Investigation of a single-stage G-M refrigerator with high cooling capacity for HTS devices

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Because the cooling of HTS device needs the cryogenic refrigerator working at 30 K, and the investigation of HTS devices are more and more considerable, the requirement for the G-M refrigerator with the cooling capacity of 50 W/30 K increases gradually. But there is no any product of the G-M refrigerator that can meet the request of cooling HTS device. In the paper we summarized the experimental work of single-stage G-M refrigerators. At present, we can get the lowest temperature of 17 K operating at 1 Hz. The cooling capacity of 27 W has been obtained at 30 K.

INTRODUCTION

In order to operate high temperature superconducting (HTS) applications under high magnetic field, liquid nitrogen is not sufficient since the temperature between 20~30 K has to be maintained continuously in order to achieve the goal of super-conduction [1,2]. Since conventional single stage G-M refrigerators cannot reach the temperature below 20 K, they cannot provide the high cooling capacity at 30 K. At the same time, the conventional double stage G-M refrigerators have a lowest temperature of the second stage, about 7 K. However, they are not efficient in the temperature range of 30~50 K. Therefore the conventional single and double stage G-M refrigerators cannot achieve the goal of cooling HTS devices. Now we are developing the single-stage G-M refrigerators that can supply the high capacity, high efficiency, and 50 W/30 K cooling requirement.

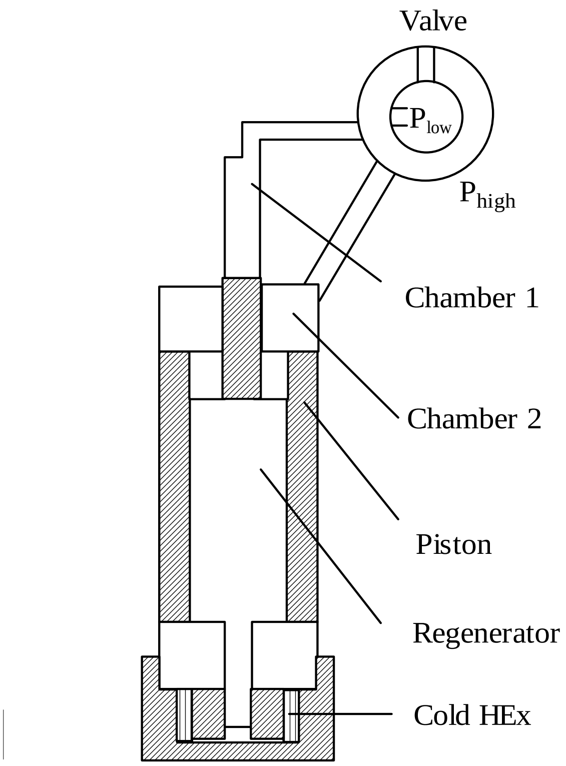

Figure 1 Schematic diagram of the G-M refrigerator

DESIGN PRINCIPLE OF THE SINGLE STAGE G-M REFRIGERATOR

The movement of the displacer is achieved by an unbalance of pressures in the variable chambers, resulting from the delivery and exhausting of gas through the rotary valve. The timing of the movement is achieved by the rotation of the valve disc on the stationary valve plate. Depending on the location of the valve disc, the supply pressure to chambers 1 and chamber 2 may be high or low [3]. Depending on the angle difference of the valve disc, cooling capacity and the bottom temperature of the cold head will change with the timing of the exhausting and delivery. Figure 1 shows the schematic diagram of the G-M refrigerator.

The theoretical calculation of the heat-loss is listed below, as Table 1 shows.

Table 1 Analysis of heat-loss of single-stage G-M cycle

List	Parameter	Calculation value（W）	Percentage of supplied
1	Theoretical Cooling power	175.8	
2	Actual Cooling power	—	
3	Loss		
3.1	P-V Loss	—	~40%
3.2	Conduction Loss	9.68	5.5%
	(a) Cylinder	(6.99)	—
	(b) Piston	(0.34)	—
	(c)Regenerative material	(2.35)	—
3.3	Motional heat loss	38.5	21.9%
	(a) Shuttle loss	(20.9)	—
	(b) Pump loss	(17.6)	—
3.4	Regenerative loss	13.6	7.7%
3.5	Radiation loss	0.209	1.2%

DEVELOPING THE SINGLE STAGE G-M REFRIGERATOR FOR HTS DEVICES

With the help of numerical simulation of single stage G-M refrigerator, we have assembled a single stage G-M refrigerator for HTS devices. The results of experiments and analysis of the results will be presented below, which will give us a way to develop a more efficient G-M refrigerator.

Influence of stroke on the capability of refrigerator

The ideal theoretical cooling capacities of each cycle were associated with the stroke, which is the main factor of cold chamber volume.

Both the bottom temperature of cold head and the cooling capacities depend on the displacer stroke. The lower temperature, 26.6 K, was obtained with 25 mm stroke, while 32.6 K of bottom temperature with 20 mm stroke. The lowest temperature may be limited by the regenerator efficiency and shuttle loss. The E1, E2 represents the corresponding experimental results of 20 mm and 25 mm displacer stroke. Table 2 gives us the results of the experiments E1, E2.

Table 2 The bottom temperature and drop speed of E1、E2

Experiment	Drop speed（K/min）	Bottom Temperature (K)
E1	8	32.6
E2	9	26.6

Influence of heat exchanger on the capability of refrigerator

The development of heat exchanger or cold head is the most important part. How to transfer the heat efficiently is the key point of the refrigerator. At first, we utilize the bronze screen to increase the heat transfer area. Figure 1 may present us some schematic diagram of cold head exchanger. Later, we use the conventional heat exchanger. F1, F2 indicate the results of different kinds of cold heat exchanger.

Table 3 Results of experiments (F1、F2)

Experiment	Drop speed (K/min)	Bottom temperature (K)	P_h/P_l (MPa/MPa)
F1	8	26.6	2.4/0.62=3.9
F2	9	17.7	2.4/0.45=5.3

We analyze the results and list the reasons as follows:

The former design has the character of large heat transfer area and high heat exchange efficiency. At same time the pressure loss was very big.

The conventional design makes good use of the narrow channels to pass through the He medium. The flow resistance and the empty volume loss are very small. But both the heat transfer area and coefficient cannot supply the efficient heat transfer.

Influence of different rotation frequency on the capability of refrigerator

The rotation frequency is associated with the moving way of displacer and intake and exhaust of high pressure and lower pressure gas. Meanwhile much conventional loss is also laid on the moving way, such as the shuttle loss, pump loss. Figure 2 and Figure 3 presented us the bottom temperature and cooling power of cold head at different frequency. Adjusting rotation frequency actually changed the timing of intake and exhaust.

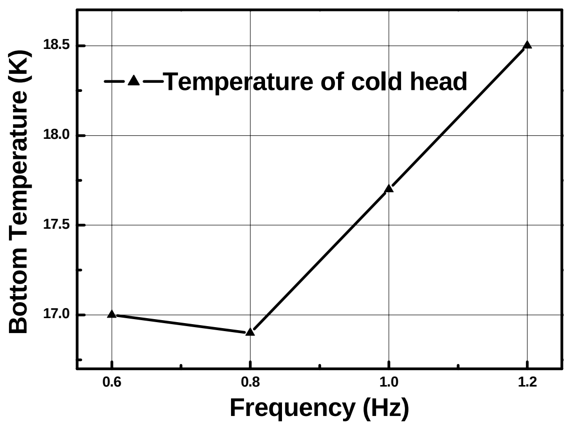

Figure 2 Bottom temperature at different rotation frequency

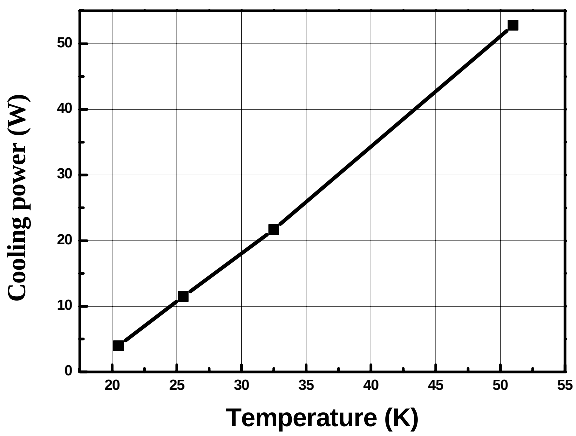

Figure 3 The cooling power of cold head

Influence of ratio of regeneration to cold chamber volume on the capability of refrigerator

The results of numerical simulation show us the relation between the loss of regenerator and the ratio of Vre/Vo. See Figure 4 below.

At different ratio of Vre/Vo, we can almost get the same bottom temperature of cold head. When Vre/Vo equates 5.1, the bottom temperature is 17.7 K while 18.0 K at 6.2. At fact, we can make the conclusion that the volume of regeneration is sufficient.

Influence of ratio of regenerative material on the capability of refrigerator

For the different specific heat of regenerative material, the ratio of regenerative material may influence the capability of regenerator. Figure 5 gives the curve of the loss of regenerator at different ratio of Lcu/Lregeneraor. Lcu and Lregeneraor represent the length of Cu regenerative material and the length of the whole regenerator, respectively. Table 4 shows us the results at different ratio of $L_{Cu} / L_{Re.}$

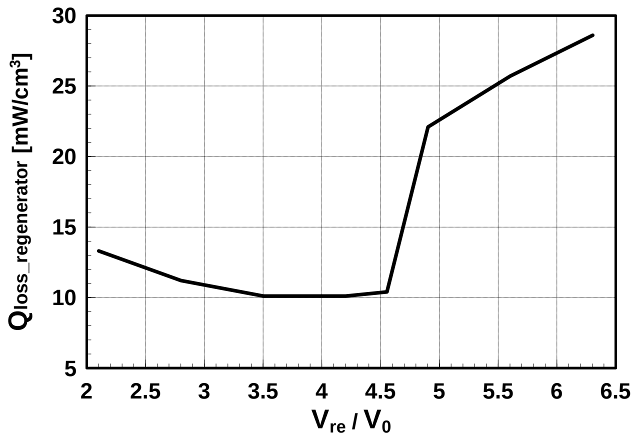

Figure 4 Loss of regenerator with the ratio of Vre/Vo

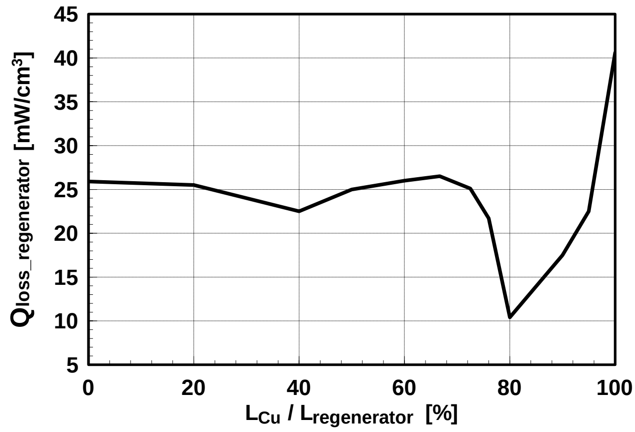

Figure 5 Loss of regenerator with the ratio of Lcu/Lre

We can find that the capacity of refrigerator varied with the ratios of Lcu/Lre. The temperature field of the regeneration was related with these two regenerative materials for the different specific heat. 70% may be the optimum value of Lcu/Lre through experiments.

Table 4 Results of experiment at different ratio value of L_{Cu} / L_{Re}

Experiment	L_{Cu} / L_{Re}	Drop speed (K/min)	Bottom temperature (K)	Ph/Pl (MPa/MPa)
H1	0.785	9	26.6	2.3/0.6=3.9(ZC40)
H2	0.70	8	17.7	2.4/0.45=5.3(ZC60)
H3	0.73	8	18.1	2.35/0.44=5.3(ZC60)

Note：ZC40/ZC60 represent the type of compressor

CONCLUSIONS

The single stage G-M refrigerator with high reliability, high capacity and high efficiency can meet 30 K cooling requirements of many of the new HTS devices. We can get the cooling power of 27 W at the 30 K and 17 K of the bottom temperature. The heat exchanger is the key part of the refrigerator in the future. We will show new results of single stage G-M refrigerator for HTS devices.

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