cdot dt$ (3)

The energy equation for the matrix in regenerator:

$$C_{mi} \cdot V_{mi} \cdot \frac{\partial T_{wi}}{\partial t} = \alpha_i \cdot A_i \cdot (T_i - T_{wi}) \quad (4)$$

It should be noted that the mass flow rate is defined as positive if the gas flows from the hot end to the cold one of the regenerator and as negative for the opposite direction. The real gas properties of helium were obtained from the NIST TN-1334. The heat transfer coefficient was from the reference[10]. A Finite difference method was used to solve the above equations[3][7]. The volume change of the cold chamber with the crank angle is also shown in Figure 3.

COMPUTATIONAL RESULTS AND ANALYSES

Main Calculation Parameters

The main calculation parameters of regenerators are shown in Table 1. The temperatures of the inlet gas and that at the wall of the cold chamber are 30K and 4.2K, respectively. The intake/exhaust opening and closing angles are 320°/145 ° and 130 ° /305 °. The volumetric ratios of three kinds of materials from the hot end to the cold end in regenerators are 40%, 30%, and 30% in sequence[6]. The volumetric ratios of two kinds of materials from the hot end to the cold end in the regenerators are both 50%. Lead sphere, ErNi, Er_3Ni, $ErNi_2$ and $ErNi_{0.9}Co_{0.1}$ grains were used for the regenerator materials.

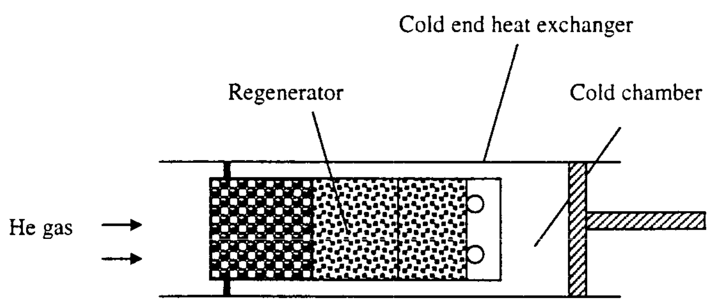

Figure 2. Physical model of the hybrid regenerator

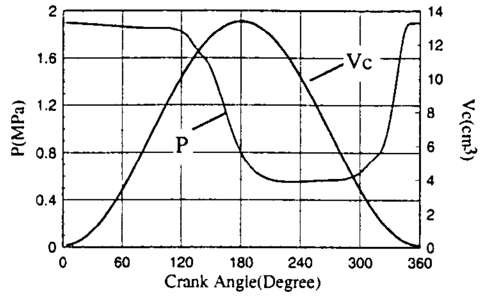

Figure 3. Pressure oscillation at the hot end of the regenerator

Computational Results and Analyses.

The calculation results are shown in Figure 4-6. T_f is the temperature of helium gas in the regenerator. Q_c is the cooling capacity. V_r/V_c is the ratio of the regenerator volume over the cold chamber one. In this paper, the cold chamber volume and the regenerator diameter constant, the variation of V_r/V_c means the change of the length size of the regenerator.

Figure 5 shows the effect of the ratio V_r/V_c on the cooling capacity Q_c and the effect of different combinations of materials in regenerators on the cooling capacity under different V_r/V_c. From the figure one can observe that with V_r/V_c increasing, Q_c increases. For the multi-layered regenerator composed of lead spheres, Er_3Ni, and $ErNi_2$ grains, when V_r/V_c is larger than 4.5, the cooling capacity rises slowly. For example, Q_c rises 12% with V_r/V_c from 2.86 to 4.30. However, it's only 1% with V_r/V_c from 5.44 to 6.3.

Figure 4 gives the temperature distribution of gas flow in regenerators under different V_r/V_c. By comparison, the gas temperature distribution in the regenerator with V_r/V_c =2.86 is higher than that in the regenerator with V_r/V_c=5.44 at the end of gas admission process of the refrigerator. There exits larger temperature range near 4.2K at the regenerator cold end for the latter than that for the former. For the former, the high temperature portion moves further towards the cold chamber. The gas temperature of the former entering the cold chamber becomes higher, and Qc is greatly reduced. With V_r/V_c increasing, the temperature region near 4.2K becomes larger, and then the gas temperature into the cold chamber lowers down, so Qc is enhanced. On the other hand, it is known that[1] the dominant heat loss for a 4K GM cryocooler is the compression heat of gas in the voids at the cold end of the low temperature regenerator. During the cycle the compression heat is partially stored in

Table 1. Main calculation parameters of regenerators

Regenerator: diameter (mm)	22
Length (mm)	190
Materials	Pb, Er_3Ni, $ErNi_2$, ErNi, $ErNi_{0.9}Co_{0.1}$ grains
Porosity	0.41
Stroke (mm)	25

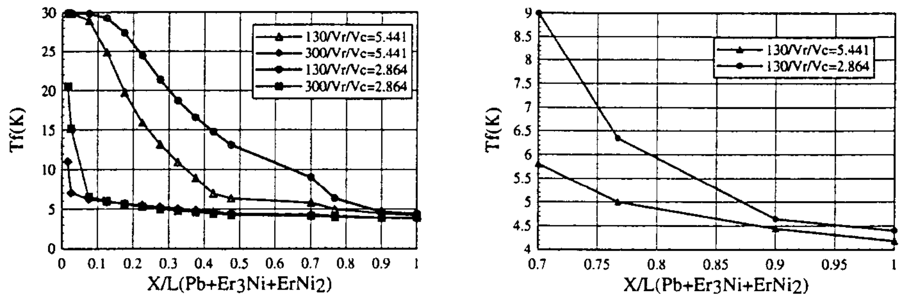

Figure 4. Temperature distribution of gas flow in the regenerators under different V_r/V_c

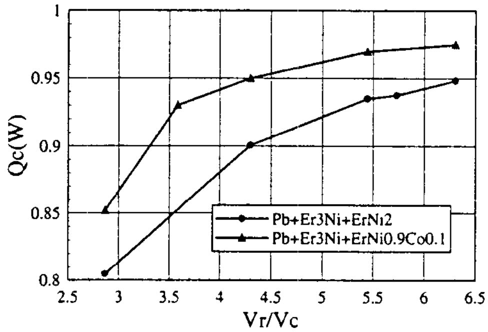

Figure 5. Effect of the ratio of the regenerator volume over the cold chamber one on the cooling performance and effect of different combinations of materials in regenerators on the cooling capacity under different V_r/V_c

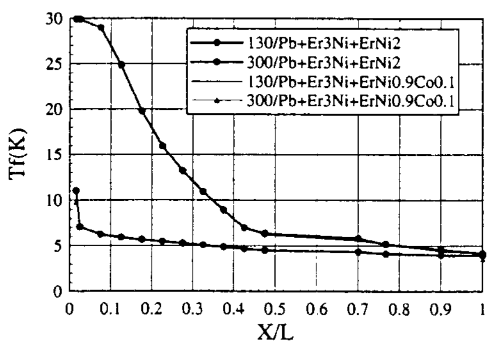

Figure 6. Temperature distribution of gas flow in regenerators with different combinations of materials

the regenerator matrix. The rest of the heat is carried into the cold chamber by the compressed gas, causing the reduction of Qc. The stored heat is determined by the ratio of the volumetric heat capacities of the matrix and of the helium in the regenerator voids at the temperatures of compression. When the matrix at liquid helium region is chosen, the compression heat stored in the regenerator matrix is almost constant. With the further increasing of V_r/V_c, Qc increases slightly. As a result, there is the minimum ratio V_r/V_c for a 4K GM refrigerator. In order to enhance the cooling capacity greatly, the matrix with high specific heat should be used.

Figure 5 also gives the comparison between the regenerator composed of lead spheres, Er_3Ni, and $ErNi_2$ grains (named the former) and that composed of lead spheres, Er_3Ni, and $ErNi_{0.9}Co_{0.1}$ grains (named the latter). The two regenerators were made up of the same materials at the hot end and different matrix at the cold end. We can find that the minimum ratio V_r/V_c of the latter is smaller than the former. For the former, $V_r/V_c=4.2$ may be the minimum size. For the latter, it is 3.6.

According to Figure 1 and Figure 6, the volumetric specific heat of $ErNi_{0.9}Co_{0.1}$ is a little higher than that of $ErNi_2$ near 4K, and the temperature of gas at the cold end of the former flowing into the cold chamber is slightly higher than that in the latter. The compression heat ratio stored in the regenerator of the former is approximately 67% and the latter is about 90% at 4K. Therefore, with the same size of the regenerator, the cooling capacity of the latter is larger than that of the former. To obtain the same cooling capacity as that of the latter, the large size for the former may be used. However, because the specific heat of the matrix at 4K region is the critical factor for the enhancement of Qc, to simply increase the size of the regenerator can not completely make up for low specific heat at the regenerator cold end.

In addition, by comparing the two regenerators with the same materials at the cold end, we found that the small geometry size can be used for the regenerator that is composed of the materials with high specific heat at the hot end.

CONCLUSIONS

1. There exits a minimum ratio of the low temperature regenerator volume over the cold chamber volume for a G-M cryocooler at 4K. The cooling capacity of the refrigerator drops sharply with smaller regenerator, and rises slowly with larger regenerator.
2. The minimum volumetric ratio should ensure that there is the gas temperature region near 4K at the cold end of the hybrid regenerator.
3. To simply increase the size of the regenerator can not completely make up for low specific heat at liquid helium region because the specific heat of the matrix at 4K region is the critical factor for the enhancement of Qc.
4. Low specific heat at the regenerator hot end can be compensated by properly increasing the geometry size of the regenerator.

ACKNOWLEDGMENT

This research was supported by the National Natural Science Foundation of China.
U.S. Department of Energy, Contract #DE-AC02-98CH10886.

REFERENCES

1. G. Ke, et al., Improvement of two-stage GM Refrigerator Performance using a hybrid regenerator, *Advance in Cryogenic Engineering*, 40A: 639(1994)
2. C. S. Hong and X. D. Xu, On the Thermodynamic Cycle of the Low Temperature G-M Refrigerator, *Cryogenics*, 34: 183, ICEC Supplement (1994)
3. L. Wang et al, A Numerical Simulation Method of a Two-stage G-M Refrigerator and Comparison with Experiment, *Advance in Cryogenic Engineering*, 43: 1799(1998)
4. X.D.Xu, L. Wang et al, Analysis on the Colder Regenerator of 4.2K G-M Refrigerator, *Advance in Cryogenic Engineering*, 43: 1605(1998)
5. A. Onishi et al, Development of 2W Class 4K Gifford-McMahon Cycle Cryocooler, *ICEC16/ICMC Proceedings*, Part 1: 335(1996)

6. T. Tsukagoshi et al, Optimum Structure of Multilayer Regenerator with Magnetic Materials, *Cryogenics,* 37:11(1997)
7. L. Wang et al, Performance Analysis of the Low Temperature Regenerator with Multi-Layered Hybrid Materials, *Proceedings of ICEC17,* 315(1998)
8. T. Tsukagoshi et al, Refrigeration Capacity of a GM Refrigerator with Magnetic Regenerator Materials, *Advance in Cryogenic Engineering,* 41: 1623(1996)
9. T. Hashimoto et al, Excellent Character of Multi-layer Type Magnetic Regenerator near 4.2K, Cryocoolers 8, 677(1995)
10. Kays, W.M. and London, A.L., *Compact Heat Exchangers* 2nd Edn(1964).