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Recent Advances in Gifford-McMahon Cryocoolers

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Abstract. Cryocoolers are devices which produce the required refrigeration at a specific low temperature, and they can replace the normal cryogenic fluids. Cryogenic fluids give refrigeration only at a specific temperature whereas cryocooler can produce refrigeration at varying low temperatures. There are many types of cryocoolers like Pulse tube, Stirling, Joule- Thomson, Gifford-McMahon (GM) etc. Many advances have occurred over the years in these cryocoolers. For obtaining very low temperatures along with large cooling powers GM and Pulse tube cryocoolers are found to be better among the others. Hence, this article focuses the advances in GM cryocoolers. This article discusses the working of GM cryocooler, importance of regenerator material and how one can use special regenerator materials to reach very low temperatures. Further, the advances in these cryocoolers such as the use of Labyrinth finish regenerators to obtain higher cooling powers etc. are also discussed. It is presumed that the reader obtains a basic understanding of the GM cryocooler, latest developments and the possible future areas for research from this article.

1. Introduction

A GM cryocooler is a low frequency device wherein a displacer is made to move within a housing from one location to another. The working fluid such as Helium is sent into and out of the system at high and low pressures using properly timed inlet and outlet valves respectively. Low temperatures are produced at a specific part of the cryocooler which is known as cold head.

GM cryocooler has a compressor separate from the expander, high and low-pressure valves either rotary or cam operated, displacer with layers of regenerator inside and a cold heat exchanger as shown in Figure 1. High pressure gas from the compressor flows into the expander through the high-pressure valve. Compressor gas is cooled in a water-cooled heat exchanger. Enthalpy of compressor gas is absorbed in the regenerator and it becomes hot and decreases temperature of gas. Then the gas undergoes expansion in the expander which further reduces its temperature. Displacer moves away from the lowest position and gas is expelled out through Low pressure valve. Refrigeration effect is produced at the lower end of the expander.

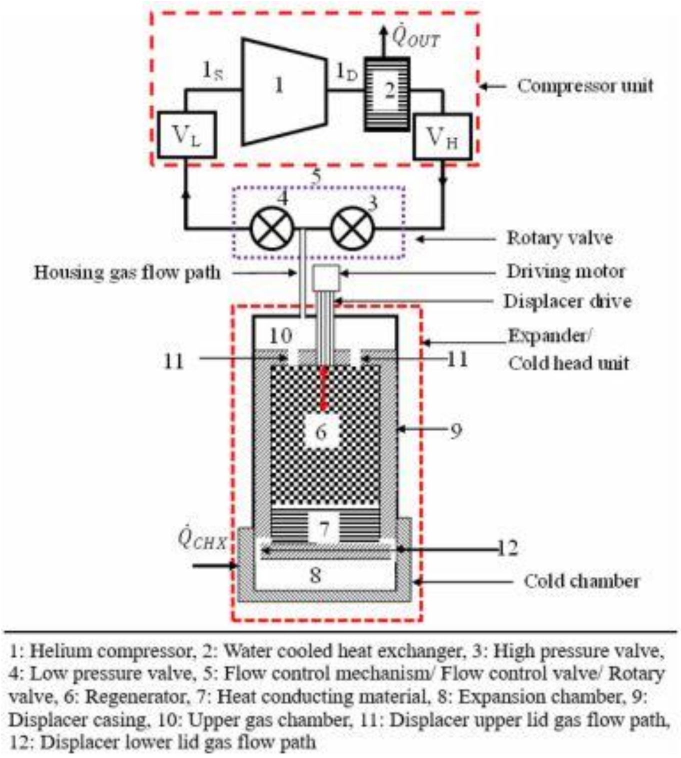

Figure 1. Schematic of a GM cryocooler [1]

2. Advances in Regenerator materials

Regenerator is the heart of a GM cryocooler. Heat capacity of Helium gas at higher pressure increases at temperatures below 20 K and exchange of heat with a regenerator becomes very difficult. There is a need for choosing a material which has similar heat capacity as Helium at low temperatures. Lead has been utilized as regenerative material since 1990s. Other magnetic materials such as Holmium Copper ($HoCu_2$), Gadolinium oxysulphide (Gd_2O_2S, GOS) [2] have good heat capacity at low temperatures. Rectification meshes were used to increase the uniformity of Helium gas flow inside regenerator and cooling capacity was improved by a factor of 1.35 at 12 K [3,4]

S Masuyama et al. [5] conducted experimental work on an RDK-408D2 (SHI) GM cryocooler by introducing a double pipe regenerator. They compared the performance of a three-layer regenerator comprising Lead, $HoCu_2$ and GOS (Figure 2a) with a three-layer layout with a pipe made of stainless steel (Figure 2b)

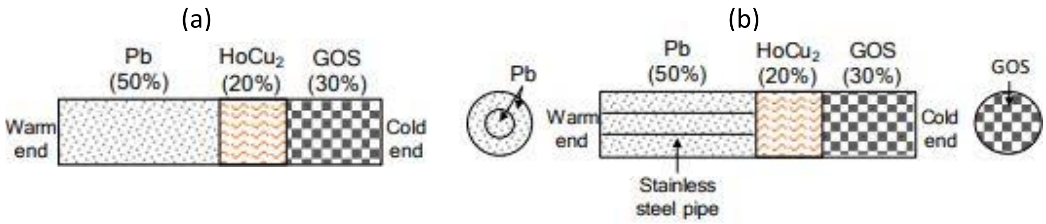

Figure 2. Regenerator arrangement (a) three-layer layout (b) three-layer layout with pipe [5]

They found that three-layer layout with pipe gave the best performance among the two with cooling power of 1.67 W at 4.2 K for second stage and 64.9 W at 50 K for first stage.

M Y Xu et al. [6] developed a tin- plated regenerator material to improve performance of a GM Cryocooler compared to a Bronze screen type regenerator. Increase in Cooling capacity of about 14% at 40 K and 90% at 30 K was observed.

Cooling capacity was compared with different materials as shown in Figure 3. Tin plated screen regenerator gave cooling power of 53.4 W at 40 K and 36.4 W at 30 K compared to 46.9 W at 40 K and 19 W at 30 K for bronze screens. Compared to Bi spheres cooling capacity increase of Tin-plated screen is marginal at 30 K because of lesser heat capacity of Tin-plated screen than Bi spheres at 30 K.

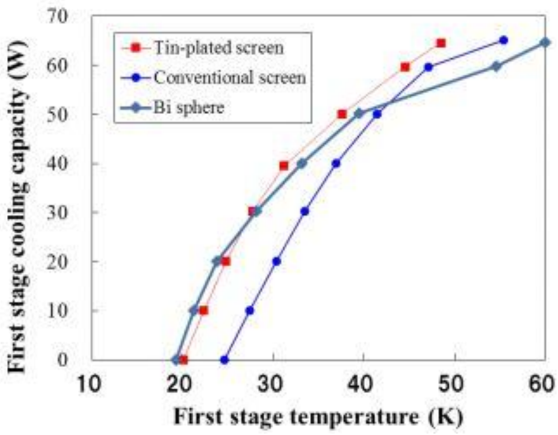

Figure 3. Cooling power comparison of different regenerator material [6]

In a similar paper by M Y Xu et al. [7] experiments were conducted by replacing first stage regenerator at cold end with Zinc plated screens. They found out that there was an increase in cooling capacity by 11% at 40 K and 60% at 30 K.

3. Compact GM cryocooler

Compact GM cryocoolers are preferred wherever end use application has size constraints for cooling. SSPD (Super Conducting Single Photon Detectors) developed by SHI for quantum cryptography communication is very small and requires low temperature of around 2.3 K. Many researches have been carried out to reduce size of the cryocooler which is discussed below.

Y Hiratsuka et al. [8] used a linear compressor instead of CNA-11 compressor for a compact 2K GM cryocooler and results were compared. Cooling performance at 4.2 K were 173 mW and 191 mW for Linear and CNA-11 respectively.

Figure 4 compares the cooling performance of the cryocooler for CNA-11 compressor and Linear compressor. It was observed that better cooling capacity was found in the case of Linear compressor for temperatures below 2.3 K and no-load temperature for Linear compressor was 2.06 K as compared to 2.11 K for CNA 11 compressor. This is because Helium's Lambda point decreases at higher operating pressures, which makes it easier to exchange heat with even a regenerator of lower specific heat and Linear compressor works at higher operating pressures. At temperatures between 3 and 4 K, as the compressor pressure increases mass flow rate decreases which reduces heat exchange between gas and regenerator.

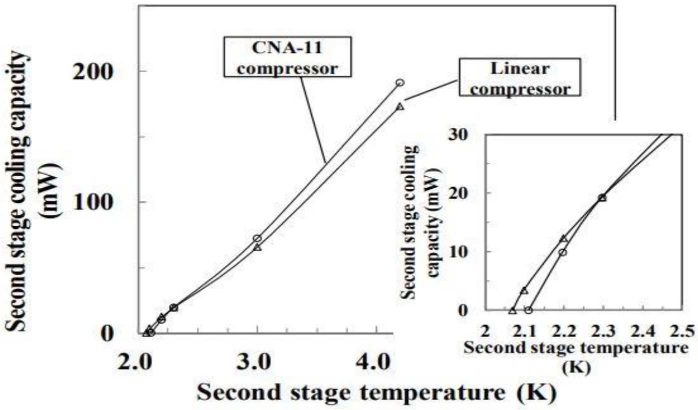

Figure 4. Cooling performance for second stage [8]

Inclination of the compressor did not influence much on the cooling performance. Sound noise and vibrations were measured. They found out that sound noise of Linear compressor was little bit higher than that of the CNA 11 compressor. At the compressor side, vibration was measured for each compressor and they found that linear compressor was showing acceleration of 2.2 G (m/s^2) which was higher than that of 0.75 G of the CNA 11 compressor

Mingyao Xu et al. [9] developed a compact 2K GM Cryocooler for cooling electronic devices like SSPD (Superconducting Single Photon Detectors). Cylinder length was reduced by 85 mm compared to a commercially available 0.1W 4K GM cryocooler. No load temperature attained was 2.1 K

A design target of reaching length of expander to 67% of RDK- 101D was set as objective. To achieve this, regenerator size should be reduced. For this a new regenerator material was introduced which can be put in the second stage regenerator's warm end. With the help of new regenerator 42.2 K and 2.41 K was reached as no load temperature at first and second stage respectively which is compared with Bismuth in Table 1. This was because temperature profile of regenerator reached a higher level with the new material

Table 1. No load temperature for different types of regenerator materials at warm end of 2nd stage [9]

Regenerator material	First stage temperature (K)	Second stage temperature (K)
Bismuth	45.7	2.46
New material	42.2	2.41

The performance of the new prototype unit is shown in Table 2. cooling capacity of 1 W at 44.4 K as compared to the objective of obtaining 1 W at 60 K was obtained at the first stage. Temperature oscillations of ± 20 mK was obtained.

Table 2. Measured results for a compact 2K GM cryocooler [9]

Item	Development Object	Measured Results
First stage temperature with 1 W	60 K	44.4 K
Second stage temperature with 20 mW	2.3 K	2.23 K
No-load second stage temperature	2.2 K	2.10 K
Expander height	67% of RDK-101D	81% of RDK-101D
Temperature oscillation	±20 mK	±20 mK

Qian Bao et al. [10] conducted experimental investigation on a compact 2K GM cryocooler. They developed a new 2K GM cryocooler which can provide necessary cooling effect as well as being compact in size. They observed that Helium gas when expanded from 2.2 MPa to 0.8 MPa attained almost no change in temperature at 2.05 K as shown in Figure 5, this observation made them to build a less thermally oscillating cryocooler.

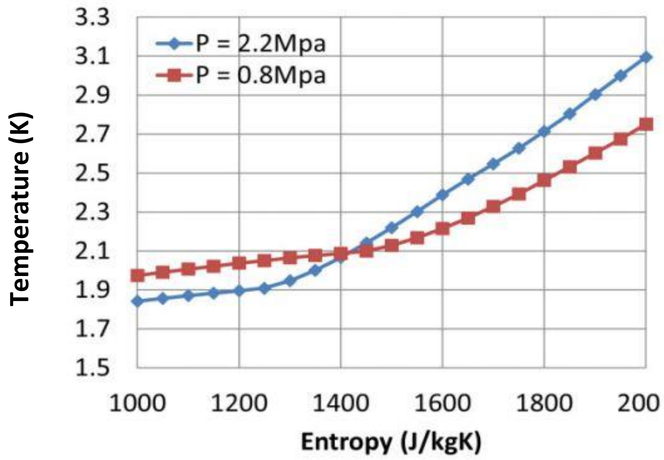

Figure 5. Helium properties [10]

Figure 6 shows variation of first stage and second stage temperature with heat load. Heat load was varied from 0 W to 4 W for the first stage and 0 W to 0.1 W for the second stage. It was observed that second stage temperature did not go less than 3 K for most of the cases.

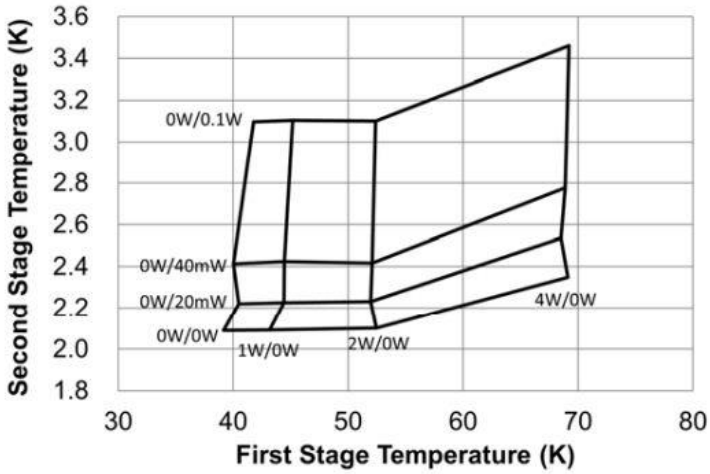

Figure 6. Load map for 1st and 2nd stage [10]

4. Large cooling capacity GM cryocooler

High Temperature superconductors (HTS) and liquid Hydrogen production requires a larger cooling capacity in the range of 20- 30 K. Cryomech inc have developed a large cooling capacity GM cryocooler AL330 for single stage which gives cooling power of 45 W at 20 K [11]

C. Wang et al. [12] developed a large cooling capacity GM cryocooler of single stage for operating temperatures of 13-30 K. It was developed to provide large cooling powers in the range of 20-30 K. The regenerator material comprises of two layers i.e., Phosphor bronze screens in the upper part and spherical materials which has high Cp at low temperatures in the lower part.

They used AL630 cryocooler [13] developed by Cryomech inc for initial tests. Cool down time for three types of regenerator materials made of Pb of different mass are shown in Figure 7. 1st type regenerator reached lowest temperature of 12.5 K and increased to 13.5 K after 70 min of operation. 2nd type shows a plateau at 14.7 K. 3rd type shows smooth cool down and reached a stable temperature of 12.6 K. It was observed that with increase in mass of regenerator material, regenerator efficiency increased.

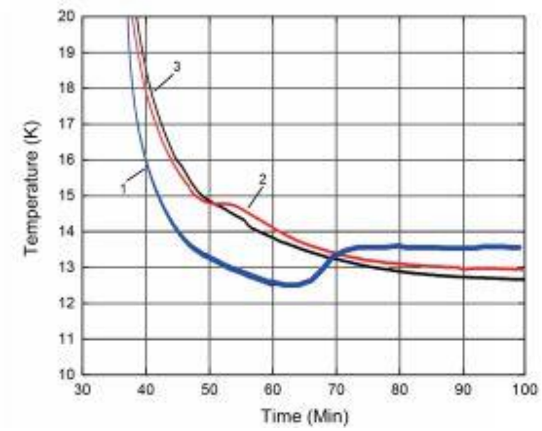

Figure 7. Cool down curves of AL630 with three regenerator packings. 1. 1100g Pb; 2. 1205g Pb; 3. 1350g Pb [12]

Different spherical type regenerators were tested at a static pressure of 1756 kPa. Pb, Sn and Er3Ni were used as regenerator materials. Er3Ni is a rare earth material and was used to explore maximum cooling capacity. Figure 8 shows the cooling performance of these three regenerator materials. Pb gave poorest performance at lowest temperature but was performing equally like the rest. Er3Ni showed better cooling capacity in the range of 30 K than Pb which is contrary to the fact that Pb has higher volumetric specific heat at this temperature than Er3Ni.

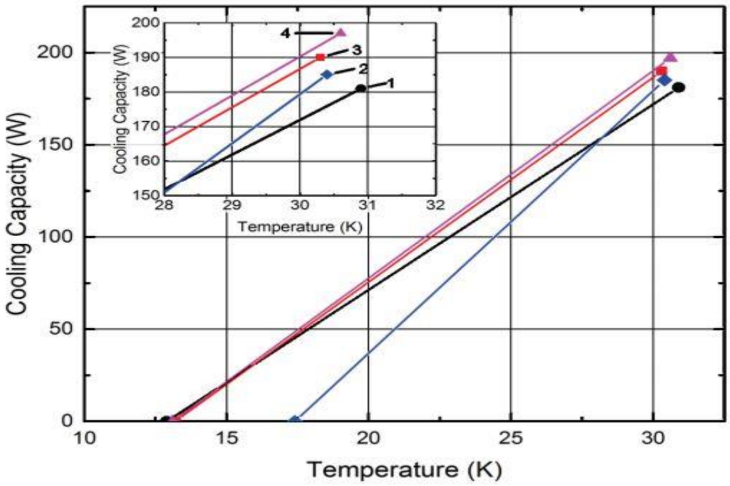

Figure 8. Cooling performance with (1) 1200g Pb, (2) 754g Sn, (3) 1400g Pb and (4) 780g Er3Ni spherical regenerator materials [12]

The existing rotary valve shown in Figure 9a is a double- rotation valve i.e., for every rotation of the valve, displacer performs two full cycles. A new single rotation rotary valve shown in Figure 3b was developed to reduce resistance of gas flow through the valve. It operates at a low frequency which doubles the rotational speed without reducing MTBM. New valve improves the cooling performance by 4 W at 30 K.

Figure 9. Rotary valve (a) Double rotation valve, (b) Single rotation valve [12]

K. Yamada [14] developed a large cooling capacity GM cryocooler of single stage for HTS (High Temperature Superconductors) applications. Cooling capacity achieved was 46/52 W at 20K or 85/96 W at 30K with 6.9/7.9 KW input power at 50/60 Hz. They studied orientation dependence of the cryocooler, 0^0 angle gave the best result whereas 180^0 gave slight loss of performance. This is due the fact that cold gas which is dense sinks down in the case of 0^0 angle and vice versa in the case of 180^0 angle. The cooling deterioration by inclination was less than 24%

They used Bi as regenerator material as Pb is banned under ROHS directive, but Bi has lesser heat capacity than Pb at the desired range of 20- 30 K. Hence additional efficiency improvements were carried out. A 60 Hz compressor was used instead of a 50 Hz because 60 Hz compressor was giving more cooling power at higher temperatures than 50 Hz. This was because 60 Hz gives more PV work, higher He flow and more expansion volume and at higher temperatures heat losses become negligible. In low temperature region this is not the case as heat losses become prominent due to lower heat capacity. So, the cooling power increases at higher temperatures in the range of 20- 30 K. Comparison of cooling powers of 60 Hz and 50 Hz compressor is given in Figure 10

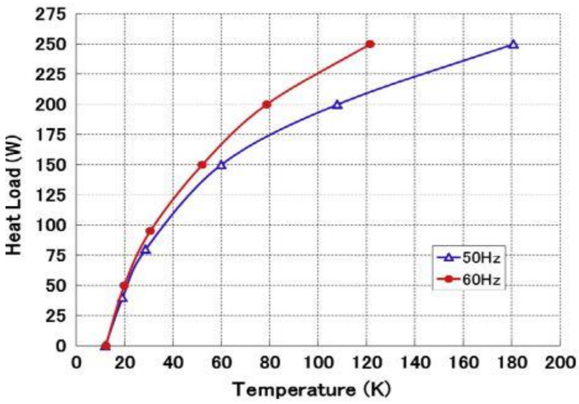

Figure 10. Cooling power comparison of 50 Hz and 60 Hz compressor [14]

X H Hao [15] developed a new 4 K pneumatically driven GM cryocooler with Advanced Research Systems (ARS) which gives cooling power observed was 1.75 W at 4.2 K. A new Helium compressor was also developed which operates at 11.8 kW and 60 Hz.

Figure 11 compares the 2[nd] stage minimum temperature for different displacer strokes and operational speed of rotary valve. It was observed that speed of rotary valve to attain lowest temperature increases with decrease in displacer stroke. It also points out that lowest temperature of 2.46 K was attained at displacer stroke of 31.8 mm and rotary valve speed of 30 rpm. This was because as displacer stroke increases PV work and expansion volume increases which increases the cooling power considerably. Also, it increases heat loss due to shuttle loss of displacer. Therefore, an optimum speed of rotary valve of 30 rpm becomes prominent.

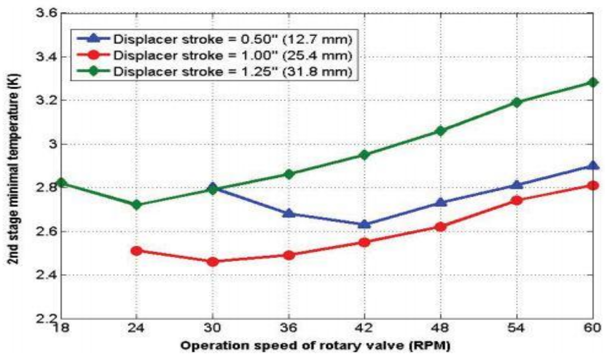

Figure 11. Comparison of cooling power for different Displacer stroke and rotary valve speed [15]

5. Labyrinth sealing

Conventional displacer sealings do not work effectively at low temperatures due to hardening, varying pressure difference observed within the expansion volume as it oscillates making the seal move, this will lead to leakage of the working gas as its viscosity decreases drastically at lower temperatures. To overcome this problem a new category of sealing called the labyrinth seal was proposed by Liu and Zhang [16,17] which increases the sealing gap between the seal and cylinder.

X.H. Hao et al. [18] conducted experimental study on Labyrinth sealing displacer and cylinder in the 10 K GM cryocooler. Displacers with different clearance space and materials were tested. Figure 12 shows structure of a Labyrinth seal displacer. It is made of rectangular grooves with width of 2 mm and depth of 1.2 mm.

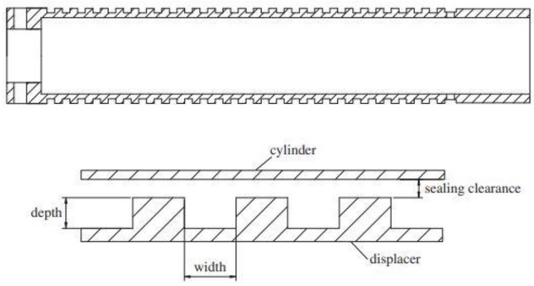

Figure 12. Structure of Labyrinth displacer [18]

Different clearance lengths were tried, out of which 0.01 mm gave the best performance with cooling capacity of 4.9 W at 20 K and lowest temperature attained was 12.3 K. Two types of sealing materials-stainless steel 304 and Inconel 718 which are referred as case E and case F respectively were tried out of which Inconel 718 gave the best performance. This is shown in Figure 13. This is because Inconel 718 has low thermal expansion coefficient than stainless steel 304.

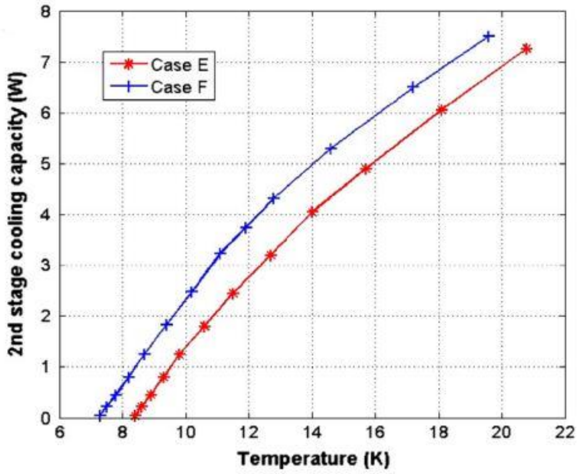

Figure 13. Cooling capacity comparison for different labyrinth seal materials [18]

C. Wang et al. [13] experimented with two types of Labyrinth sealings viz grooved and spiral labyrinth as shown in Figure 14. Shuttle loss can be decreased with increase in the clearance between the displacer and cylinder. With labyrinth sealings the clearance increases which can be used to decrease the shuttle loss.

(a) (b)

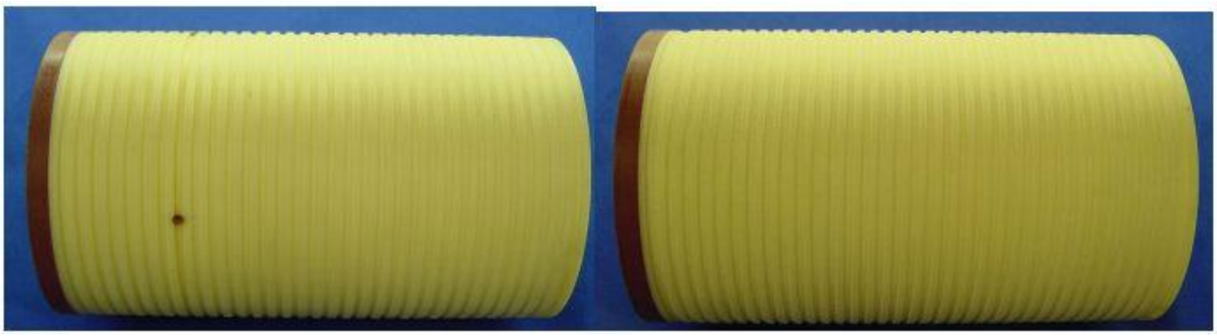

Figure 14. Types of labyrinth sealings (a) grooved, (b) spiral [13]

From Table 3 it is observed that labyrinth seals did not improve performance as expected by the authors, but they can be used to reduce the maintenance intervals.

Table 3. Comparison of different labyrinth seals for cooling performance [13]

	No load temperature	With heat load
No labyrinth seal	11.0 K	106W @ 25.0 K
Grooved labyrinth seal	10.9 K	106W @ 25.0 K
Spiral labyrinth seal	10.9 K	106W @ 25.2 K

6. Other Advances

Jun Shen et al. [19] did experimental studies on a hybrid refrigerator comprising of GM and magnetic refrigeration. ErNi and TmCuAl which possess large magnetocaloric effect are put in the second stage regenerator and magnetic field between 0 to 1 tesla was applied alternatively. 60° phase angle which is the angle between magnetic field and displacer motion gave the best performance.

Xu Li et al. [20] worked on a superfluid ^{4}He (II) production with GM cryocooler. ^{4}He (II) is used to cool cryogenic devices like Large hadron collider (LHC), sealed lambda- point devices and photon detectors which work below 2 K [21-23]. In this design ^{4}He (II) is generated by liquefying ^{4}He and then producing ^{4}He (II) at a separate pot so that ^{4}He will be at ambient temperature. Temperature oscillations of ± 2 mK at 1.78 K was demonstrated for operating continuously.

7. Conclusion

Many researches have been being carried out on the performance improvement of GM Cryocooler by varying many parameters such as rotational speed of rotary valve, charge pressure of expander, regenerator material etc. New methods to improve performance are being carried out such as using a linear compressor, Labyrinth sealing etc. It is observed that performance improvement is carried out based on the output usage of GM cryocooler such as low-end temperature, cooling capacity, compactness.

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