A Large Single-Stage GM Cryocooler for Operating Temperatures of 13-30K

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ABSTRACT

A single-stage, low temperature Gifford-McMahon (GM) cryocooler, Cryomech Model AL630, has been developed to provide large cooling capacities at the temperatures of 20-30 K. The GM cryocooler has been designed and experimentally optimized with respect to structure and operating parameters. The performance of the cryocooler has been studied with different spherical regenerative materials at the low temperature region of the regenerator, such as Sn, Pb and Er3Ni. The optimum operating frequency has been successfully reduced from 2.0 Hz to 1.4 Hz for increasing meantime between maintenance (MTBM). So far, the single stage GM cryocooler can reach a minimum temperature of ~12 K, and provide 104 W of cooling at 20 K and 204 W of cooling at 30 K while consuming ~13 kW of electrical power.

INTRODUCTION

Applications of cooling high temperature superconductors and liquefying hydrogen require large cooling capacities between 20 and 30 K. A normal single stage Gifford-Mcmahon (GM) cryocooler has a low cooling temperature between 20 and 25 K and cannot provide a high cooling capacity at 30 K. The conventional two-stage GM has a bottom temperature around 7 K with the second stage, but is not efficient in the temperature range of 20 to 30 K.

Two–stage Stirling cryocoolers with large capacities at 25 K have a low COP of 0.45% [1]. The maintenance interval of these Stirling cryocoolers is only a few thousand hours and is too short for these applications.

Low temperature, single-stage GM cryocoolers had been developed at Cryomech, Inc. by introducing lead spheres in the lower portion of the regenerator. These cryocoolers demonstrate high cooling capacity (up to 100 W @ 25 K) and efficiency (~1.0 % of COP at 25 K) [2,3] at a low temperature range of 20 K to 40 K. The single stage GM cryocoolers are work horses for many High Temperature Superconductivity (HTS) devices being developed in laboratories and industry.

To respond to the market demand, we have developed a single stage GM cryocooler, Model AL630, to provide large cooling capacities from 20 to 30 K based on Cryomech largest compressor model CP1114. This paper presents the development results of the single stage GM cryocooler.

DESIGN OF THE GM CRYOCOOLER

Figure 1 shows a photo of the AL630 cold head and Figure 2 shows the cutaway of the GM cold head. The AL630 takes a standard GM cryocooler design made by Cryomech [2,3]. It has a

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Figure 1. Photo of the AL630 cold head

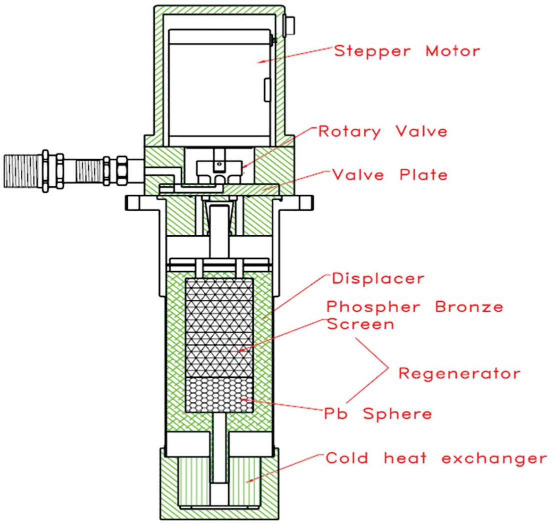

Figure 2. Schematic of the GM cold head.

pneumatically driven displacer. The rotary valve at the warm end of the cold head is for gas distribution. The cold head motor is a DC stepper motor, which can be programmed to change the operating frequency of the cold head. The regenerator consists of two layers of regenerative materials: Phosphor Bronze screens in the upper part and spherical materials with higher low-temperature specific heat in the lower part.

The compressor for the system is a Cryomech model CP1114 with nominal power input of ~13 kW. It uses a helium scroll compressor module.

RESULTS AND DISCUSSION

In the prototype testing of the AL630, the regenerator, displacer stroke and displacer frequency were optimized. The initial tests were performed with a static pressure of 1687 kPa. The pressure was then optimized for maximum performance and optimal system life.

At the beginning of testing, an interesting phenomenon was found during the cool-down process. The cold head heat exchanger reaches a minimum temperature of 12.5 K in ~60 min and then

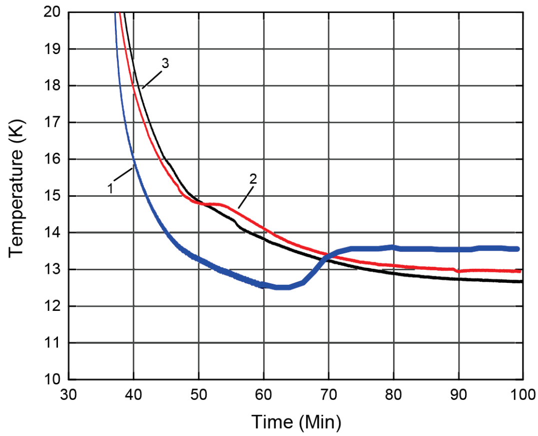

Figure 3. Cool-down curves of the AL630 with three regenerator packings. 1. Regenerator with 1100g Pb; 2. Regenerator with 1205 g Pb; 3. Regenerator with 1350 g Pb.

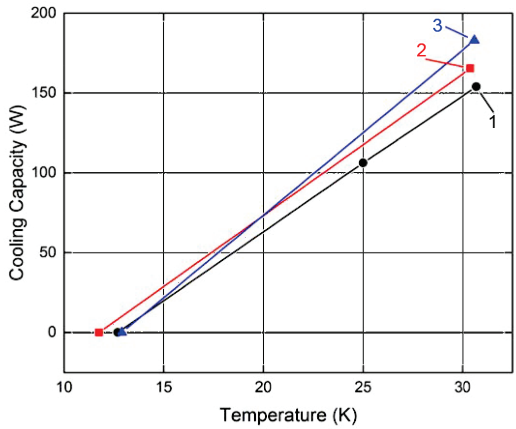

Figure 4. Cooling performance of the three regenerators. 1. original design; 2. increased length by 11.9 mm; (3) increased diameter by 3.2 mm based the regenerator 2.

increases to 13.7 K and levels out, as seen in curve 1 in Figure 3. Figure 3 also displays the cool-down curve changes with three different regenerator packings. Regenerator 1 is packed with 1100g Pb, regenerator 2 with 1205g Pb and regenerator 3 with 1350g Pb. The cool-down curve 2 shows a plateau at the temperature of ~14.7 K. Cool-down curve 3 shows a smooth cooling process. This phenomenon could be related to the regenerator efficiency at low temperatures. Adding enough lead spheres in the regenerator increases the regenerator efficiency at these temperatures. The prototype AL630 with the regenerator 3 reached the lowest stable temperature of 12.6 K.

The optimization of structural parameters focused on the geometrical parameters of the regenerator. The originally designed regenerator is first modified to increase the length of the regenerator by 11.9 mm. To further increase the regenerator volume, the diameter was then increased by 3.2 mm. It was found that the regenerator losses associated with a large diameter regenerator are bigger than predicted due to the difficulties of regenerator packing and non-uniformity of regenerator temperature in the large size regenerator. Figure 4 shows the performance of each of the three regenerator dimensions tested. Regenerator 2 had the lowest base temperature of 11.8 K, however, regenerator 3 had the highest cooling capacity of 183 W at 30.5 K The following results are reported using regenerator 3.

Displacer stroke and frequency were then optimized simultaneously for maximum performance at 30 K. Stroke was varied by placing aluminum spacers on the displacer. Frequency was optimized by using a stepper motor within the cold head and a variable frequency drive (VFD). Figure 5 shows the cooling capacity at 30 K as a function of displacer frequency and stroke. A maximum cooling performance of 183 W at 30 K was achieved with a frequency of 1.4 Hz and a stroke of 24.4 mm.

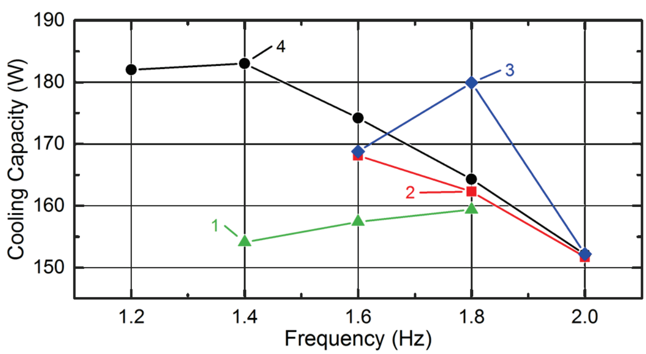

Figure 5. Cooling Capacity at 30 K vs frequency for displacer strokes of 1. 17.5 mm, 2. 20.3 mm, 3. 22.9 mm and 4. 24.4 mm

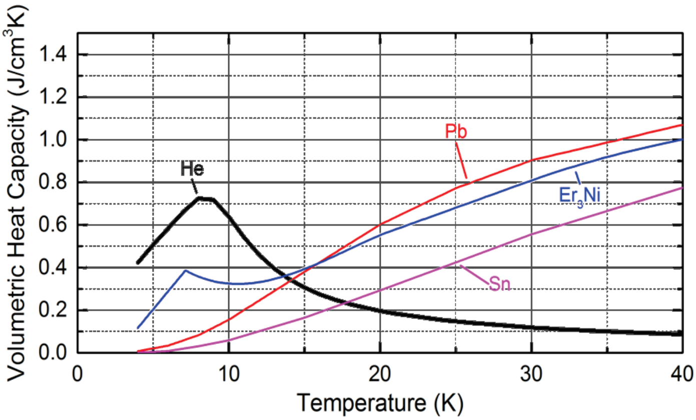

Figure 6. Specific Heat of Pb, Er3Ni, Sn and He gas from 4 K to 40 K [4,5]

The following results with the first prototype are reported with this stroke and frequency. Increasing the regenerator diameter helped to lower the operating frequency of the cold head, which will increase the MTBM of the cryocooler.

The input power with a static pressure of 1687 kPa was measured to be 12.2 kW in steady state operation. The static pressure was then increased to 1756 kPa which increased the cooling performance to 190 W at 30.3 K. The input power increased to 12.7 kW in steady state operation as well.

Different spherical regenerator materials were then tested with this static pressure. The materials tested were Pb, Er3Ni and Sn spheres in the cold end of the regenerator. The rare earth material Er3Ni was tested to explore the best performance that could possibly be obtained at 20-30 K for this cryocooler. The material is not suitable for commercial products because of its high price. The material of Sn in the regenerator was tested for potential lead replacement for RoHS compliance in the future. Figure 6 shows the volumetric heat capacity of these regenerator materials in comparison to helium [4,5]. Figure 7 shows the cooling performance with each spherical regenerator material. Replacing Pb with Er3Ni increased the performance at 30 K from 190 W to 197 W and the base temperature remained the same. This is contrary to what was expected as Pb has a higher heat capacity at 30 K than Er3Ni and Er3Ni has a high heat capacity at temperatures below 16 K. This result needs to be investigated further. The cold head with Sn spheres could only reach the no-load temperature of ~17 K and has poor performance at 20 K. However, it does have a similar cooling capacity at 30 K when comparing to the cold head performances with Pb or Er3Ni in the regenerator.

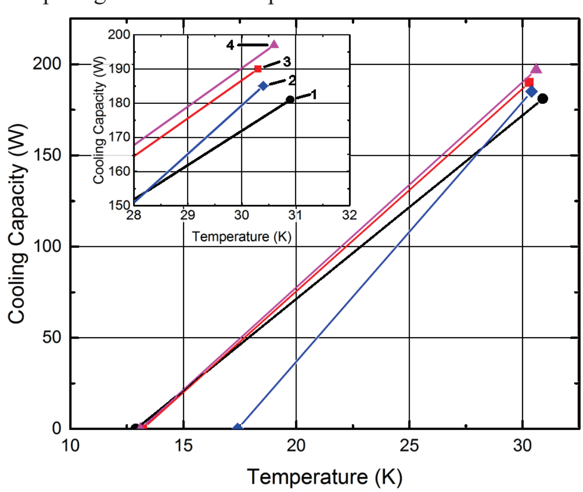

Figure 7. Cooling performance with (1) 1200g Pb, (2) 754g Sn, (3) 1400g Pb and (4) 780g Er3Ni spherical regenerator materials

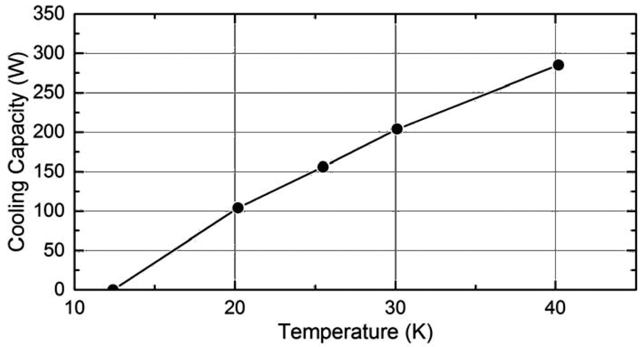

Figure 8. Capacity Curve for the prototype AL630 at 60Hz operation

Table 1. Cryocooler efficiency from 15 K to 50 K

Cooling Temperature (K)	15	20	25	30	40	50
Cooling Capacity (W)	34.1	104	159.5	204	285	319.2
Input Power (kW)	12.46	12.87	13.09	13.24	13.34	13.41
COP_{actual}	0.0027	0.0081	0.0122	0.0154	0.0214	0.0238
Percent Carnot	5.2	11.3	13.4	13.9	13.9	11.9

As stated previously, Er3Ni is a rare earth alloy which is significantly more expensive than Pb and Sn regenerator provides poor performance at 20 K. Therefore, the remainder of testing used Pb as the spherical regenerator material. To reduce the weight of the displacer the amount of Pb was decreased by 200g and performance was gained through other modifications.

Based on the above testing, a second prototype cold head of the AL630 was built. It had a larger cold end heat exchanger to improve heat transfer efficiency. It has a displacer stroke of 22.6 mm and operating frequency of 1.4 Hz. Figure 8 shows its cooling capacity at temperatures up to 40 K. It reached a no-load temperature of 12.4 K and has 104 W at 20 K and 204 W at 30 K. Table 2 gives the performance, power consumption and efficiency of the AL630. It has a power input of ~13 kW in the temperature range of 20-30 K. The percent Carnot efficiency is 11.3% at 20 K, 13.4% at 25 K and 13.9 % at 30 K.

Figure 9 shows the cool-down curve of the AL630. It takes 80 min to reach the bottom temperature of 12.4 K. The cooling process is smooth. The concerns of cooling curve 1 and 2 in Figure 3 don't show up in the testing of the second prototype AL630.

The existing rotary valve in the production is a double-rotation valve given in Figure 10 (a). This means that for every one rotation of the valve, the displacer undergoes two full cycles. A new

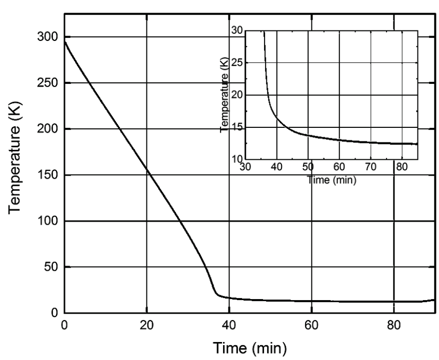

Figure 9. Cool-down curve for prototype AL630

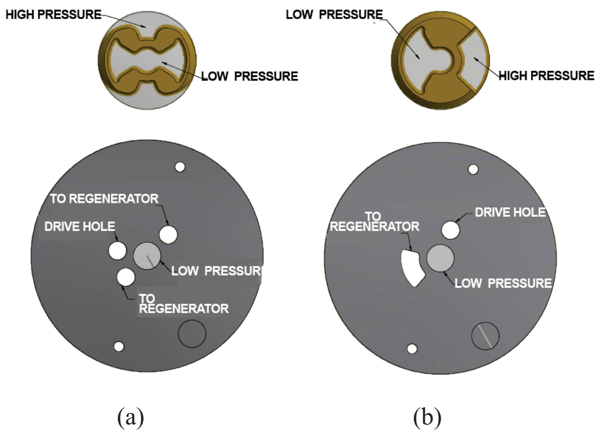

Figure 10. Two type designs of rotary valve. (a) Existing double-rotation valve; (b) New single-rotation valve.

Table 2. Cooling performance with the standard rotatory valve and new rotary valve

	Base Temperature	Cooling Capacity at 30 K
Standard Valve	12.4 K	204 W
New Valve	12.2 K	208 W

single-rotation valve in Figure 10 (b) was designed to reduce the gas flow resistance through the rotary valve. The low operating frequency allows the valve rotational speed to be doubled without reducing the MTBM. The initial test shows a promising improvement on the cooling performance. Table 2 compares performance of the AL630 with the two different valves. The new rotary slightly improves the base temperature and cooling capacity by 4 W at 30 K. More investigation will be continued on the new rotary valve design.

CONCLUSION

A low temperature, single-stage GM cryocooler has been developed at Cryomech, Inc. to provide large cooling capacities of >100 W at 20 K and >200 W at 30 K with a power input of ~13 kW. It has percent Carnot efficiency of 11.3% at 20 K and 13.9% at 30 K. It will be used for liquefying hydrogen and cooling HTS devices.

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