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Performance improvement of a large capacity GM cryocooler

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Abstract. This paper presents the improvement of a large GM cryocooler, Cryomech model AL600, based on redesigning a cold head stem seal, regenerator, heat exchanger and displacer bumper as well as optimizing operating parameters. The no-load temperature is reduced from 26.6 K to 23.4 K. The cooling capacity is improved from 615 W to 701W at 80 K with a power input of 12.5 kW. It has the highest relative Carnot Efficiency at 15.4%. The vibration of AL600 is investigated experimentally. The new displacer bumper significantly reduces the vibration force on the room temperature flange by 82 % from 520 N to 93 N.

1. Introduction

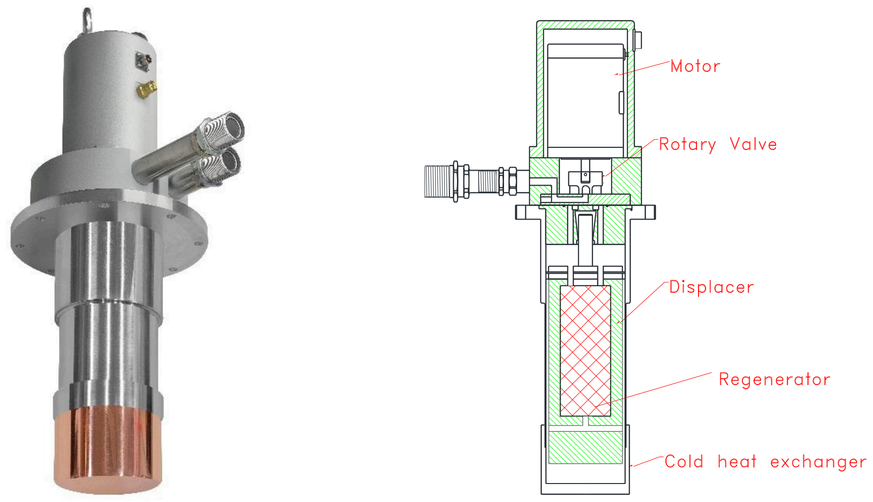
Applications such as cooling high temperature superconductors, and recondensing and liquefying nitrogen, hydrogen and natural gas, require cooling capacities from few hundred watts to a thousand watts at temperatures from 20 to 120 K. Stirling cryocoolers have higher efficiency. However, existing commercial high capacity Stirling cryocoolers have oil lubricated piston seals and require frequent maintenance after a few thousand hours [1]. Large capacity Stirling and pulse tube cryocoolers are being developed with dry linear compressors [2-3]. It is uncertain whether these future cryocoolers will be cost-effective. A Turbo-Brayton cryocooler has been scaled down for a capacity of two kilowatts at 80 K [4]. The physical size and cost of the Turbo-Brayton cryocooler cause concerns for some applications.

GM cryocoolers have the advantage of being lower cost, having reasonable maintenance intervals and employing user friendly interfaces. They are the current workhorses for cooling HTS generators, motors, fault current limiters, induction heaters, cables, etc.

Cryomech, Inc. has produced a large variety of high capacity GM cryocoolers, such as the AL300 with 300 W at 80 K, the AL330 with 100 W at 30 K, the AL325 with 100 W at 25 K and lastly the AL600 with 600 W at 80 K. Lately, the largest GM cryocooler (Model AL600) has been improved to increase its cooling capacity, reduce vibration levels and increase its mean time between maintenance (MTBM). The results are presented in this paper.

2. System configuration

The AL600 is a pneumatically driven single stage GM cryocooler. Figure 1 (a) and Figure 1 (b) show a photo and schematic of the AL600. The rotary valve in the cold head is driven by a stepper motor. In most tests, the stepper motor has a speed of 72 rpm and result in a cold head frequency of 2.4 Hz. The regenerator is made of phosphor bronze screens. Two screen sizes,150 mesh and 200 mesh, are tested in the present study. The cold head is driven by a compressor, model CP1114, with a nominal input power of ~12 kW. Two 1” diameter SS flexible lines with a length of 3.3 meters connect the cold head and compressor.



(a) (b)

Figure 1. Photo and schematic of AL600 cold head.

3. Performance and discussion

3.1. Performance improvement

Regenerator efficiency is investigated by using different sizes of phosphor bronze screens. The flow rates of two regenerators made of 150 mesh and 200 mesh screens were measured with the given pressure drops. The results are displayed in table 1. The regenerator with 150 mesh screens has less flow resistance than the one with 200 mesh screens.

The regenerator in production is made of 200 mesh screens. The performance improvement of the new regenerator with 150 mesh screens is given in figure 2. Figure 2 also shows the performance comparisons of a newly designed cold heat exchanger and the cold heat exchanger in production. The cooling capacity at 80 K increased from 615 W to 625 W with the new heat exchanger and further increases to 659 W with the new regenerator. The no-load temperature of the cold head is reduced from 26.6 K to 23.4 K with these improvements.

The cold head operating frequency is optimized with the new heat exchanger and regenerator. The results are given in figure 3. The best performance is obtained with the operating frequency of 2.4 Hz, which is the original design frequency for the AL600. The optimum frequency does not change with the newly designed heat exchanger and regenerator. The following results are obtained with these new designs and an operating frequency of 2.4 Hz.

Table 1. Flow resistance measurement of the two regenerators.

	Regenerator pressure drop 34.5 kPa	Regenerator pressure drop 68.9 kPa
Flow rate with 150 mesh screen	0.714 SCFM	1.498 SCFM
Flow rate with 200 mesh screen	0.599 SCFM	1.378 SCFM

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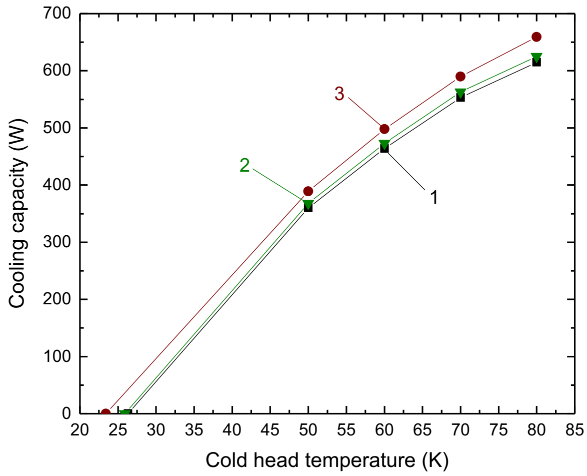

Figure 2. Performance improvements based new cold heat exchanger and regenerator: 1. Production; 2. New heat exchanger; 3. New heat exchanger and regenerator.

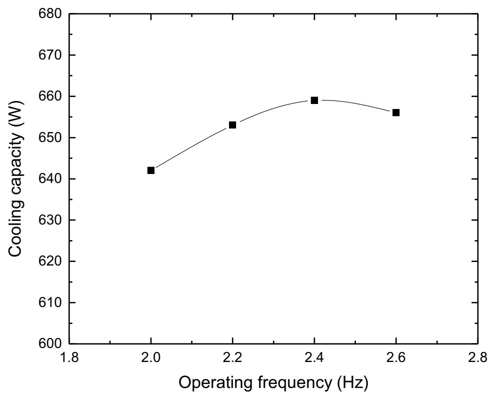

Figure 3. Effect of the operating frequency on the cooling performance.

Figure 4 shows the performance improvement with a new stem seal and a longer displacer stroke. The newly designed stem seal reduces the no-load temperature from 23.4 K to 22.5 K and increases the cooling capacity at 80 K by 8 W. Due to the better efficiency of the regenerator, the optimum displacer stroke can be increased from 25.4 mm to 28.4 mm. With the longer displacer stroke, the AL600 obtains a cooling capacity of 685 W at 80 K.

In the above testing, the flexible lines connecting the cold head were 3.3 m long. The AL600 cold head has a large volume and needs more gas at cryogenic temperatures. Considering future producibility, each high and low pressure line was added with a 12-liter buffer volume respectively. Figure 5 shows the performance of the AL600 with and without additional volumes. The additional buffer volumes increase the cooling capacity at 80 K from 685 W to 701 W and increases the power input from 11.8 kW to 12.5 kW. The improved AL600 has no-load temperature of 23.5 K and can provide 129 W at 30 K, 516 W at 60 K and 1005 W at 120 K. The relative Carnot efficiency is 15.4% at 80 K, which is the highest efficiency any GM cryocooler to date.

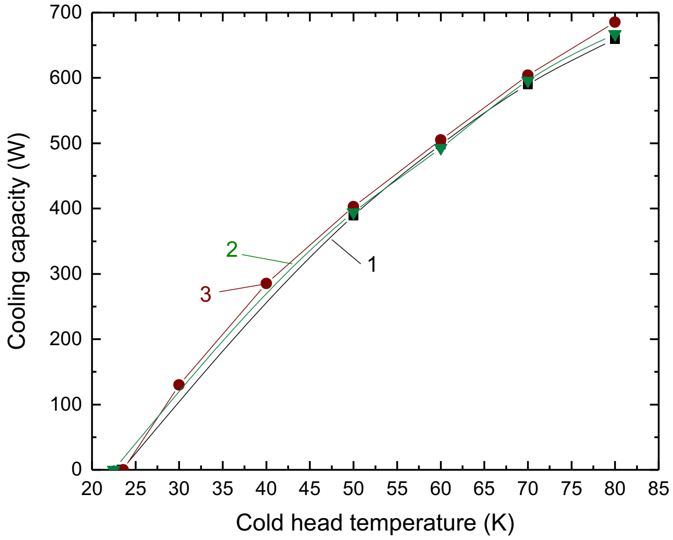

Figure 4. Cooling performance improved with a new stem seal and longer stroke: 1. Before changes; 2. new stem seal; 3. New stem seal and longer stroke.

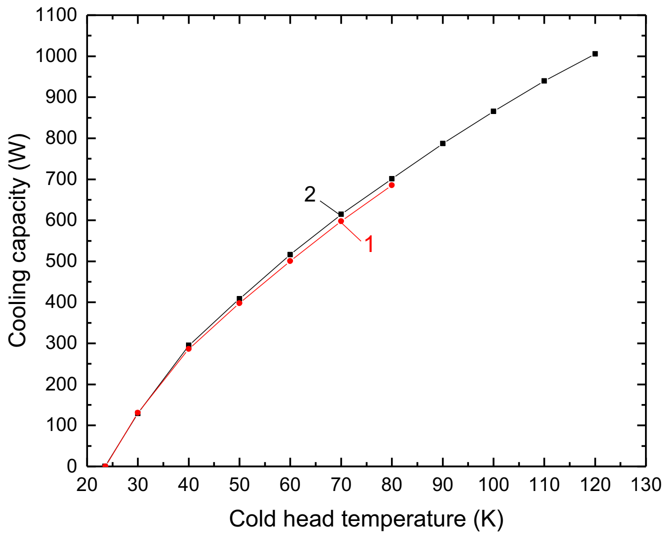

Figure 5. Cooling performance of AL600 with and without additional volumes: 1. Without volumes; 2. Two volumes on the high and low lines.

Figure 6 shows the cool-down curve of the improved AL600 with no heat load on the cold heat exchanger. It takes 18 minutes for the cold head to reach the bottom temperature of 23.5 K. The AL600 has the fastest cool-down among all GM cryocoolers we produce.

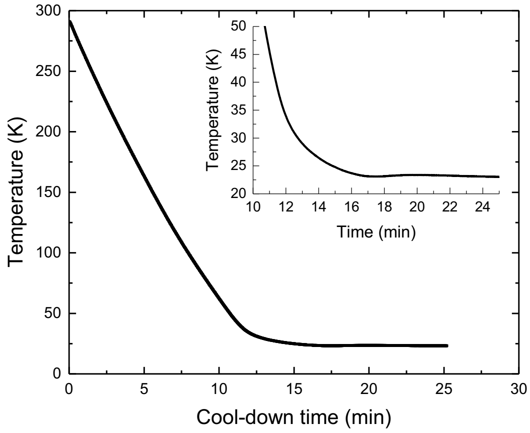

Figure 6. Cool-down curve of new AL600.

3.2. Vibration analysis

An experimental setup was established to determine the source of the greatest forces and to track the changes in the system. The tests were conducted using a PCB Piezotronics force sensor (model 208C03) that reads in both tension and compression. A production AL600 was mounted on this force sensor and two additional supports were added. A mounting screw was then used to fix the force sensor to the cryocooler to allow for tension measurements. The two supports were left unfixed (figure 7). Measurements were taken at startup and then at 5 minute intervals (figure 8).

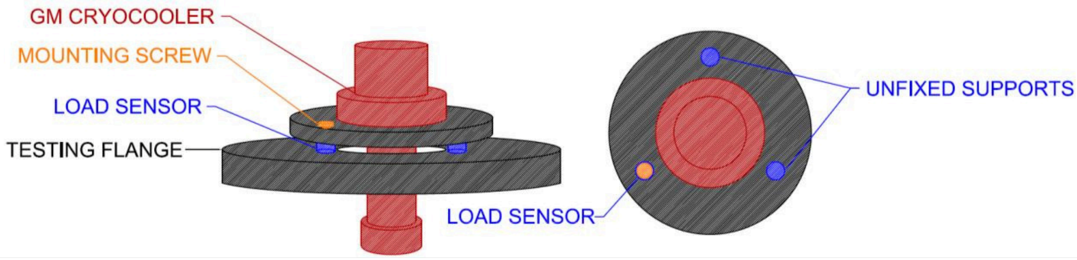

Figure 7. Placement of load sensor and unfixed supports (front view and top-down view).

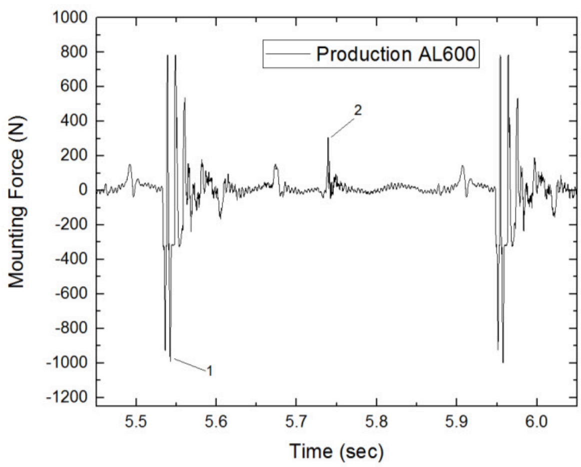

Figure 8. Impact forces measured using experimental setup: 1. Impact from upward stroke; 2. Impact from downward stroke.

One would expect the downward stroke to produce a greater force than the upward stroke due to the effects of gravitational acceleration. However, the experimental data shows that the forces seen in tension (upward stroke) are several times greater than the forces in compression (downward stroke). Over several runs, the displacer striking the top would generate forces of ~900 N. Conversely, the impact forces of the downward stroke were ~220 N. This contrast in forces can be explained with the design of the displacer. The displacer had springs integrated into the bottom of it, which would reduce the measured impact forces, and O-ring damper on the top. Knowing this, the attention was turned to modifying the top of the displacer to reduce the impact forces seen on an upward stroke.

The force of impact (F) can be determined if the change in velocity (Δv), mass (m) and duration of impact (Δt) are known.

$$F = \frac{m \cdot \Delta v}{\Delta t} \quad (1)$$

The impact forces can be reduced by altering several parameters. Decreasing the mass and velocity would yield lower forces, but the mass of the displacer/regenerator cannot be modified. The most practical approach would be to increase the duration of the impact. The existing displacer incorporated a HDPE top bumper. To increase the impact time, the bumper was modified into a two-piece design that would house either damping materials, mechanical springs or a mixture of both. This two-piece design allows the bumper to have more travel, causing a longer impact duration, resulting in lower forces. Three damper arrangements tested are listed in table 2. The properties of the wavesprings employed can be found in table 3.

Table 2. Bumper damper configurations tested.

#1 damper	1/8” Leather Pad + 1 Wavespring
#2 damper	1/8” Leather Pad + 2 Wavesprings
#3 damper	1/8” Leather Pad + 3 Wavesprings

Table 3. Wavespring Properties.

Configuration	Spring Rate (N/m)	Max Deflection (m)
1 Wavespring	161,642	.0033
2 Wavesprings	323,284	
3 Wavesprings	484,926	

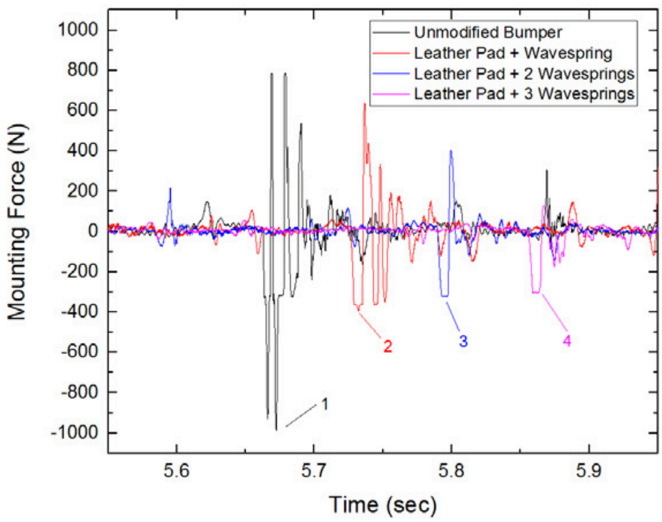

Figure 9. Measured impact forces for various configurations upon startup: 1. Standard unmodified bumper; 2. #1 damper; 3. #2 damper; 4. #3 damper.

Figure 9 shows impact forces for various damper configurations measured at system startup. Varying the damper configuration of the top bumper produced changes in the peak forces seen in tension, while keeping the forces seen in compression relatively unaffected. This was further confirmation that the maximum impact forces were a result of the upward stroke. The impact force reductions with various dampers are listed in table 4. The best result is obtained with #3 damper, which reduces the force by 69.4%.

Table 4. Summary of damper configurations tested (upon startup).

Configuration	Maximum Force (N)	% Reduction
Unmodified bumper	988	0
#1 damper	454	54.0
#2 damper	320	67.6
#3 damper	302	69.4

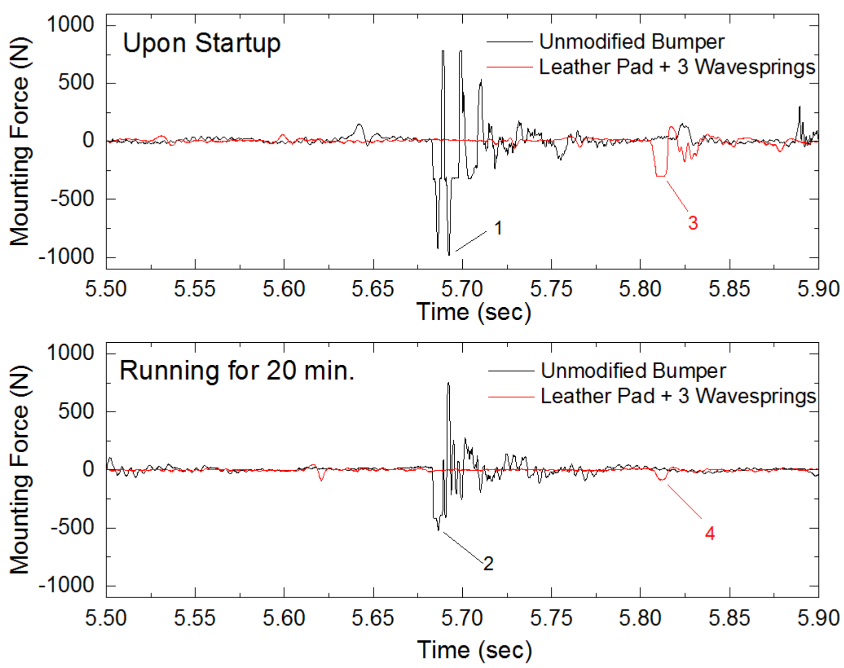

Figure 10. Comparison of unmodified bumper and updated bumper with #3 damper at two different times: 1. Startup force for unmodified bumper; 2. Force for unmodified bumper after running for 20 min; 3. Startup force for updated bumper; 4. Force for updated bumper after running for 20 min.

Figure 10 shows a comparison between the unmodified bumper and the updated bumper (with #3 damper) at two different times. The measurements were taken with the cold head exposed to atmosphere, not in a vacuum. The forces produced by the AL600 are very dependent on the temperature of the coldhead. The impact forces upon startup are the highest forces produced. While the AL600 begins to cool, the impact forces decrease over time due to the decreased pressure differential with lower cold head temperature. The updated damper design reduced both the startup forces as well as the forces at lower temperatures.

Table 5 lists peak mounting forces comparing the unmodified bumper to the updated bumper with #3 damper over various operating times. The mounting force with updated bumper reduces from 302 N to 93 N after 20 minutes of operation. The vibration reduction ratio with the updated bumper is higher when the cold head temperature is lower, which indicates better vibration damping at low temperatures. When looking at the vibrations after 20 minutes of operation, the updated bumper (with #3 damper) yields significant reductions over the unmodified bumper. The mounting force decreased from 520 N to 93 N with the updated setup. This yields an 82.1% force reduction.

Table 5. Peak mounting force with unmodified bumper and updated bumper with #3 damper over various operating times

Running Time (min)	Unmodified Bumper Peak Force (N)	Updated Bumper Peak Force (N)	% Reduction
0	988	302	69.4
10	552	115	79.2
20	520	93	82.1

4. Conclusion

The cooling performance of a large cooling capacity GM cryocooler, Cryomech model AL600, has been improved by redesigning the heat exchanger, regenerator and stem seal as well as optimizing operating parameters. The AL600 is able to provide 129W at 30 K, 701 W at 80 K and 1005 W at 120 K. This GM cryocooler has highest cooling capacity, highest efficiency and fastest cool down speed of any GM cryocooler to date. The vibrations of the cold head have been reduced by 82 % by utilizing a new bumper design. This new generation AL600 GM cryocooler will be more attractive for many applications.

5. References

[1] Brochure from Stirling Cryogenics, BV, the Netherlands
[2] Ko. J., Yeom, H., Hong, Y.J., "Progress in development of high capacity Stirling cryocooler using a linear compressor", Cryocooler 19, ICC press (2016), pp.177-181
[3] Zia, J.H., "A Pulse Tube Cryocooler with 300W Refrigeration at 80K and an Operating Efficiency of 19% Carnot", Cryocooler 14, ICC press (2008), pp.141-147
[4] Brochure from Taiyo Nippon Sanso, Co., Japan