DEVELOPMENT OF TWO STAGE GIFFORD McMAHON CRYOCOOLER

PROJECT REPORT

Submitted by

RAHUL R

TKM22MEIR02

to

The APJ Abdul Kalam Technological University in partial fulfilment of the requirements for the award of Master of Technology in Mechanical Engineering with specialization of Industrial Refrigeration and Cryogenic Engineering

Department of Mechanical Engineering

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CERTIFICATE

Certified that this report entitled "**Development of two stage Gifford McMahon Cryocooler**" presented by **RAHUL R,** Registration No: **TKM22MEIR02** during **2022-2024** in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Industrial Refrigeration and Cryogenic Engineering of Mechanical Engineering of the *APJ Abdul Kalam Technological University*

Dr. RIJO JACOB THOMAS
Project Guide.
Department of Mechanical Engineering,
TKM College of Engineering, Kollam.

Dr. SRINIVASAN KASTHURIRENGAN
Co-Guide.
Centre for Cryogenic Technology,
IISc, Bangalore.

Dr. SADIQ A
P.G Coordinator.
Department of Mechanical Engineering,
TKM College of Engineering, Kollam.

Dr. SHAFI K A
Head of Department.
Department of Mechanical Engineering,
TKM College of Engineering, Kollam.

DECLARATION

I, Rahul R hereby declare that, this project report entitled '**Development of two stage Gifford McMahon Cryocooler**' is the bonafide work of mine carried out under the supervision of, Dr. Rijo Jacob Thomas (Associate Professor). I declare that, to the best of my knowledge, the work reported herein does not form part of any other project report or dissertation on the basis of which a degree or award was conferred on an earlier occasion to any other candidate. The content of this report is not being presented by any other student to this or any other University for the award of a degree.

Signature:

Place: Kollam　　　　Name of the Student: **RAHUL R**

Date: 03/06/2024　　　　University Registration No: **TKM22MEIR02**

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Place: Bangalore, 560012 **Rahul R**
Date: 31/05/2024

ABSTRACT

Cryocoolers are devices that produce very low temperatures and provide adequate amount of cooling power at a specific location and hence can replace the conventional cryogenic fluids. The main difference between cryocoolers and cryogenic fluids is that cryocoolers can produce refrigeration at various low temperatures, while cryogenic fluids only provide refrigeration at specific temperatures, namely their boiling points.

Cryocoolers can be classified into different types based on the heat exchangers used in them. They are regenerative and recuperative types. Regenerative type cryocoolers are further classified into three types namely, Stirling, Gifford McMahon (GM) and Pulse Tube.

The CTI GM type cryocooler (Model: Cryodyne, Number:350C) had been chosen in our studies to understand its design, working and also to reverse engineer its development. One could learn the assembly of the system and also how it can be dismantled without damaging the components. After preparing the dimensional drawing of the displacer, Bakelite has been used for its fabrication, since it forms an equivalent substitute for the original Micarta material. The newly fabricated displacer housing was filled with the original regenerator materials and assembled into the coldhead housing. The temperature sensors were incorporated for the first and second stage cold heads. The system was tested for its performance to determine its lowest temperature reached.

The regenerator materials and the sealings form the crucial components for the improved performance of the cryocooler. Both Teflon split rings and Rulon split rings have been used as sealings in our studies. Presently second stage temperature ~11.5K has been measured with lead as the regenerator material, with a water cooled 3kW helium compressor. On the other hand, with 1.5kW helium compressor, a temperature of 14.7K has been measured with lead as the regenerator material. With the same helium compressor, temperatures of 15.48K and 19.45K have been measured with Holmium copper and Erbium Nickel as regenerator material respectively. Since the above values are higher than those of with Lead as regenerator, we suspect the above regenerator materials have aged and are not performing satisfactorily.

The first stage temperatures have been measured as 75.96 K and 58.93 K for Holmium copper and Erbium Nickel as second stage regenerator materials respectively. The first stage regenerator material used in the setup is copper meshes (< 200 mesh size).

We have successfully designed and fabricated the displacer housing of the GM cryocooler system. Experiment have been performed using both labyrinth and non-labyrinth type housing. The performance of the system with indigenously designed displacer is quite satisfactory.

Also, the theoretical analysis of the single stage GM Cryocooler has been attempted using the open-source regions software. By this analysis one can evaluate the cooling power, COP and inefficiency of the system as a function of various design and operational parameters.

Following are the outcomes of the project.

1. Complete design drawings of the first and second stage displacer along with its housing.
2. Both Labyrinth type and non-labyrinth type displacers I have been designed, fabricated and tested.
3. Teflon silly rings are formed to perform better than the plastic sealing rings

The results indicate that the performance of the regenerator materials such as Holmium Copper and Erbium Nickel is not satisfactory due to the aging effect and perhaps one should look for fresh regenerator materials.

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CHAPTER 1

INTRODUCTION

A cryocooler is a type of mechanical refrigerator that is specifically designed to achieve low temperatures for cryogenic application. At temperatures below 1 K, cryogenics requires a distinct combination of skills and testing methods related to temperature. One attribute is the science and engineering behind reaching extremely low temperatures, done through the development of cryogenic refrigerators also known as cryocoolers. In the temperature range between 77 K and 4K Cryo coolers play an important role for a variety of applications. Several cryocoolers Such as sterling, gm and pulse tube systems have been used for cooling applications such as MRI, Sensor cooling, cryosorption pumps etc.

In MRI System, Cryocoolers are used to cool the superconducting magnets in MRI machines, ensuring they remain in a superconducting state, which is essential for the high magnetic fields required for medical imaging. In Space Telescopes Cryocoolers cool the detectors to reduce thermal noise, enhancing the sensitivity and accuracy of observations. Examples include the Hubble Space Telescope, James Webb Space Telescope etc. Many satellite-based instruments, like infrared sensors, require cryogenic temperatures to function with minimal noise level. Superconducting Quantum Interference Devices (SQUIDs) require cryogenic temperatures and they are used in various applications, including geophysics and medical diagnostics.

Another important application of cryogenics is in Quantum computers. Cryocoolers are often used to maintain qubits at extremely low temperatures, minimizing thermal noise and preserving quantum coherence. In Particle Physics applications, Cryocoolers are used for energising superconducting magnets in particle accelerators and high vacuum pumps, such as those at CERN, to maintain low temperatures. Research areas like superconductivity, superfluidity, and other quantum phenomena often requires cryogenic temperatures. For Military and Defence, Infrared Sensors are used in night vision equipment, missile guidance systems, and other applications.

Industrial Applications such as liquefaction of gases like helium, hydrogen, and nitrogen for industrial processes and storage. Cryocoolers are essential for advanced technology to maintain stable low temperatures in a compact and often portable form.

Cryocoolers are classified into 2 different categories- — recuperative cycles and regenerative cycles.

Recuperative cycle cryocoolers are Joule-Thomson, Brayton and Claude. In recuperative heat cycle, the heat exchange between the hot and cold fluids occurs through a solid wall that separates the fluids. The heat is transferred from the hot fluid to the wall, and then from the wall to the cold fluid. Figure.1 shows the Joule-Thomson cryocoolers wherein a JT valve is used for cooling the gas. In the Brayton cycle, an expansion device is used, while in the Claude cycle, both an expansion device and JT valves are used. These are also shown in figure. 1.1

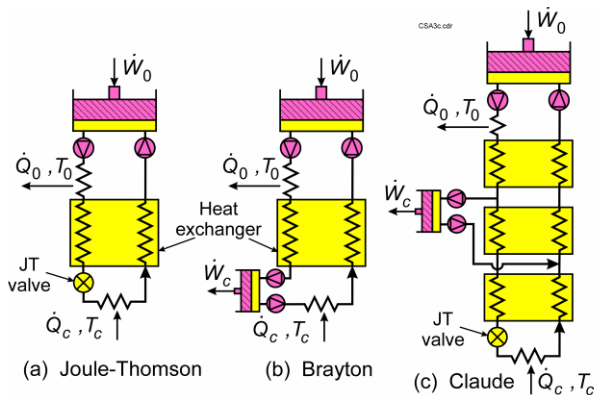


Figure 1.1: Schematic of Recuperative Cycles

Regenerative type cryocoolers are Stirling, Pulse tube and Gifford-McMahon cryocoolers. In these cryocoolers regenerative type heat exchangers are used. Regenerative heat exchangers use a single flow path for both hot and cold fluids, alternately storing heat in a thermal storage medium (such as a matrix) and then transferring it to the cold fluid. In Stirling and GM cryocoolers a regenerative heat exchanger is used. This is mounted inside the displacer of the system. During the compression part of the cycle, the gas is moved to the cold head zone. Durning the expansion part of the cycle, cooling is produced by the gas expansion. The movement of the displacer is synchronised with the movement of the compressor piston in the Stirling cycle system. On the other hand, the movement of the displacer is synchronised with the valve openings in the case of a GM-Cryocooler.

Figure 1.2 shows the schematic of Stirling and GM Cryocoolers based on regenerative type heat exchangers. In the case of Pulse tube cryocooler, the displacer piston is absent which enables the working fluid to perform as a gas piston. By this there are no moving components in the cold zone of the pulse tube cryocooler which increases its reliability in performance.

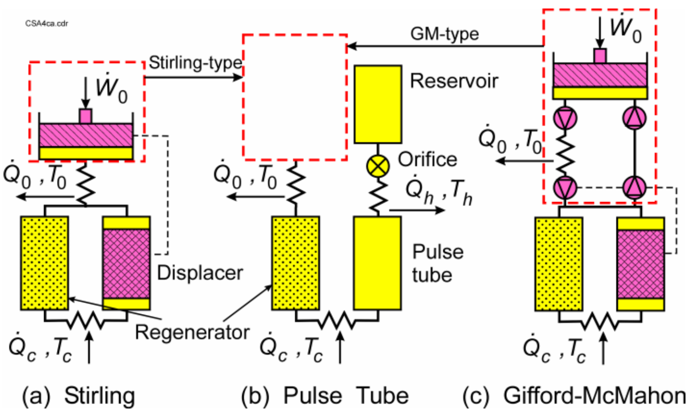
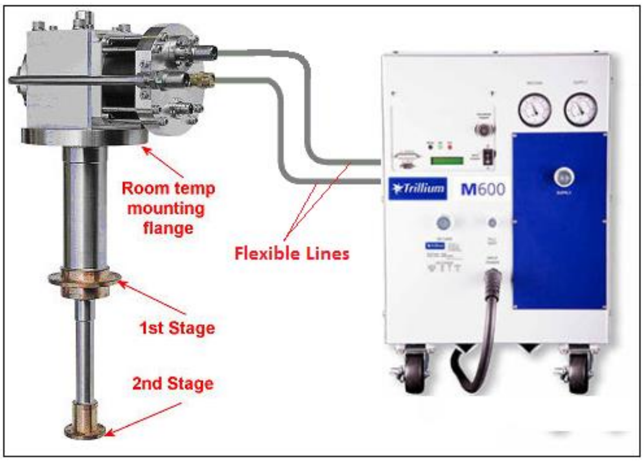


Figure 1.2: Schematic of Regenerative Cycle based cryocoolers (a) Stirling (b) Pulse tube and (c) Gifford McMahon

We will discuss in detail the working of the GM-Cryocooler which concerns the major part of this work.

1.1 GM-CRYOCOOLER

In a GM Cryocooler, cooling at the cold end is accomplished by pressure oscillations. Cooling will be maximum when there are proper phase angles between the mass flow rate and the pressure. Usually, the GM cryocooler runs at 1 to 2 Hz. GM cryocooler uses helium as the working fluid. GM cycle consists of 2 constant pressure processes and 2 isothermal processes and is known as Ericssion cycle. The lowest temperature of the order of 8 K is obtained when using lead as the regenerator material. However, still lower temperatures close to 4K can be reached by using rare-earth-based regenerator materials.



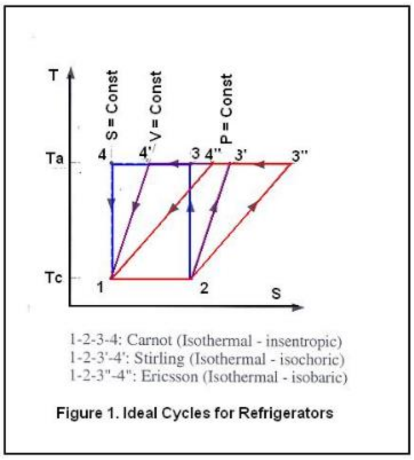
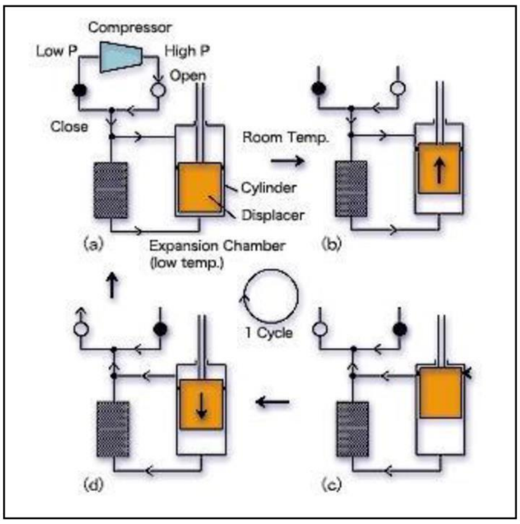


Fig. 1.3 GM Cryocooler and the associated thermodynamic cycle involves two isothermals and two constant pressure processes known as Ericsson cycle

1.2 GM Refrigerator Cycle

The working of the GM Cycle refrigeration system is described below.[1]



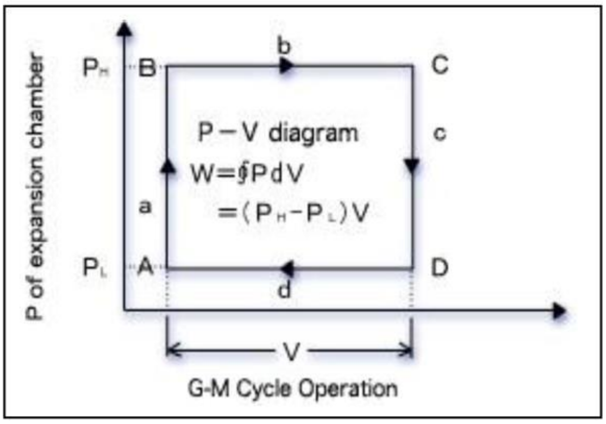


Fig 1.4: Working cycle of GM-Cryocooler

- The P_L valve is shut, and both the P_H and displacer valves are opened. The displacer is placed at the bottom of the cylinder - Point A.

- The pressure that is present inside the cylinder rises from P_L to P_H as compressed helium is added. - Process (a)
- The cylinder is under the P_H of pressure. Staying open is the high-pressure valve - At Point B
- Gas is displaced up by the displacing device through the regenerator, which has already chilled from the previous cycle to the lower expansion volume - Process (b)
- Displacer is in the first place. The low-pressure is released as the high-pressure valve shuts - Point C
- During this procedure, gas in the cylinder's bottom volume expands by a J-T like reaction - Process (c)
- Keeps the low-pressure valve open - At Point D
- Displacer begins to descend, displacing the leftover gas from the lower portion of a cylinder through the refrigeration space - Process (d)

1.3 Regenerator materials

In terms of materials research related to the low-temperature region, the most up-to-date regenerator materials continue to be a crucial component in raising the price and performance of cryocoolers. Hence different regenerators show various performances which will help in the field of the development of cryocoolers.

The 1st stage usually contains meshes of different materials such as copper and brass. Usually, the mesh size is based on the mesh number where you count the number of openings in one linear inch of screen. At the end and top of the 1st stage usually, coarser meshes are kept whereas finer meshes are placed at the centre of it. Fig. 1.5 shows the coarser meshes placed inside the 1st stage displacer.

Since 1990, major developments in low-temperature cryogenics have been made thanks to low-temperature regenerator materials like lanthanide. Erbium Nickel (Er3Ni) which has a more specific heat capacity at liquid-helium temperature was the first material to be used in two stages cryocooler which was later replaced by lead (Pb). Toshiba scientists reduced the range of the GMC from 10 K to 4.2 K by considering those modifications in the regenerator material. Later other lanthanide materials such as HoCu2 was used for cooling down to 4K. Researchers continue to look for better regenerator materials to improve the efficiency of Stirling, PT, and GM cryocoolers.

Fig:1.5 Different Regenerator Material (a) ErNi (b) HoCu2 (c) Copper Meshes (First stage)

1.3.1 Regenerator Design

Above 10K

For temperatures above 10K, porous materials with high heat capacity have been used to manage thermal gradients effectively. The stack geometry of these materials is designed to reduce parasitic heat load and increase thermal resistance through contact conductance. Specifically, between 300K and 80K, metal wire discs made of stainless steel or phosphor bronze with diameters ranging from 100μm to 400μm are used. From 80K to 10K, lead shots with a diameter of 200μm are utilized due to their increased heat capacity, which is critical for maintaining low temperatures.

Below 10 K

Below 10K, the choice of regenerative materials becomes even more specialized due to the rapid decrease in volumetric specific heat (C_p) of most materials, contrasted with the rapid increase in Specific heat (C_p) of helium. To address this, special magnetic regenerator materials are employed. These materials are designed to leverage their unique thermal properties at ultra-low temperatures, ensuring effective cooling and stability in the lower stages of the GM cryocooler.

1.3.2 Newer Regenerator Materials

Perfect regenerator should have large volumetric heat capacity in the specific temperature range. Large Heat transfer coefficient & low flow resistance Discovery of rare earth based magnetic materials which have large specific heat below 10 K Need to match the specific heat of helium

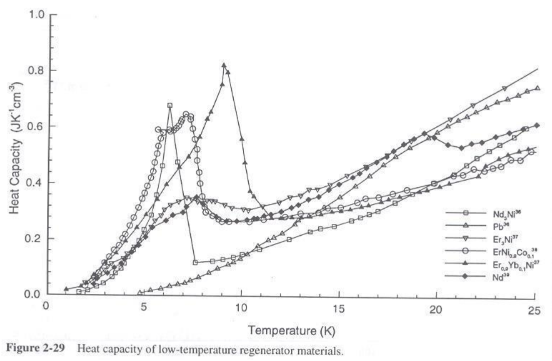


Figure:1.6 Heat Capacity of low-temperature regenerator materials

Since the development of GM Cryocooler in 1959, considerable improvements have been made in the design in terms of the regenerator material, cold head etc. Multi stage systems are needed for obtaining lower temperatures close to 10 K. As discussed above they search for newer Regenerator materials have continued. Currently the GM crack coolers cryo coolers serve the work courses horses for obtaining low temperatures down to 4 K for cooling applications such as cryopumping and MRI magnet cooling etc.

Low temperature GM cryocoolers has usually two regenerators' stages namely the first stage and the second stage. The first stage regenerator consists of copper meshes. The second stage regenerator is filled with either lead (Pb) or Holmium Copper ($HoCu_2$) or Erbium Nickel (Er_3Ni). The materials utilized in the second-stage regenerator play a significant role in determining the performance and efficiency of 4K-GM cryocoolers.

Objectives of this Work

The objective of this work is to indigenously develop the GM-Cryocooler. Since regenerator with its housing is one of the critical components of the GM Cryo cooler, the indigenisation of this component is taken up in initially.

Specific details are as follows

- To take up the fabrication of the displacer of a two-stage GMC by replicating the original system.
- To conduct experiments by integrating a newly built displacer into an existing housing for a displacer, and to achieve the lowest temperature by using the best regenerator material.
- Testing of new Regenerative materials.
- Fabrication of Labyrinth type second stage displacer housing.

Organisation of this report

The report is organised as given below. Following this introduction chapter the literature review is discussed in the second chapter. The experimental setup and its procedures for conducting the experiments are discussed in chapter 3. The next chapter discuss the theoretical analysis of the single stage type GM Cryocooler using REGEN software The experimental results are discussed in the next chapter detail discussions on the expert results are presented in chapter number 5 the last chapter discusses the conclusions and the scope for future work in this area.

CHAPTER 2

LITERATURE SURVEY

Introduction

In the last 20 years, cryocoolers have greatly advanced, enabling many more cryogenics applications to develop and enter the market. Cryocoolers have a number of traits, much like other emerging technologies, that make it impossible for them to successfully compete with methods that use ambient temperature. Cryocoolers also have a number of advantages, but these advantages only hold true if they outweigh the negatives, which provide a potential obstacle to cryocoolers' general market acceptability [6]. The operational distribution of cryocoolers present in the direction of refrigeration power vs. temperature is depicted in the following fig. 2.3 [6].

2.1 Developments in GM cryocooler

M. Thirumaleshwar *et al* [3] have developed a two-stage GM cryo-refrigerator and tested, achieved a second-stage temperature of 15.5.K. The gas intake and exhaust of this machine are operated by several methods. To achieve this, the author created and built a spool valve mechanism. When compared to a cam-operated valve, this technique is incredibly inventive yet straightforward. The displacer rod directly drives the spool valve through an actuator. It is quite easy to adjust this valve in relation to the displacer. At room temperature, the valve is functional. It takes just 50 minutes to reach a temperature of 20 K. At 25 K, the refrigeration load is 2.5.W, while at 60 K, it is 12 W. At 70 K and 100 K, the 1st stage refrigeration capacity is 18.W and 26.W, respectively. This two-stage refrigerator's figure of merit is = 0.83%.

K. Y. Hiratsuka, *et al.* [4] have conducted study on Small GM cryocoolers which are recommended in locations where there are cooling space restrictions. A low temperature of about 2.3 K is necessary for SSPDi (Super Conducting Single PhotoniDetectors) for quantum cryptography transmission.A linear compressor were made by them for a small 2K GMC, and the outcomes were distinguished. For Linear and CNA-11, the cryocooler's cooling outcome at 4.2 K was 173 mW and 191 mW, respectively . The data indicate that linear compressors have a greater cooling efficiency below 2.3 K; the linear compressor observed no-load temperature was 2.06 K. The linear compressor operates at greater working pressures because Helium'ssLambda point falls at better working pressures, making it simpler to transmit heat even using a regenerator with a lower heat capacity.

C.Wang, *et al.* [5] have conducted experimental study on the large cooling capacity GM cryocooler, a single-stage, large thermal capacity GMC for the 13–30 K temperature range has been created by them. In the initial stage of the GMC, a rather large cooling power was intended to be provided. The fig. 2.2 shows the graph of temperature vs time for three different regenerator materials.

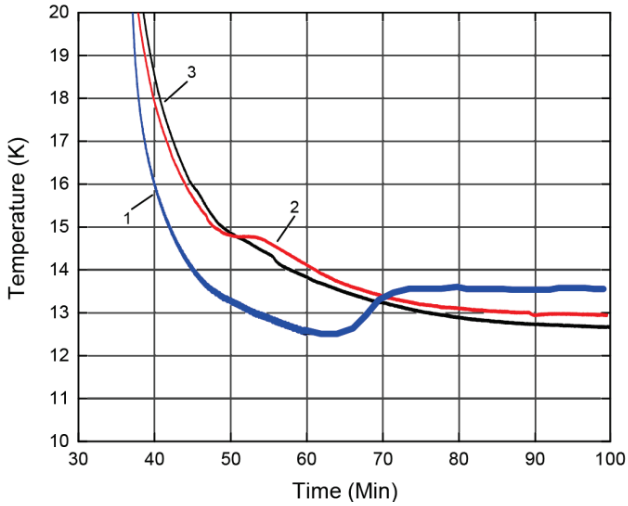


Fig 2.2: Temperature vs Time [3]

The regenerator was set up in three different ways. The regenerator material is divided into two layers, with spherical materials that have a large Cp at low temperatures present in the bottom layer and phosphor bronze panels in the upper layer. For their initial studies, they made use of the AL630 cryocooler created by Cryomech Inc. The temperature of the first type of regenerator dropped to 12.5 K and then rose to 13.5 K after operating for 70 minutes. At 14.7 K, the 2nd type has a plateau. The third type exhibits a gradual cooling process and stabilized around 12.6 K. The researcher came to the conclusion that regenerator efficiency improves with regenerator mass.

K.A. Gschneidner *et al.* [6] have conducted study on regenerative materials by alloying them. Any given material can have its low-temperature magnetic heat capacity changed by alloying with either a rare-earth metal or a non-rare-earth metal. When conducting doping experiments for alloying substitutions, a variety of parameters must be taken into account. The deGennes factor, the crystalline electric field influences, the RKKY contact, and the lattice specific heat are significant among them Although systematic patterns are well understood and reasonably well established, when the concentration of the alloying agent is changed, considerable and unanticipated aberrations take place. It is therefore required to combine an Edisonian approach with systematics to develop better cryocooler regenerator components for uses below 10 K.

C. Wang *et al.* [7] has developed and adjusted the single-stage GMC to achieve maximum performance at the first stage temperature of 25 K. In order to successfully fulfil the 17-cooling demand of some HTS devices. This is accomplished by minimizing losses in the regenerator and rotary valves of the cryocooler. The upgraded GM cryocooler operates with a 50Hz electrical source and has a cooling capability of 109 W at 25 K with an energy input of 10.4 kW. Future HTS devices will require greater cooling capacity at temperatures between 20 and 25 K. The two-stage Stirling cryocoolers currently available have a relatively low COP of 0.45 and have a huge capacity at 25 K. Stirling cryocoolers have a much shorter maintenance interval for HTS devices, while pulse tube-type cryocooler advancements are way behind schedule.

X H Hao, [8] have conducted tests on the GM Cryocooler. They had increased the cooling performance of the ARS pneumatic drive was from 0.8 W to 1.1 W at 4.2 K by optimizing the packing ratio within the 2nd stage and the materials and operating conditions for the regenerator. By enhancing the displacer stroke and operational circumstances, cooling power was increased to 1.5.They had created new helium compressor, the ARS-20's cooling power was able to reach 1.75 W at 4.2 K while the compressor's input was 11.8 KW at 60 Hz

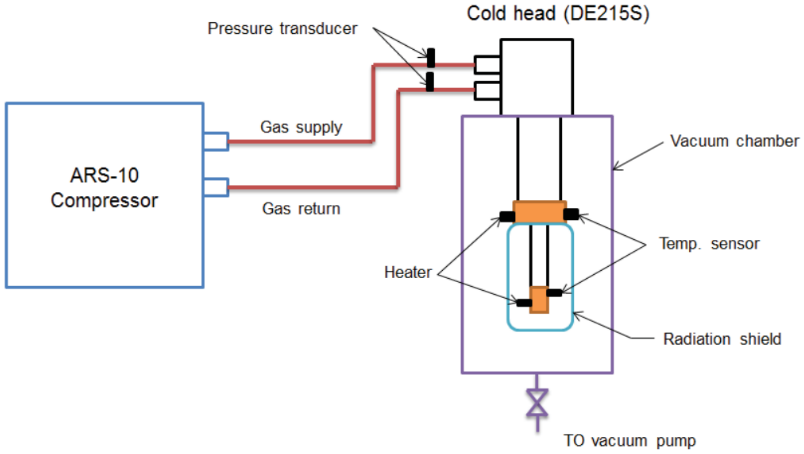


Fig 2.2: Modified Cryocooler [8] Fig 2.3: Cryocooler Setup [8]

Fig. 2.2 shows the complete setup of the cryocooler which can be modified shown in fig. 2.3. Two distinct helium compressors, the ARS-10, and the newly created, modified ARS-20, were used for the test. Using a modified and newly created ARS-20 Helium compressor, cooling output at the 2nd stage of the GMC improves from 1.5 kW to 1.75 kW at a temperature of 4.2 K. However, power input to the compressor also rises, and it is clear that this increase outpaces the rise in cooling capacity, resulting in a decline in COP at 4.2 K.

Rui Li, *et al* [9] had done some theoretical analysis for a compact cryocooler. Some of the crucial requirements to be met included the 1st stage cooling power of 1 W, 2nd stage cooling capacity at 2.3 K 20 mW, and no-load 2nd stage temperature of 2.2 K.The first-stage temperature and second-stage temperature were 45K and 4.2K respectively, when simulation results were received. Before taking into account the real gas impact, P-V power at the 1st and 2nd stages, respectively, was 17.4 W and 3.27 W. However, after taking everything into account that dropped to 17.2 W and 0.56 W.

Qian Baoa *et al.*[10] had created a 2K cryocooler using a standard 4K cryocooler as a base. Cryocooler is small in size and has a very good cooling capability. To verify and check the properties and cooling capacity of this cryocooler, various experiments were conducted. At the second step, 2.1K temperature was attained with no load and even with a 1W load with a 20mW load fluctuation. According to the experiment findings, they discovered or developed a new regenerator component in the warm end of the 2nd stage in place utilizing bismuth as a regenerator material. By using this newly discovered warm side second stage regenerator material, the first stage and second temperatures of the cryocooler using bismuth, which was 45.7, K and 2.46, K, were lowered to 42.2, K and 2.41, K, respectively. Additionally, Gd_2O_2S was used in place of $HoCu_2$ at the cold end of the second-stage regenerator, which resulted in a 0.1 K decrease in no-load temperature. A prototype unit's cooling performance was 44.4 K at the initial stage of testing with a 1 W cooling capacity. 2.23, K was the measured second-stage temperature with a cooling capability of 20 mW. The second stage's no-load temperature was 2.10, K.

A. Bagdinova *et al* [11] have looked at how magnetic fields impact a cryocooler's ability to cool. They found that the magnetic field limits the G-M cryocooler's operational parameters. This restriction has a significant impact on the cryogen-free magnet design. Due to its straightforward and inexpensive operation, cryocooler-based superconducting magnetic devices are becoming more and more common in research labs. Superconducting magnets are cooled using G-M or pulse tube cryocoolers. The cryogen-free magnetic system's weight and dimensions are forced to be increased by the designer due to the magnetic field's uncertainty. The author concludes that after the magnetic threshold of 0.6 T, the cooling capacity of the cold head continues to decline. For a cooling capacity of 0.5 W to 1.5 W, it drops by 22 to 49% at 1.0 T and by 43 to 68% at 1.8 T. In magnetic fields up to 0.6.T, the cooling power essentially does not decrease. The cold head may operate abnormally in magnetic fields greater than 1.95 T.

T. Morie**,** *et al* [12] has opted for a wholly theoretical approach and has created a specific numerical simulation software to theoretically calculate the cooling capacity and estimate losses in the regenerator and heat exchangers. The pressure and volume variation simulation results as well as the Pressure-Volume energy in the second stage expansion volume agree with the measurements. Because a significant quantity of additional enthalpy flow is introduced into the 2nd stage expansion volume from the 2nd stage regenerator, the cooling capacity after accounting for the actual gas impact at the second stage is significantly lower than the Pressure-Volume power. The observed pumping loss was considerably less than the shuttle loss. Due to the limited volume of the clearance or spiral groove, the pulse tube cooling impact is relatively minimal.

Y. Paradis**,** *et al* [13] are working to test and create a low-cost technique for cryocooler maintenance. Here, they have created a heating system that, by maintaining the cold mass at a very low temperature, warms both phases of the cryocooler to room temperature a specialized testing platform with turbo pumps and additional heating system parts. Two kW of electricity and 1.5 KW of power, respectively, were installed in each of the four-second stages. After the SC magnet had cooled, a local heating system was employed to warm up each cryocooler head in order to replicate a maintenance scenario. While the first stage was left at room temperature for 40 minutes, the second stage was maintained there for 30 minutes. During this maintenance simulation, the greatest cold mass temperature was 65 K.

Jean-Louis, *et al* [14] have conducted various by combing cold head and compressor. First they had combined one cold head and one compressor, for the 1st stage they got a temperature of 80K, for the combination of two cold heads and one compressor, it was 100.K, and 80.K for the corresponding cold heads, and for the pairing of three cold heads and one compressor, it was 120.K, 100.K, and 80.K for the corresponding cold heads . The most powerful cooling power of 290 W at 80.K is achieved by the final configuration of 3 cold heads and 2 compressors.7.2% efficiency is achieved using 128 W of cooling power at 80.K when single cold head and single compressor are used together. With a cooling capacity of 150 W at 80.K, the arrangement of 2 cold heads and 1 compressor achieves an efficiency of 8%. In order to provide a cooling capacity of 125 W at 80.K, 3 cold heads and 1 compressor work together to reach an efficiency of 6.6%. For a cooling capacity of 290 W at 80.K, the final configuration of 3 cold heads and 2 compressors yields an efficiency of 8%. These are the performances of single and multiple systems at 80 K. The below fig. 2.9 shows different combinations

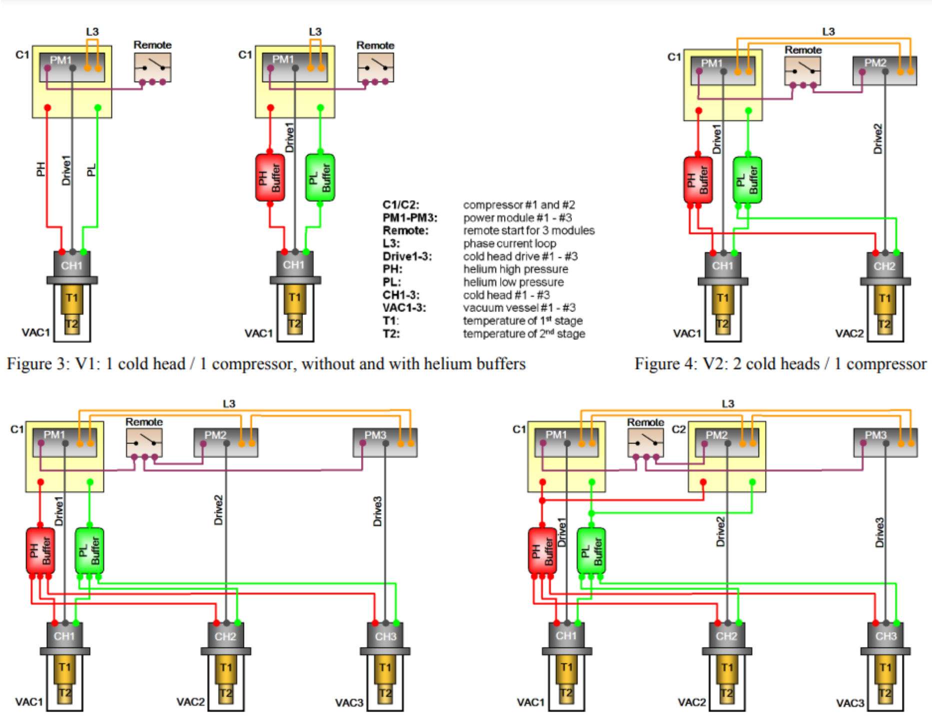


Figure 3: V1: 1 cold head / 1 compressor, without and with helium buffers

Figure 4: V2: 2 cold heads / 1 compressor

Figure 5: V3: 3 cold heads / 1 compressor

Figure 6: V3_2: 3 cold heads / 2 compressors

Fig 2.4: Various Combinations of Cold Head and Compressors [14]

S.C. Chang *et al.* [15] in their current work, a regenerator half-cycle average energy approach is formulated in place of the regenerator's transient heat transfer analysis. The momentum and mass evens of a GMC's dynamic equations are first calculated and numerically solved for the time variables. The regenerator half-cycle average energy equation is then used to obtain the half-cycle average variables and the regenerator effectiveness. The final answers can be reached by an iteration process, and from there, the system capacity of the GMC can be assessed. A systematic study of a single-stage cryocooler was also developed using the PC-based simulation program GMSYS. Finally, it has been empirically demonstrated that the performance forecast closely matches the test results.

XU Xiang-dong *et al.* [16] have conducted a theoretical analysis for choosing the matrix for temperatures where helium gas is compressed in the regenerator, it is essential that the material has high values of Cm (T). This will result in a reduced f value and less loss during refrigeration. As can be observed, this temperature range for Er3Ni and ErNi2 is between 4.K and 6.K and depends on Cm (T) itself. An increase in regenerator duration can easily offset the negative effects of relatively low values of Cm (T) at elevated temperatures. For regenerators with matrix porosity of p=0.42, it is recommended that the regenerator void volume be marginally higher than what is required to hold all of the M at the conclusion of the cold phase.

For Er3Ni and ErNi2, this specifies a regenerator volume-to-expansion space volume ratio of 3.to 3.5.

C Wang, J Cosco**,** *et al.* [17] had modified, redesigned and the operational parameters have been optimized for Cryomech type AL600, The AL600 has a 129W at 30.K, 701.W at 80 K, and 1005.W at 120.K output capacity. This GM cryocooler is the most efficient, effective, and quick to cool down of any GM Cryocooler to date. The use of a redesigned bumper design has resulted in an 82% reduction in cold head vibrations. For many applications, this latest generation AL600 GM cryocooler promises to be more appealing.

Anand *et al.* [18] had determined the rate of heat transfer from radiation is 0.371 W. The rate of heat transfer from pipe conduction is 1.0932 W while the heat transfer rate from molecular gas conduction is 0.00292 W. All of these rates of heat transfer values were measured with the sample holder positioned on a cold finger that was maintained at the same temperature of 4.K. At a constant temperature of 4.K, the total heat transfer rate is equal to 0.371 + 0.00292 + 1.0932 = 1.46712 W. The cryocooler's rated capacity is 1.5.W at 4.K temperature.

Ray Radebaugh, *et al* [2] have conducted study on packing of different regenerator materials inside the regenerator..They had conducted experiment on RDK-408D2 (SHI) GM cryocooler, by employing a double-pipe regenerator arrangement for the 1st time. The effectiveness of a 3-layer regenerator made up of Pb, HoCu2, and GOS was compared to a three-layer configuration using a stainless-steel pipe, as illustrated in the fig. 2.5 shown below.

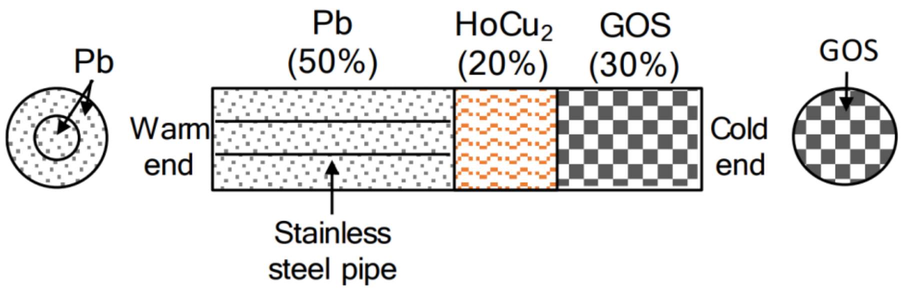


Fig 2.5: Three-layer Regenerator [17]

Takaaki Moriea *et al.* [19] had conducted study on The SHI 1W 4K GM cryocooler, which is maintained in its chilling capacity under a magnetic force of up to 2.0 T by using a hybrid regenerator made of HoCu2/Gd2O2S. Maintaining the second stage underneath the helium-roiling boil of 4.2.K in a magnetic force of up to 2.0.T is particularly dependent on the magnetic regenerator component Gd2O2S. Additionally, it is anticipated that an operating cryocooler will produce less magnetic noise. It's feasible to make superconducting magnet systems, like MRIs, more compact by using this type of cryocooler. Additionally, it can be used to cool a system of superconducting magnets that produces a strong magnetic field.

S Masuyama *et. al* [19] had conducted experiment on the second stage displacer. A double pipe regenerator was added to the 2nd stage regenerator of a GM Cryocooler made of lead, HoCu2, and GOSi spheres in order to increase efficiency and cooling capacity at 4.2.K. It was possible to achieve first-stage cooling efficiency of 64.9 W at 50 K and 2nd stage cooling efficiency of 1.67 W at 4.2.K. According to the experimental findings, the second-stage cooling capacity at 4.2iK can be improved by the double-pipe regenerator. According to the regenerator analysis, the double-pipe regenerator may reduce non-uniform flow and then boost cold-end mass flow rates. At the 1st stage temperature of about 50.K, this effect becomes significant.

Ray Radebaughh., *et al* [21] have demonstrate that for regenerators running down to 4 K, decreased porosity can dramatically minimize regenerator loss. The regenerator's volume should be kept to a minimum in order for the temperature profile covers the majority of the device without "breaking through" at the cold end. Only when the ratio of void volume to swept volume is set fairly big (>5) can the regenerator loss at a frequency as high as 20 Hz be kept as low as that for 2 Hz . Large phase angles (>30°) between the mass flow at the two ends of the regenerator are caused by such high-volume ratios. Such a wide phase angle can be supported in a two-stage system with a suitably large phase difference present at the cold end without adversely affecting the 1st stage's performance.

T. Yanagitani**,** *et al.* [22] had conducted experiment on a 4.K cryocoolers and modified the regenerator to a brand-new magnetic regenerator alloy called GOS has been created. In addition to realizing lower costs compared to conventional metallic magnetic regenerator components, the fabrication procedures are improving to generate more uniform sphere particles with adequate stiffness as the regenerator material. Industrial cryocoolers are currently being used in long-term studies. No broken particles were discovered, and a heat load of 1 W led to a temperature stability unit of measure at the second stage regenerator of 45 mK after a month of nonstop operation. To accommodate the wider temperature ranges, numerous more ceramic magnetic regenerator elements are now being developed. Additionally, new creative strategies are being researched to use flexible ceramic fabrication to make the regenerator setup much simpler.

T. Izawa**,** *et al.* [23], have modified the regenerator by creating nitriding metallic spheres, HoN and ErN spheres and the performance of their regenerators were assessed by evaluating the cooling power, or CP, of a GMC that was filled with the samples. Under 4.2 K was the temperature that was reached. The cooling capacity of the nitride structures was decreased by contact area, oxide, and porosity impurities. The cooling capacity of ErN was calculated and discovered to be greater than that of HoCu2 by taking these defects into consideration. The significant specific heat, which is generated by the magnetic transition and spikes at about 5K, is what gives this excellent performance.

Vikas. R *et al*. [24] conducted study on displacer sealing and finds that the standard displacer sealings become ineffective at low temperatures because of hardening and variations in pressure differences that are seen inside the expansion volume as it oscillates, which causes the seal to shift. This causes leakage of the working gas because the viscosity of the working gas decreases significantly at lower temperatures.

Xihuan Hao et.al.[25] their experimental studies have indicated that the sealing between the first and second stages of the displacers is quite important. The experimental studies performed by them shows that there are significant improvements in the performances of 2 stage GM cryocooler by the use of labyrinth type regenerator. The dimensional details are given in the publications listed below in figure 2.6

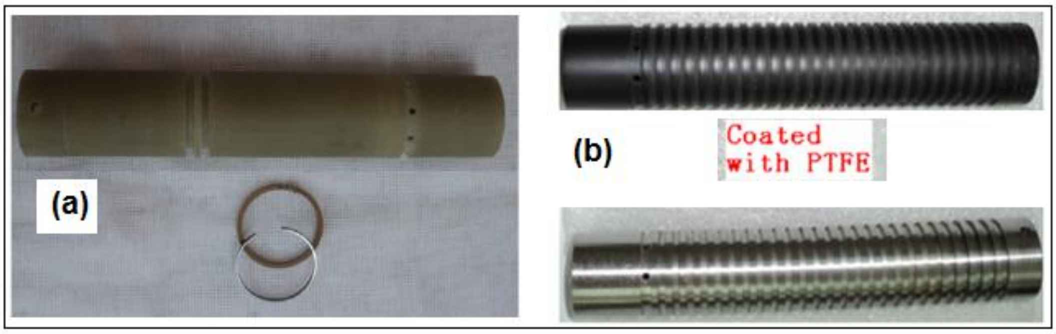


Fig.2.6. (a) Original displacer with seal ring. (b) Labyrinth type displacer- Upper one is Teflon coated and the lower one is made of thin-walled stainless tube

This chapter reviews research conducted on the performance of GM cryocoolers, focusing particularly on modifications to the regenerator material and structure. One key area of investigation has been the impact of changing the regenerator material on the cryocooler's efficiency and cooling capacity. Additionally, structural modifications to the regenerator, such as implementing a layered design or transforming the body into a labyrinth type, have been explored to enhance performance. The chapter synthesizes findings from various studies documented in the literature, providing a comprehensive overview of the advancements and experimental outcomes in this field.

CHAPTER 3

EXPERIMENTAL PROCEDURE

3.1 CTI model 350C Cryodyne Cryocooler

Although our objective is to develop high performance 4K GM cryocoolers, to start with one should take a prototype of smaller capacity. It should be easy to fabricate and test and also should be scalable to bigger sizes. We have chosen the model 350C CTI Cryodyne cryocooler for the initial development through reverse engineering. This system provides reliable refrigeration at cryogenic temperatures for long, continuous periods. Also, a couple of units are available in CCT which can be dismantled for obtaining dimensional details. This cryocooler consists of the Model 350CP Cold Head, the Model SC Compressor Unit, interconnecting piping. The total system consists of the Model 350CP Cold Head, the Model SC Compressor Unit and the interconnecting helium hoses.

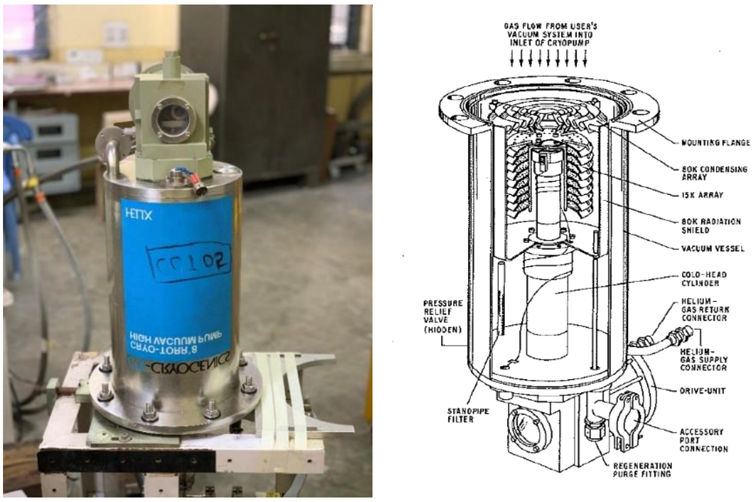


Figure:3.1 Cutaway view of cryopump

3.2. Components of cryocooler

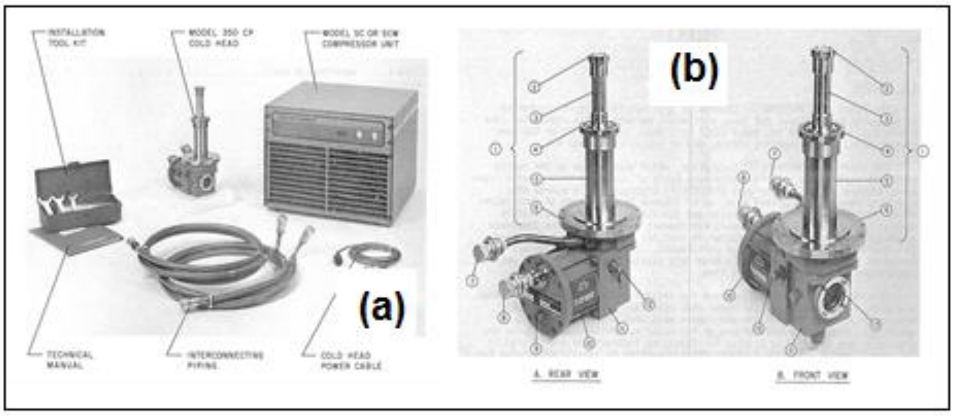


Figure 3.2. CTI model 350C Cryodyne Cryocooler: (a) All components and (b) front and back views of the cold head

The main components of this cryocooler are the following. (1) Cold head zones of the first and second stages where the refrigeration is produced, (2) its internal part namely the first stage and second stage displacers with regenerator materials (3) the cam drive mechanism which allows the displacers movement up and down, (4) the right regenerator materials and (5) vacuum jacket. Of the above, the most critical parts are the cold head housing and its internal parts namely regenerators for the first and second stages and the materials used for the regenerators. The design and fabrication of these components must be addressed to start with. Hence, this work was taken up under the above project.

From the manuals provided by the manufacturer, we obtained the proper procedures for dismantling the system without any damage. Further, we started with the design and fabrication of the displacers for the first and second stages. The new regenerator fabricated can then be tested within the cold head housing to evaluate the cryocooler performances. The available parts of the Cryodyne system such as the sealing rings between the first and second stages, the cam drive mechanism with its motor, the air-cooled helium compressor with its hoses etc. were used to test the above indigenously developed system. On successful completion of the above tasks, the development of other components of the cryocooler can then be taken up.

3.2.1 Cold Head

The cold head comprises a two-stage cold head cylinder, integrated within the vacuum vessel, and a drive unit displacer assembly. Together, these components facilitate closed-cycle refrigeration, achieving temperatures ranging from 50 for the first-stage cold station and 10 to 20K for the second-stage cold station, contingent upon operational parameters. Within the drive unit displacer assembly, the displacer-regenerator assembly, actuated by the drive unit, controls the helium flow into the cold head. The drive unit encompasses the crankcase and a direct-drive constant-speed motor, functioning at 72 rpm with 60Hz power and 60 rpm with 50 Hz power. During operation, high-pressure helium from the compressor enters the cold head via the helium supply connector, traverses through the displacer-regenerator assembly, crankcase, and motor housing, and exits through the helium gas return connector to return to the compressor. Helium expansion within the displacer-regenerator assembly facilitates cooling at both the first and second-stage cold stations.

Figure:3.3 (a) and (b) Coldhead bottom view side view

3.2.2 Helium Compressor

A traditional compressor equipped with inlet and outlet valves, or alternatively a scroll compressor, serves as the means to create high- and low-pressure sources. These compressors are standard oil-lubricated units commonly found in air conditioning or refrigeration systems, adapted for helium gas applications, particularly in commercial cryocoolers where cost-effectiveness is paramount. Oil removal apparatus can be installed along the high-pressure line to mitigate pressure fluctuations. While the inclusion of valves significantly impacts system efficiency, they enable the utilization of readily available mass-produced refrigeration compressors.
The compression of gases at cryogenic temperatures presents unique challenges due to the properties of these low-temperature fluids. Cryogenic compressors must be able to handle the low temperatures without compromising their performance or integrity. They are typically designed to operate in a closed-loop system that involves cooling the gas or vapor to cryogenic temperatures, compressing it, and then raising its temperature back to ambient conditions for further processing or storage.

Figure:3.4 Helium Compressor

3.2.3 Vacuum Pump

Vacuum pumps are critical components in cryogenic systems, which often require extremely low pressures to achieve and maintain cryogenic temperatures. In cryogenics, vacuum pumps are used to evacuate air and other gases from a chamber to create a low-pressure environment. Here are the main types of vacuum pumps used in cryogenics and their roles:

1. Creating and Maintaining Low Pressure: Essential for reducing the thermal load due to residual gas molecules, which can affect the cooling efficiency and temperature stability of cryogenic systems.
2. Reducing Heat Transfer: By removing gas molecules, vacuum pumps reduce convective heat transfer, allowing cryogenic systems to maintain lower temperatures with less thermal input.
3. Supporting Cryogenic Insulation: In systems like cryostats or cryogenic storage vessels, high vacuum levels provide insulation by minimizing gaseous conduction.

4. Facilitating Rapid Cool-Down: Efficient evacuation of gases allows cryogenic systems to reach desired low temperatures more quickly, improving the overall efficiency and reducing operational time.
5. Maintaining Clean Environments: Especially in applications like cryogenic particle detectors or space simulations, vacuum pumps ensure that the environment remains free from contaminants that could interfere with sensitive processes or measurements.

Types of Vacuum Pumps Used in Cryogenics are Rotary Vane Pumps, Scroll Pumps, Turbo Molecular Pumps (TMP), Cryosorption Pumps, Diffusion Pumps, Ion Pumps.

Figure:3.5 Vacuum Pump

3.3 Dimensional drawings of various components

Detailed dimensional drawings were prepared which are shown below-

The following figures shows the Coldhead of the GM cryocooler.

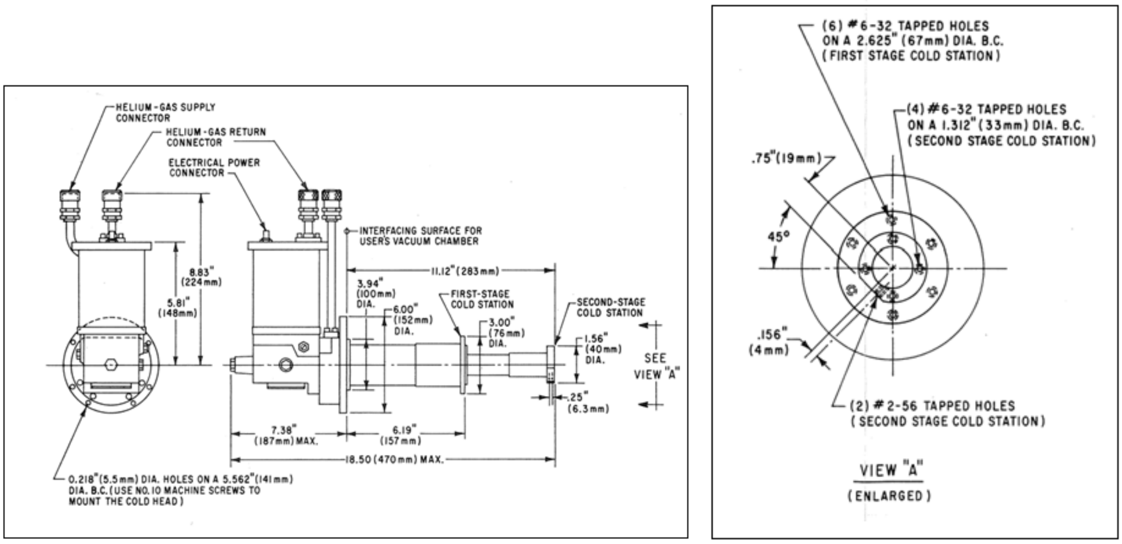


Figure 3.6. Dimentional details and the installation Interface of the model 350C cold head

Figure 3.6 shows the front and back views of the cold head and External dimensional details and the installation Interface of the model 350C cold head.

The most critical part in the GM cryocooler is its cold head, which is the cold producing machinery. One should prepare the detailed dimensional drawing of this part. This consists of the cold head heat exchangers for the 1st and 2nd stages (which form the part of the chamber wherein working fluid undergoes expansion), the displacer, which is the moving component and has the regenerator within it. The drive mechanism can be cam operated type or rotary valve type. In the present case, cam operated type drive system is used.

Detailed dimensional drawings of the first and second stage displacer

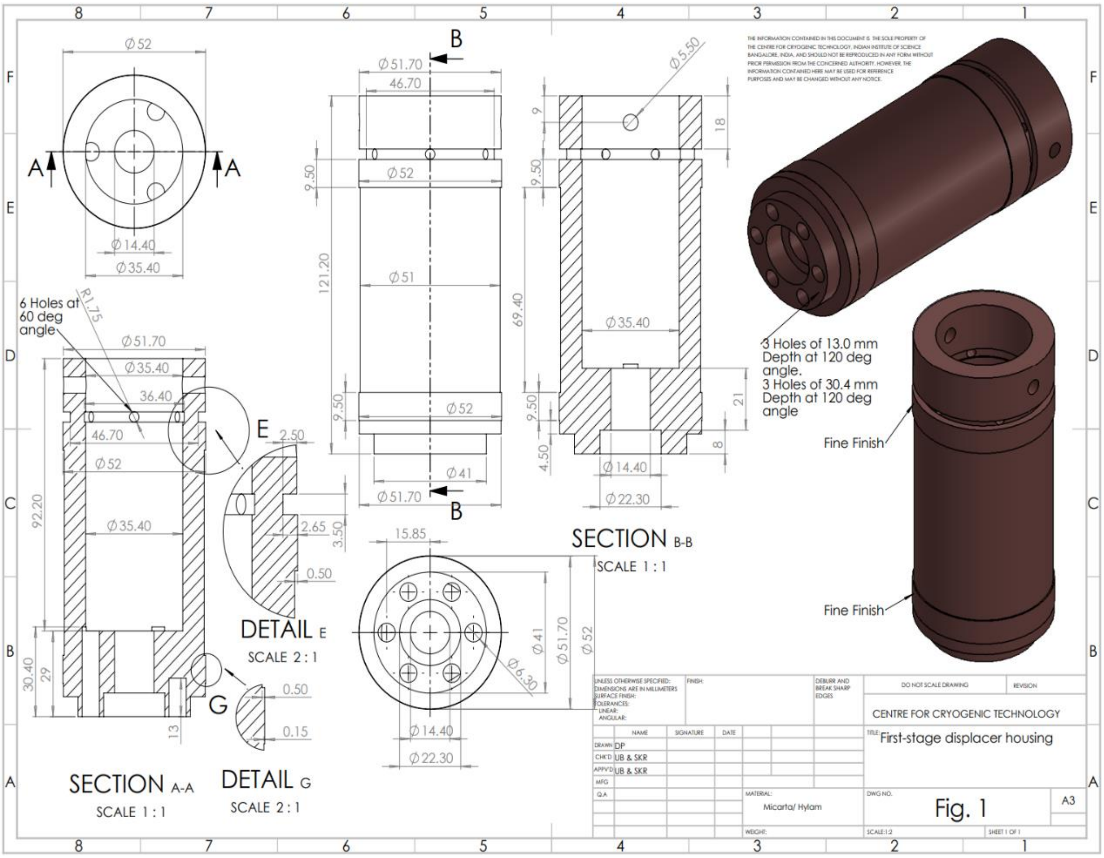


Fig: 3.7 1st stage displacer

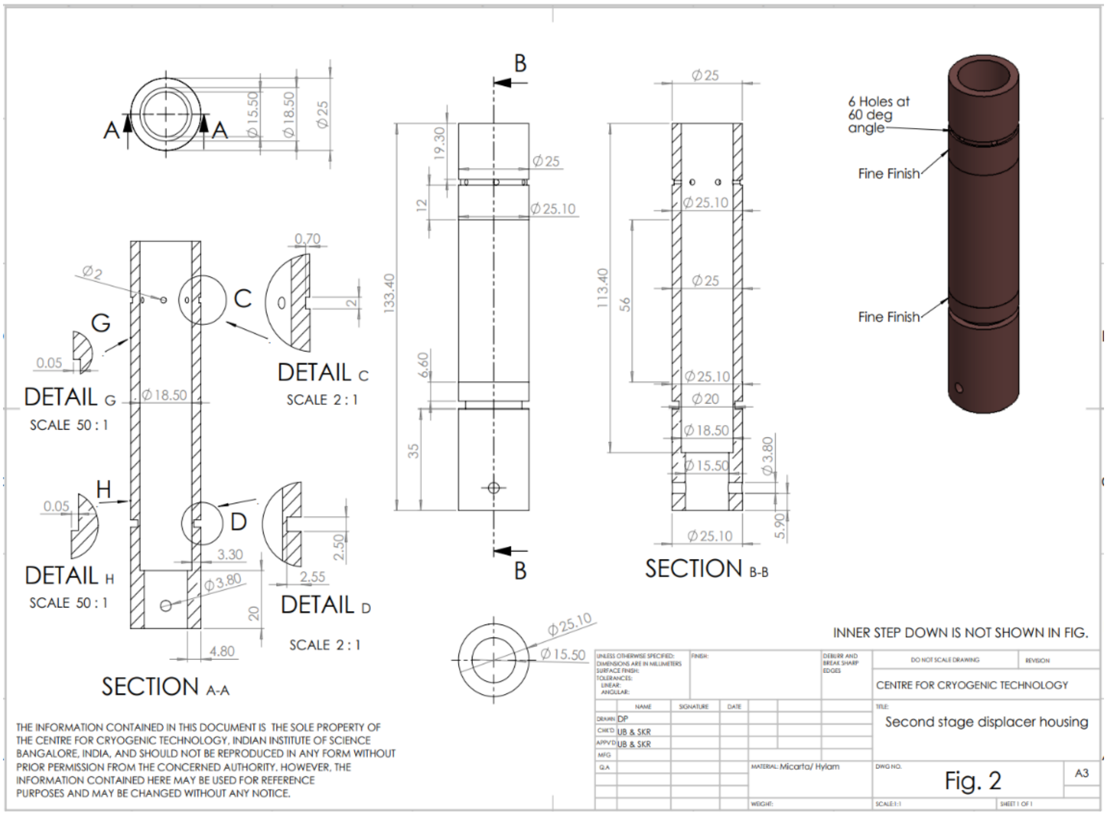
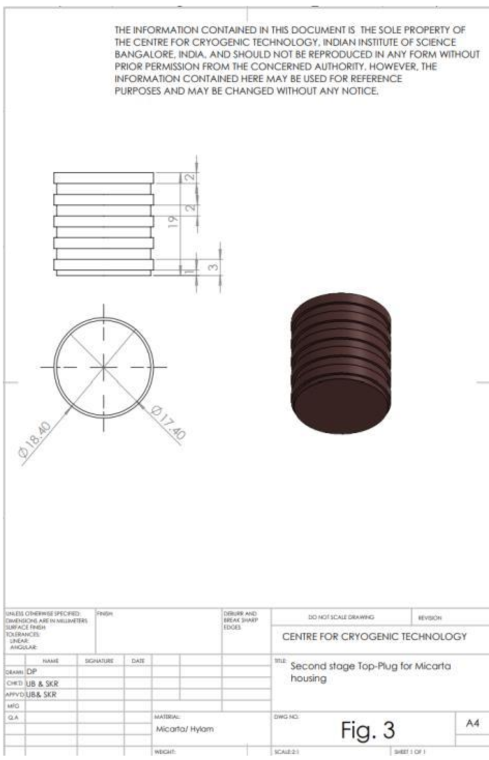


Fig 3.8 2nd stage displacer



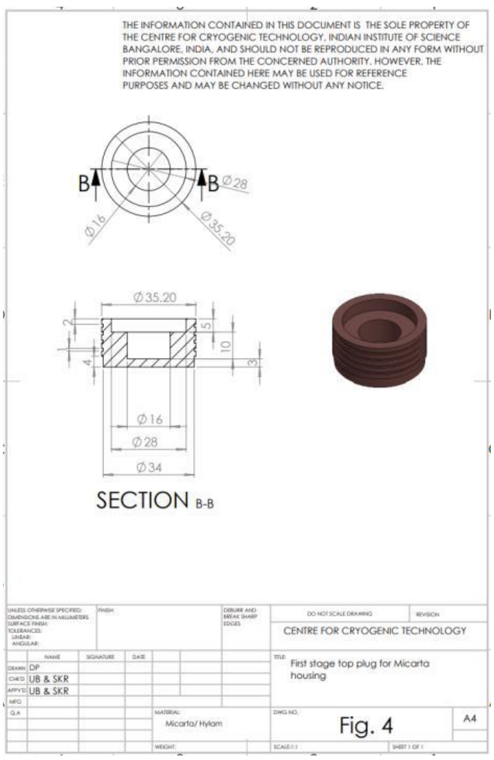


Fig:3.9 2nd Stage Top-Plug   Fig:3.10 1st Stage Top-Plug

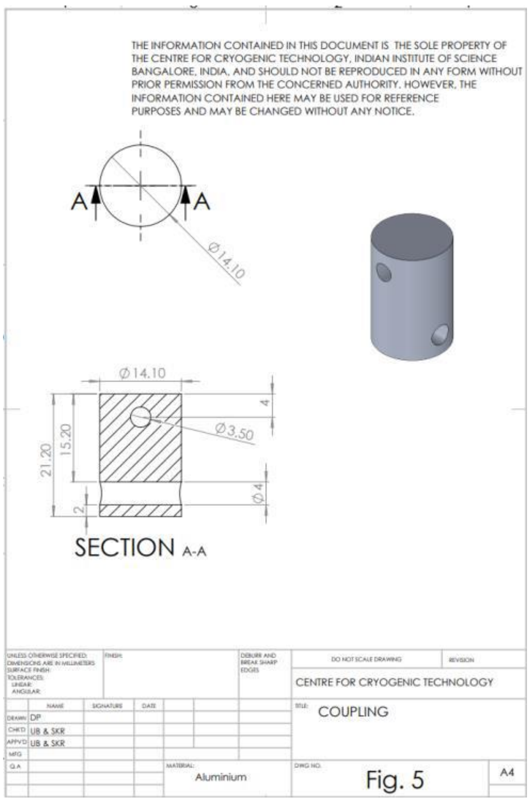


Fig:3.11 Aluminium Coupling

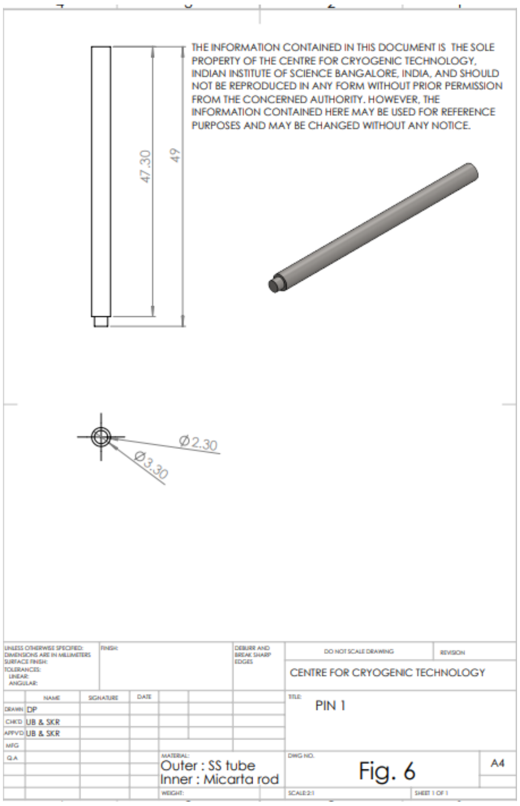


Fig: 3.12 Pin-1

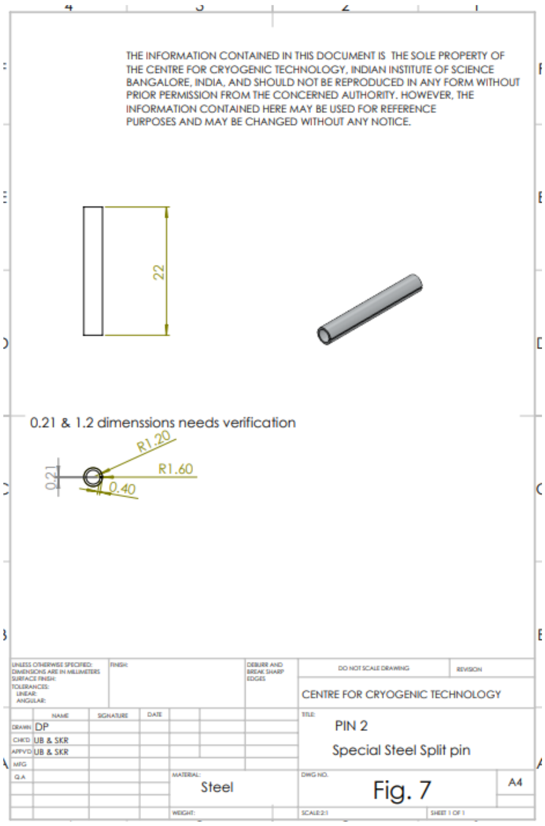


Fig 3.13: Pin-2

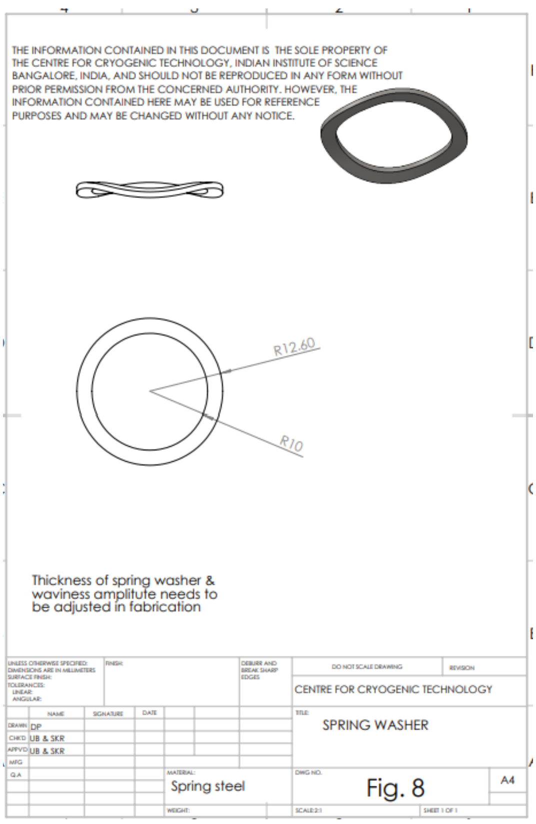


Fig :3.14 Spring Washer

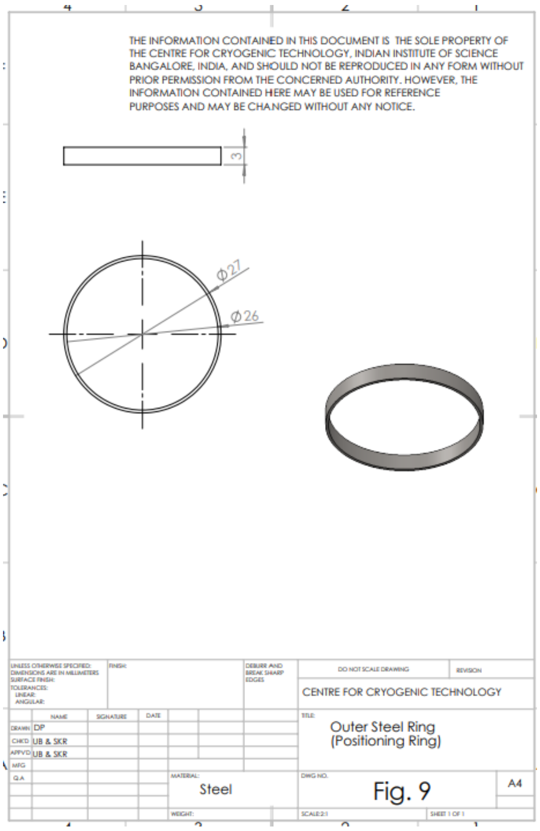


Fig :3.15 Outer Steel Ring

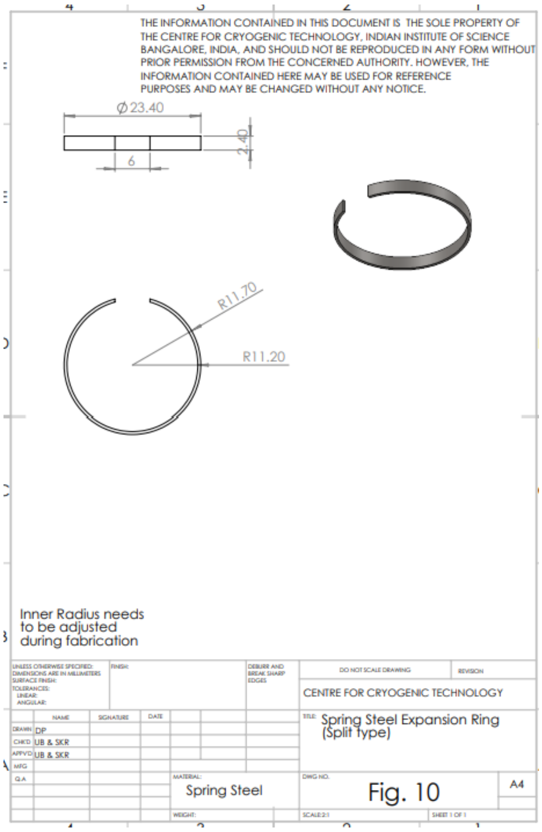


Fig:3.16 Spring Steel Expansion Ring

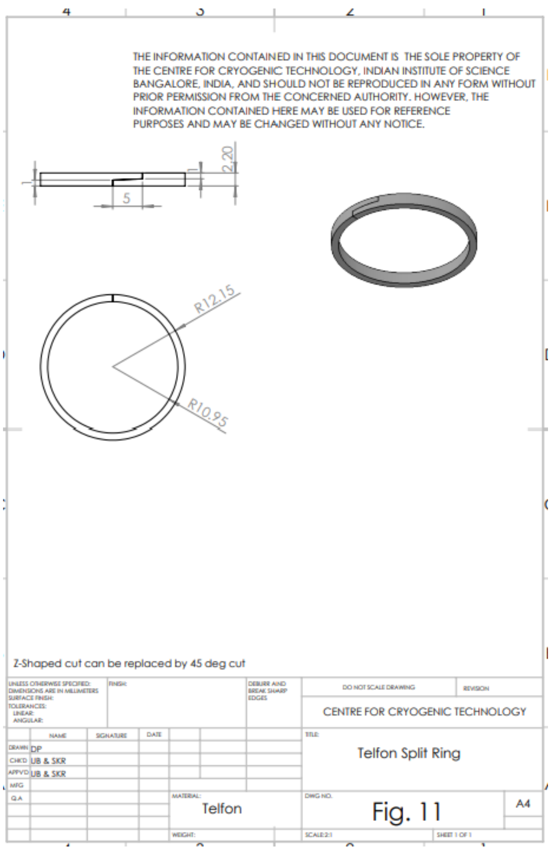


Fig 3.17: Teflon Split Ring

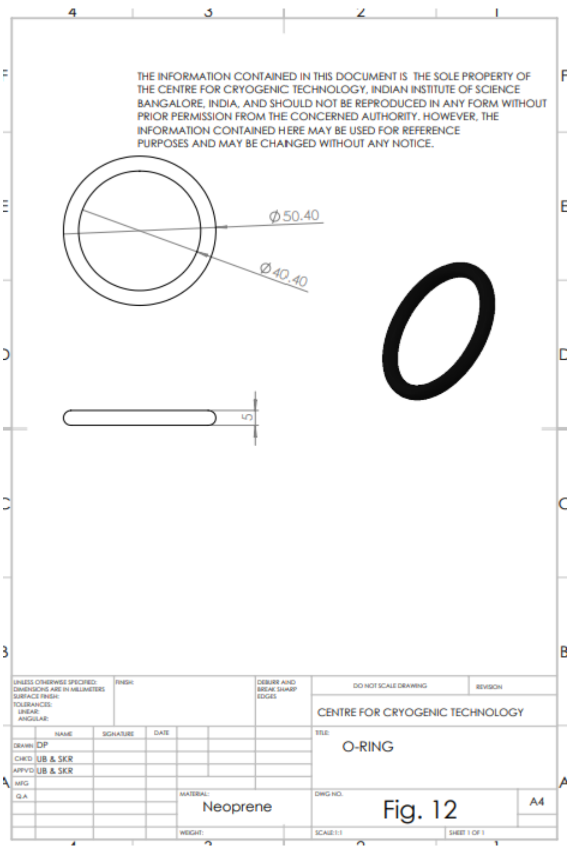


Fig 3.18: O-Ring

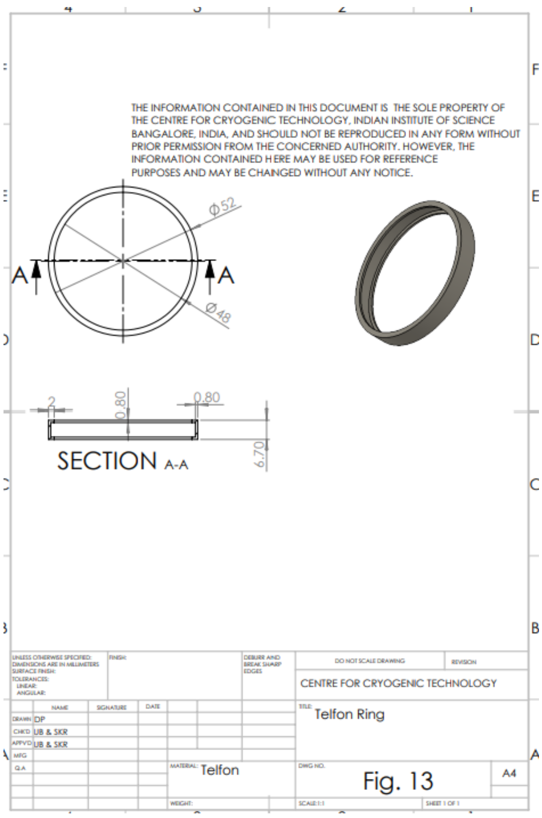


Fig 3.19: Teflon Ring

3.4 Procedure *for dismantling and assembling*:

After releasing the internal gas pressure, the displacer is removed from the cold head by unscrewing the appropriate screws. Next, the total displacer assembly is removed from the cold head housing. Next the 1st and 2nd stage displacers are separated by removing the intermediate connecting pin.

The coupling in between the stages is made of a small aluminium cylinder. The connecting pins for the first and second stages are mounted in the perpendicular holes on this cylinder.

Now the second stage displacer is machined at its top to remove the closing plug and expose the top zone of the regenerator. The structure of filling the regenerator materials as well as its weight are noted. Now a new plug has to be used to close the top part of the displacer by an adhesive. On the other hand, a threaded arrangement will also be suitable in case the same plug needs to be used many times.

The regenerator materials used for the first stage are copper meshes, with coarser meshes at the top and bottom parts and finer meshes in the mid zone to maintain the proper gas flow. The regenerator material used in the second stage original Cryodyne system is lead powder along with felt to ensure that powder does not get carried towards the compressor side.

The sealing of the first stage in the cold head housing by a Teflon ring backed by an O-ring. On the other hand, the sealing for the 2nd stage is done by a Teflon split ring expanded by a suitable ring of spring steel. An appropriate mounting tool is used for the fixing of the sealing rings in the first and end stages.

After dismantling both stages, detailed dimensional drawings were prepared for the individual components. Bakelite rods of suitable dimensions were procured from the suppliers and they were used in place of Micarta to fabricate the displacer housings and the plugs. The dimensional drawings of the various components in figure 3.20.

We have used the old regenerator materials into the new displacer housings and the entire system was assembled into cold head housing of the cryocooler. Few preliminary runs were made to ensure proper movement of the displacer within the cold head housing. Subsequently, temperature sensors were mounted to the first and second stages. The system was run to for long hours to obtain the lowest possible temperature in the first and second stages. The regenerator material structure should be optimized to obtain the best performance of the cryocooler.

As discussed, regenerator housings were fabricated using Hylam / Bakelite rods as per the complete dimensional drawings. Subsequently different regenerator materials have been filled in the 2nd stage. In the first stage the original meshes are filled. With the same cam assembly for the displacer movement and air-cooled helium compressor (1.5 kW) for tests, all the experiments have been performed. Photographs of the various components are shown Fig. 3.20, while those of regenerator materials in Fig. 1.5.

Fig.3.20 Regenerators, their housings, cam arrangement and assembly

3.5 THERMAL INSULATION

Figure 3.21: First stage insulated Figure 3.22: Second stage insulated

Figure 3.23: Insulated with MLI Figure 3.24: Second stage with Radiation Shield

Effective thermal insulation is critical in cryocooler systems to minimize heat transfer and enhance cooling performance. In this study, the cryocooler was insulated using multilayer insulation (MLI) to prevent radiative heat transfer, which is a significant source of thermal load in cryogenic systems. The first stage of the cryocooler was equipped with multilayer insulation, as shown in Figure 3.21. This insulation layer serves to significantly reduce radiative heat transfer, thereby maintaining lower temperatures at the first stage and improving overall system efficiency.

Similarly, the second stage was also provided with multilayer insulation, as shown in Figure 3.22. The use of MLI at this stage is crucial as it further reduces the radiative heat load, ensuring that the second stage can reach and maintain the desired low temperatures. To enhance the thermal insulation of the second stage, a copper plate was integrated as shown in Figure 3.23. The copper plate acts as an additional barrier to radiative heat transfer, complementing the multilayer insulation. Copper's high thermal conductivity helps in evenly distributing any absorbed heat, thereby protecting the second stage from localized thermal hotspots. Finally, both the first and second stages, equipped with their respective multilayer insulation and additional copper plate for the second stage, are shown in Figure 3.24. The combined insulation setup ensures a robust barrier against radiative heat transfer across both stages, contributing to the overall thermal stability and efficiency of the cryocooler.

3.6 Displacer Developed

Figure:3.23 Second stage Displacer   Figure:3.24 First stage Displacer

The body of the original displacer is made of “Micarta”, which is not available in our country and hence needs to be imported. We have gone ahead by choosing “Bakelite” which is perhaps the near equivalent for the above. In First stage the regenerative materials which are meshes and are coarser on the top and bottom in the middle the material is finer. In the second stage

3.7 Labyrinth Type Displacer Developed

The labyrinth type displacer developed at CCT is shown in Fig.3.25 The regenerator filling is carried out as in the earlier cases. Fig.3.26 shows the detailed dimensional drawing of the displacer. The width of the groove is 2.0 mm and its depth is 1.2 mm. The same dimensions are followed in our fabrications as well.

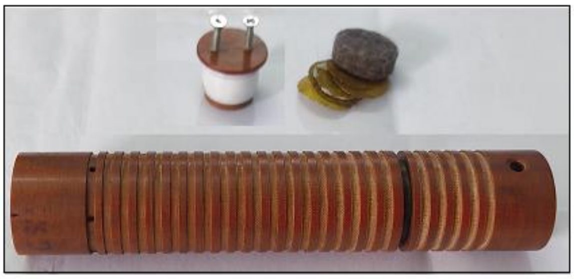


Fig.3.25. Labyrinth type displacer, top plug, felt and top meshes

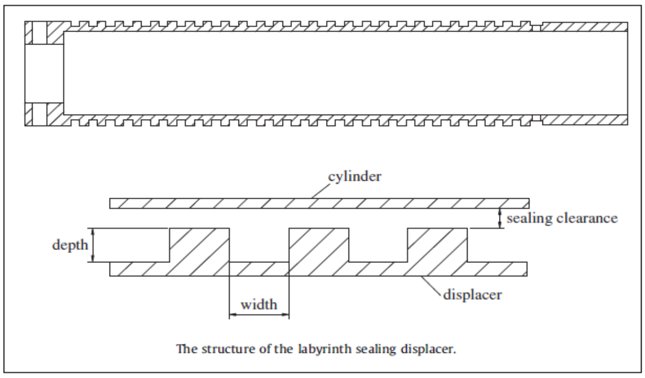


Fig.3.26. Dimensional details of the Labyrinth type displacer

3.8 EXPERIMENTAL SETUP

The second stage regenerator filled with the appropriate regenerator material is selected for experiments. Next, the displacer of the GM cryocooler is assembled on the Cam drive as shown in Fig. 3.27. The total experimental setup is also shown in the same Figure. After preliminary checks on running, this is mounted inside the cold head housing. It is evacuated very well to remove air impurity. It is also purged with pure helium gas of 99.999% purity two times. Subsequently, it is filled to the charging pressure of 250 psi

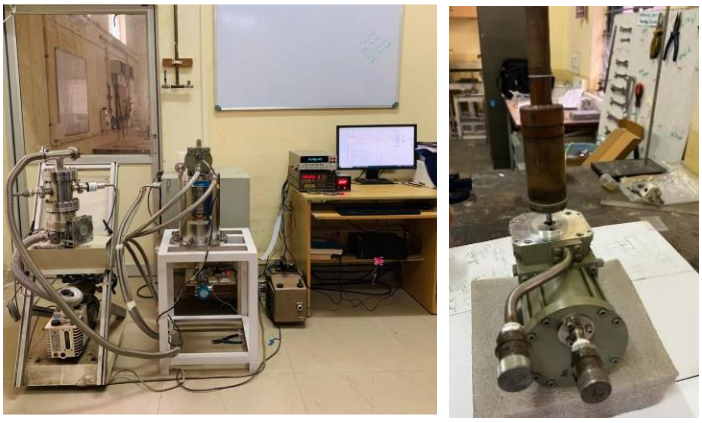


Fig 3.27. Displacers assembled on the Cam drive and the compete experimental setup

The typical experimental procedure is as follows. After mounting temperature sensors on the first and second stages, it is super insulated and mounted inside the vacuum jacket. Initially the vacuum jacket is evacuated by starting the vacuum pump. The interspace pressure is monitored in the Pirani gauge. Once an acceptable vacuum level (say < 0.10 mbar) is obtained in the vacuum jacket, the helium compressor is switched on and this enables the displacer movement and cold head refrigeration starts. The data acquisition is carried out by the DAQ interfaced with the computer to monitor the temperatures of the 1st and 2nd stages.

The first stage temperature is measured by PT100 sensor and the second stage temperature is measured by a calibrated Si410 sensor. The temperature sensors are supplied with a current of 10 μA source from the constant current source. Once the temperature of the 2nd stage cold head falls below 50K, cryo pumping takes over and so the pumping valve is closed to enable further drop in the cold head temperature. The temperatures are monitored till it reaches the steady value. Results of some of the experiments performed in the next section.

3.8.1 Temperature Sensors and their Calibration

Silicon diodes are useful for temperatures down to ~1K. They exhibit two slopes ans so they are quite suitable for instrumentation. They are normally calibrated against a standard pre-calibrated sensor. These sensors are normally encapsulated in a gold-plated copper case with 4 each 36 AWG Polyimide insulated, color-coded, phosphor bronze leads with the case size with 0.093” diameter and 0.250” long. Individual Model Si410 sensors are usually calibrated at 10 microamps over various standard temperature ranges. A Polynomial Fit curve was generated for the PT100 and Si410 sensors, establishing the functional relationship between the voltage data and the corresponding temperature. When voltage is measured one can obtain the corresponding temperature

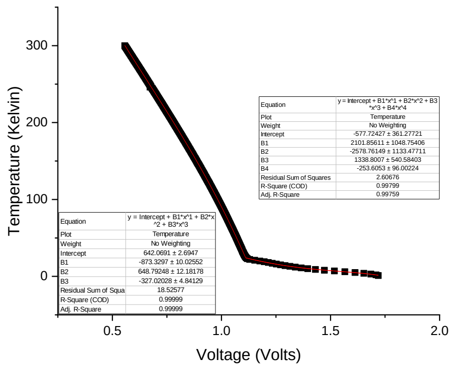


Fig 3.28 (a). Calibration curve for Silicon diode

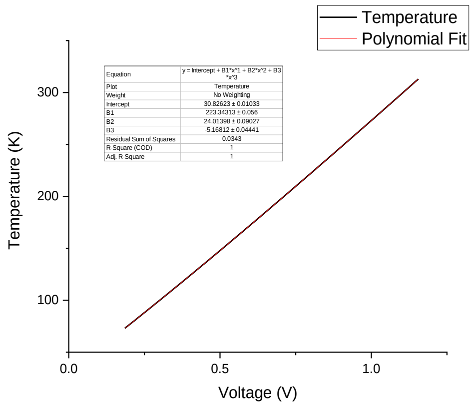


Fig.3.29 (b). Calibration curve for PT100 sensor

3.8.2Temperature Sensor Wiring

In this experiment, we use 36-gauge manganin wire. To avoid the influence of wire resistance on measurements, four-wire configurations (v+, v-, i+, i-) are recommended for temperature sensors. The wires should be arranged in twisted pairs (v+, v-) and (i+, i-) to minimize noise interference. These wires generally connect from 300 K to cryogenic temperatures, requiring them to have small cross-sections and low thermal conductivity.

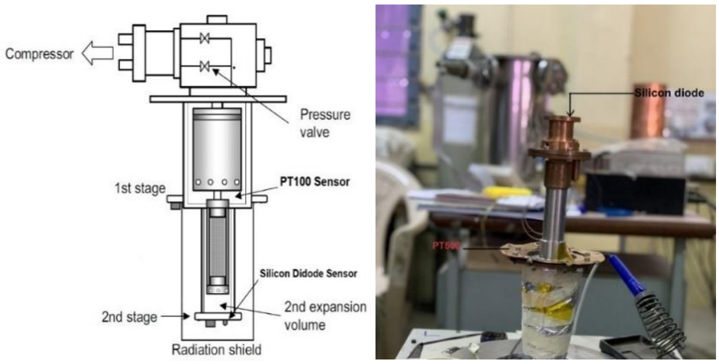


Figure.3.30. Schematic of GM with sensor and 2^{nd} stage cold head with sensor

3.8.3 Porosity Estimation

Total weight of second stage without Lead=51g

Total weight after filling Lead=207-51=156g

Internal length of filled lead=7.5cm   Density of lead = 11.34 g/cm^3

Volume of filled space= $\pi r^2 h = \pi \times \frac{d^2}{4} \times h = \pi \times \frac{18.5^2}{4} \times 75$=20160$mm^3$=20.16$cm^3$

Weight of Lead cylinder = 11.34×20.16 =228.61g

Filling Factor = $\frac{156}{228.61}$ =0.682.

Hence Porosity = $1 - 0.682 = 0.318 \sim 32\%$

3.8.4 LAB VIEW PROGRAM

LabVIEW (short for Laboratory Virtual Instrument Engineering Workbench) is a system-design platform and development environment from National Instruments (NI). It is primarily used for data acquisition, instrument control, and industrial automation on a variety of operating systems

For Data Acquisition and Instrument Control LabVIEW is widely used for interfacing with various hardware devices such as sensors, data acquisition cards, and instruments through GPIB, PXI, PCI, and other standards.

Here we use Keithley 2000 Digital Multimeter (DMM) for measuring the voltage. LabVIEW support the Keithley 2000 DMM through built-in drivers through GPIB device GPIB device are General Purpose Interface Bus, also known as IEEE-488, is a standard interface used for connecting and controlling multiple devices such as instruments, its integration with LabVIEW program which continually allows us collect the data from the DMM.

Here, our program collects data from the DMM every 10 seconds. The user interface of the program and the block diagram are shown below.

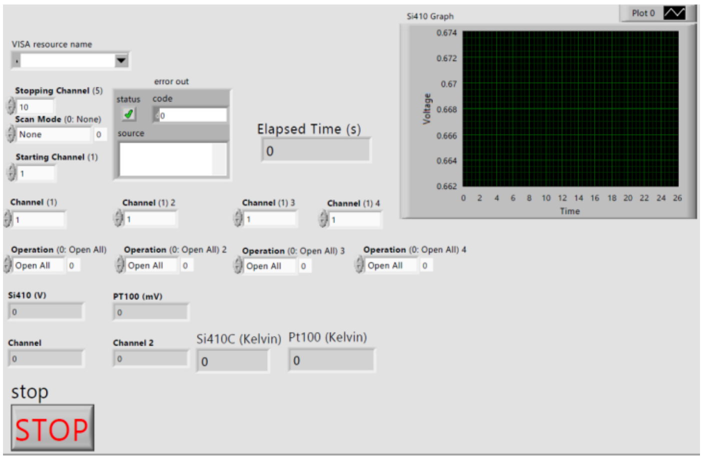


Fig: 3.31 (a) Front panel for the LabVIEW Program

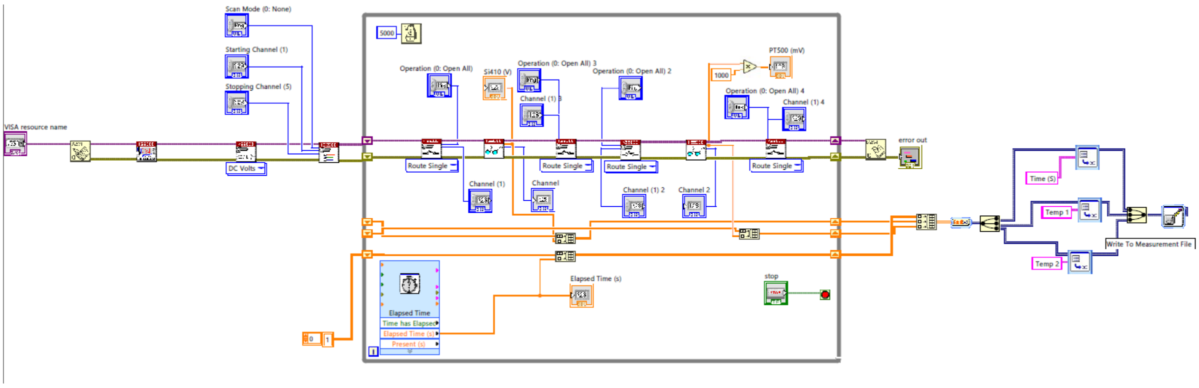


Fig: 3.32 (b) Blockdiagram of the LabVIEW Program

3.9 Conclusion

In this chapter we have discussed the overview of the experimental procedures undertaken in the development of indigeneous GM Cryocooler. Detailed dimensional drawings of the various components are presented, illustrating precise design and specifications used. The chapter also covers the step-by-step procedure of dismantling, assembling, and testing the GM cryocooler. Thermal insulation techniques are discussed. Additionally, the chapter explains the methodology for temperature measurement, utilizing a LabVIEW program to ensure accurate and reliable data collection. In the next chapter we will discuss the experimental results along with discussion.

CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, we'll discuss the experimental results obtained by using different regenerator materials in the second stage of the GM cryocooler. We have tested 3 different regenerator materials such as Lead, Erbium nickel, and Holmium copper in the newly fabricated second stage displacer housing with Labyrinth and non-labyrinth arrangements. We have also studied the effect of mass flow rate in the performance of the system.

4.2 Experiments with Pb as the regenerator material:

In this case the second stage regenerator material is chosen as lead (Pb). Many experiments have been performed and the best result is presented here. It can be seen that the second stage temperature is close to 16.5K while the first stage reaches 81K.

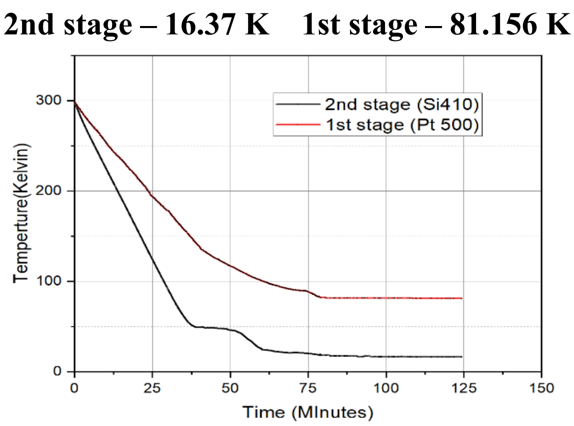


Fig.4.1 Experimental results with lead as the regenerator material

4.3 Experiments with ErNi as regenerator material

Next the experiments have been performed with the replacement of the Lead which is the original regenerator material used in the system. For making multiple experiments with the same regenerator housing, the upper end plug of the second stage regenerator is prepared with threads and Teflon tape is used for sealing it with the body of the regenerator.

Regenerator material filling is described briefly below. For enabling the regenerator filling, the housing is prepared properly. Initially it is clean quite well. Both the bottom and top meshes are cleaned well and approximately 5 meshes are assembled at the base. Next the felt material is positioned properly. Next the regenerate material is gradually filled in ensuring good packing of this material. When the filling reach is top most one a bigger size felt is located. Also five numbers of larger diameter measures are positioned. The threaded top plug is fitted using Teflon tape. The porosity can be estimated from the weight of regenerator material filled and the internal dimensions of the regenerator housing.

The results of experimental studies using ErNi are presented in Fig.4.2 We have used two types of seals on the second stage regenerator namely, a plastic and also Teflon, to take care of the leakage of gas between the first and second stages. The sealing is found to be better with Teflon seal and hence we should use only Teflon seal ring in our experiments. These experiments have been performed with newly fabricated first stage and second stage displacer housings.

2nd stage – 21.192 K 1st stage – 69.723 K **2nd stage – 19.45 K 1st stage – 58.95 K**

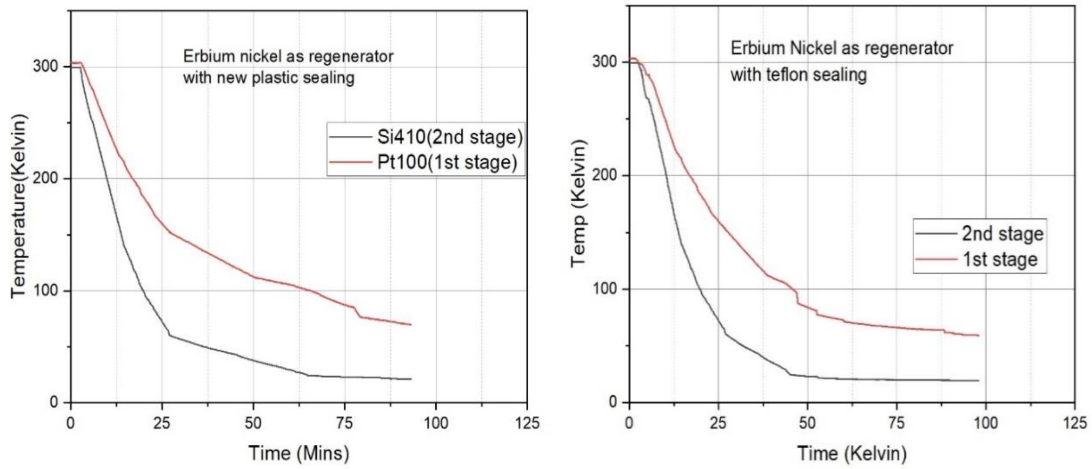


Fig.4.2 . Experimental results with ErNi as the regenerator material in the second stage

4.4 Experiments with HoCu2 as the regenerator material

Next, experiments have been performed with HoCu2 as the regenerator material. The procedure of filling the regenerator materials remains exactly the same as before. In this case also we have studied the effect of both plastic as well as Teflon seals on the lowest temperatures obtained in the second stage cold head. The results are shown in Fig. 4.3. These experiments have also been performed with newly fabricated first stage and second stage displacer housings.

2nd stage – 19.27 K 1st stage – 73.62 K *2nd stage – 15.48 K 1st stage – 75.967 K*

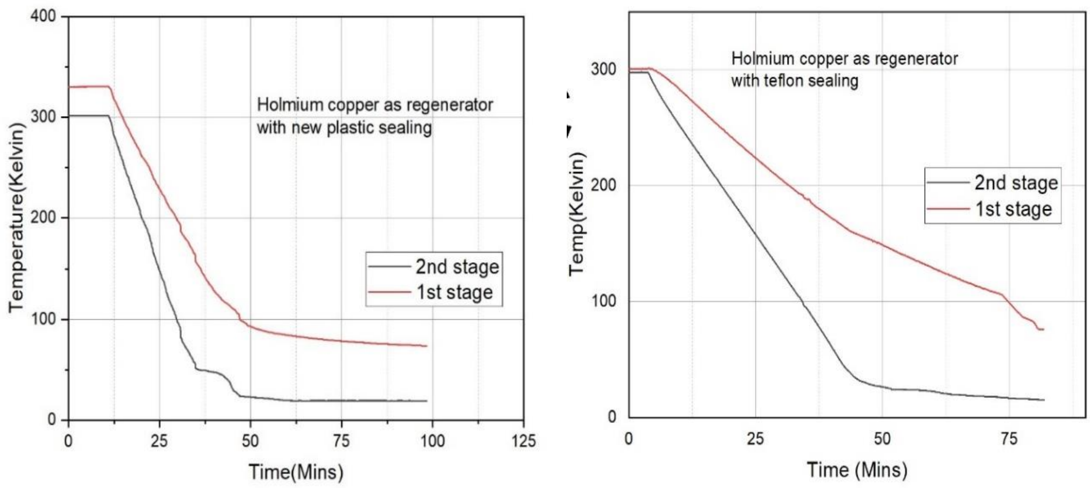


Fig.4.3 Experimental results with HoCu2 as the regenerator material in the second stage

4.5 Experiments with Labyrinth Type Displacer with Pb as the regenerator material:

Several experiments have been performed with labyrinth type displacer in the second stage. In Fig.4.4(a) and (b), two results are presented. It is seen that the second stage temperature is about ~20.7 K, when the compressor running pressure is 212 psi. The system reached a temperature of 17.9 K when the compressor running pressure is 245 psi. Since the interspace pressure between the cold head and its vacuum jacket was poor, we expect a better performance after the rework on this system.

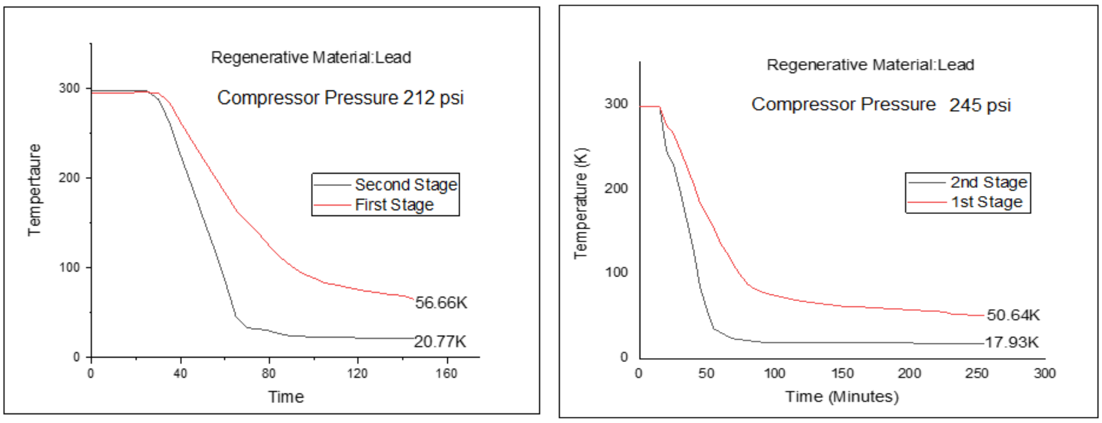


Fig.4.4 (a) and (b) Results with labyrinth displacer for different compressor run pressures

4.6 Experiments with Labyrinth Type Displacer Er3Ni as the regenerator material:

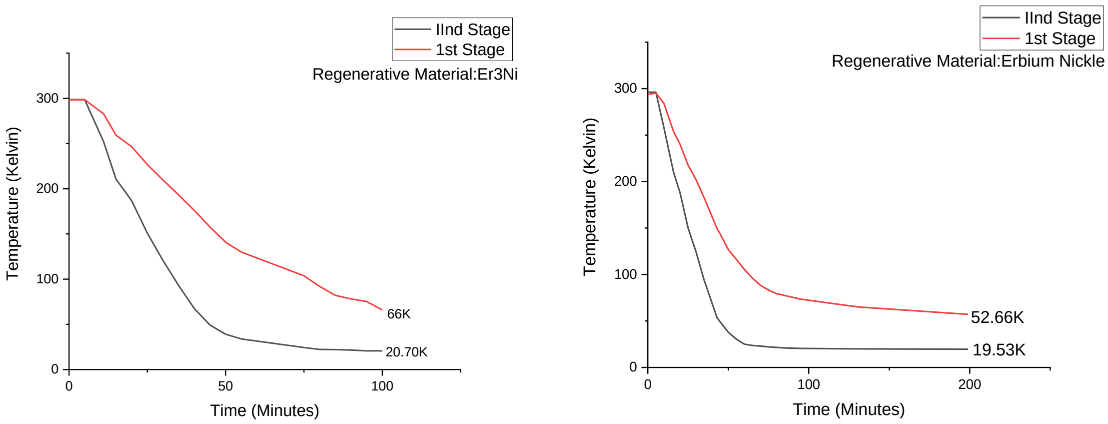


Figure 4.5: (a) and (b) Results for Er3Ni with labyrinth displacer for different compressor run pressures

Experiments has been conducted replacing the second stage displacer with erbium-nickel as the regenerator material. In one experiment, shown in Figure 4.5 (a), the running time of the compressor was set to 100 minutes. Under these conditions, the lowest recorded temperature for the second stage was 20.70 K, while the first stage reached 66 K. In a subsequent experiment shown in Figure 4.5 (b), the running time of the compressor was increased to 200 minutes. This adjustment resulted in the second stage achieving a temperature of 19.53 K, and the first stage reaching a temperature of 52.66 K. These experiments show that by increasing the running time of the compressor results in increasing the first stage temperature of the cold head.

4.7 *Experiments with Labyrinth Type Displacer HoCu2 as the regenerator material:*

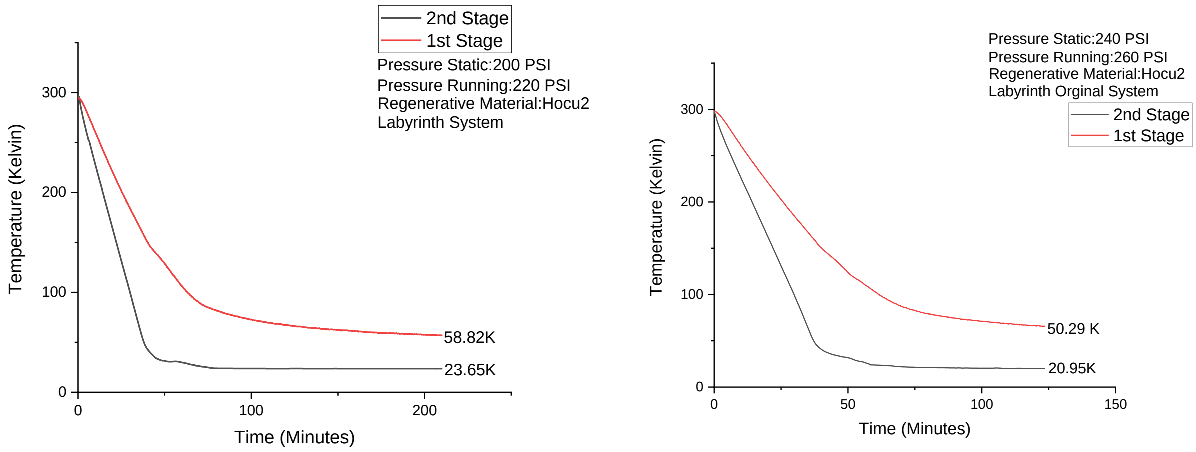


Figure 4.6: (a) and (b) Results for HoCu2 with labyrinth displacer for different compressor run pressures

Here the experiment conducted with holmium-copper as the regenerator material under two different operating pressures of the compressor. Initially, the experiment was conducted with a static pressure of 200 psi and a running pressure of 220 psi. As shown in Figure 4.6 (a), by decreasing the compressor pressure under these conditions, the second stage of the cryocooler reached a temperature of 23.65 K, while the first stage achieved a temperature of 58.82 K. In figure 4.6(b), experiment was conducted by increased the static pressure to 240 psi and the running pressure to 260 psi. Under these conditions, the second stage reached a temperature of 20.95 K, and the first stage reached a temperature of 50.29 K. These results indicate that higher operating pressures of the compressor lead to lower temperatures achieved in both stages.

4.8 *Experiments were conducted by increasing the mass flow rate using lead as the regenerator material.*

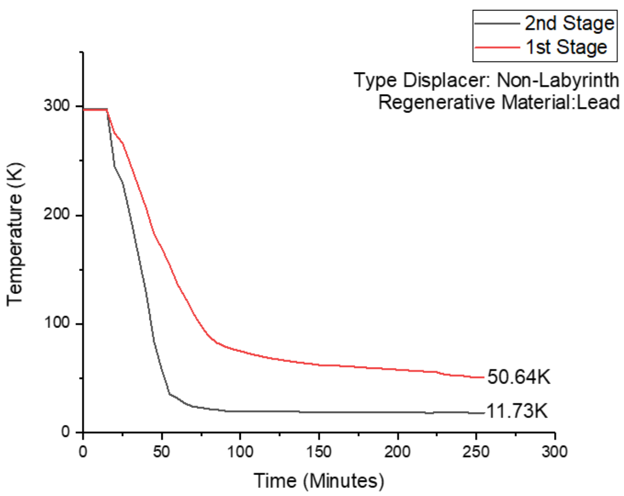


Fig.4.7 Experimental results with Lead as the regenerator material in the second stage

Experiment conducted using lead as regenerative material in the second stage displacer. The figure 4.7 shows the temperature changes over time for both stages of the GM cryocooler. After the initial rapid cooling, both stages gradually approach their respective stable temperatures. The first stage stabilizes at a temperature of 50.63 K and the second stage stabilizes at a temperature of 11.73K. The increase in mass flow rate appears to enhance the cooling performance, allowing both stages to reach lower temperatures. In this experiment, the mass flow rate of the compressor was increased by switching to a 3-kW water-cooled compressor.

4.9 Conclusion

The experimental investigations on the GM cryocooler shows the performance impacts of different regenerator materials and structural modifications. Initially, tests were conducted with a non-labyrinth type displacer using lead as the regenerator material. Subsequent experiments conducted by testing with erbium nickel and holmium copper, incorporating Teflon and Rulon sealing. Results indicated that Teflon sealing provided superior performance.

Further tests with a labyrinth type displacer using the same regenerator materials (lead, erbium nickel, and holmium copper) did not yield expected improvements due to fabrication error in the displacer dimensions.

However, optimizing the mass flow rate of helium gas in the system led to a significant enhancement in performance. Specifically, using lead as the regenerator material under these conditions achieved an impressive lowest temperature of 11.7 K.

These findings underscore the critical importance of precise fabrication and optimization of operational parameters, such as mass flow rate, to maximize the efficiency of GM cryocoolers. The superior performance of Teflon sealing had also highlight potential pathways for further improving cryocooler performance.

CHAPTER 5

THEORETICAL ANALYSIS OF GM-CRYOCOOLER

5.1 Introduction

Theoretical analysis of GM Cryocoolers is essential for understanding and optimizing their performance. GM Cryocoolers, widely used in applications requiring reliable and efficient cryogenic cooling, benefit significantly from such analyses. This report presents a comprehensive theoretical analysis of a single-stage GM Cryocooler, utilizing the software REGEN, version 3.3. developed by the National Institute of Standards and Technology (NIST), USA. REGEN is a freely available software specifically designed to facilitate the study of regenerative cryocoolers.

The study focuses on a single-stage regenerator within the GM Cryocooler, examining various input parameters such as pressure ratio, mass flow rate, regenerator diameter, and regenerator length. In particular, the first stage of the displacer was analysed, exploring the impact of different geometrical parameters including the length of the regenerator material, pressure ratio, diameter, and mass flow rate.

REGEN employs a one-dimensional approach to solve the governing equations through the finite difference method. This method enables the detailed assessment of the thermal regenerator's effectiveness by evaluating key performance indicators, such as gross refrigeration power, adjusted gross refrigeration power, net cooling power, and acoustic power losses, coefficient of performance, and exergy efficiency or second law efficiency. Through this analysis, we aim to gain insights into the performance characteristics of the GM Cryocooler and identify potential areas for improvement.

The findings of this theoretical analysis are expected to contribute to the optimization of GM Cryocoolers.

The coefficient of performance measures the ratio of adjusted refrigeration power to the acoustic power at the hot end of the regenerator. Mathematically,

$$COP = \frac{Net\ Adjusted\ Cooling\ power}{PV - work\ at\ thewarmend\ of\ regenerator}$$

Exergy efficiency or second law efficiency is a measure of COP to Carnot’s COP. It is related to coefficient of performance as

$$\eta_{ex} = COP\ \frac{T_h}{T_c}$$

In the hot end of the regenerator, acoustic power is supplied using a compressor. During the flow of working fluid, acoustic power loss occurs due to the inefficiency of the regenerator, conduction in the matrix of regenerator, conduction in the regenerator wall, temperature swing loss of matrix, pressurization loss etc. Also, some amount of acoustic power losses occurs due to the expansion. The ultimate acoustic power at the cold end of the regenerator is to measure the cooling capacity as a product of dynamic pressure and volumetric flow rate in one cycle. After subtracting the two major losses for example regenerator ineffectiveness loss and conduction loss of matrix gross refrigeration power is calculated. The second law efficiency or exergy efficiency. This is the product of the coefficient of performance with the ratio of the temperature.

Net refrigeration power is calculated by subtracting regenerator ineffectiveness loss and pressurization loss from adjusted gross cooling power. NTCADJ (W).

$$\mathrm{NTCADJ} = \mathrm{GRCADJ} - \mathrm{RGLOSS} - \mathrm{HTFLUX} - \mathrm{TUBECD}$$

5.2 REGEN Input parameters

The input parameters for the simulation are shown in Table 5.1. These parameters are based on the first stage of the CTI cryocooler-based system. The hydraulic diameter used in the simulation is assumed based on values from the literature, and the meshes employed are made of stainless steel. This study investigates the effect of various parameters on the coefficient of performance (COP), including pressure ratio, diameter of the displacer, mass flow rate, and length of the displacer.

Input Parameters		
Parameters	**Value**	**Unit**
Refrigeration Temperature	50	Kelvin
Hot end Temperature	300	Kelvin
Pressure ratio	1.25	-
Diameter of Regenerator	35.4	mm
Length of Regenerator	77	mm
Porosity	0.69	-
Operating Frequency	1.2	Hz
Hydraulic Diameter	5.8×10^{-5}	m
Phase Angle	26°	degree

In the UI, users are required to input key parameters that influence the performance of the GM Cryocooler. These parameters include pressure ratio, diameter of the displacer, mass flow rate, and length of the displacer.

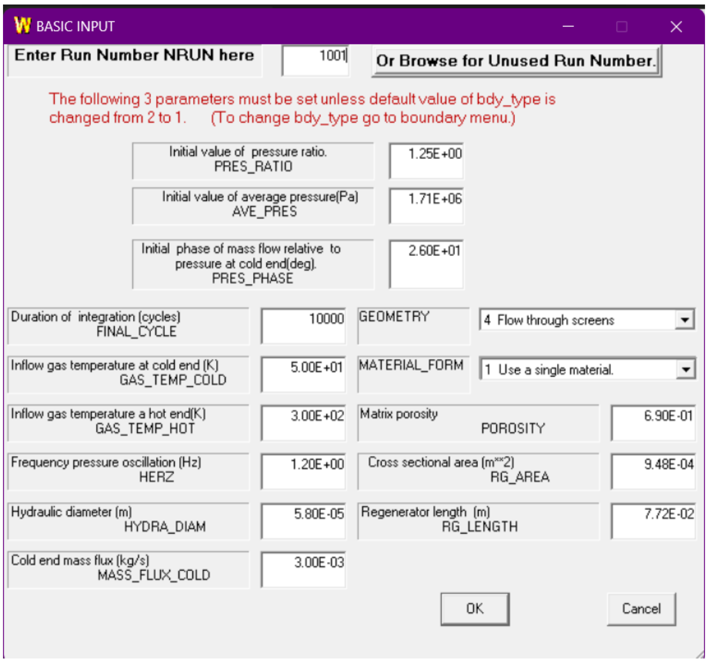


Figure: 5.1 User interface of Regen Software

5.3 Results and Discussion

The results of the theoretical analysis of the GM Cryocooler using the REGEN software are presented in this section. The study focused on varying the pressure ratio, mass flow rate of helium gas, diameter of the regenerator, and the length of the regenerator to observe their impacts on two key performance metrics: the coefficient of performance (COP) and the net refrigeration power.

5.3.1 Effect of pressure ratio

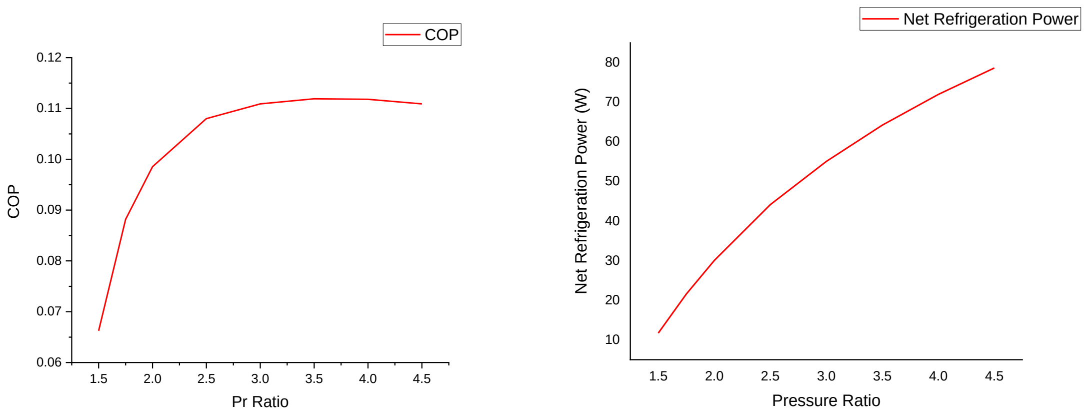


Figure 5.2 (a) illustrates the relationship between the pressure ratio and the COP. Figure 5.2 (b) shows the variation of net refrigeration power with the pressure ratio

As shown in Figure 5.2 (a), the COP increases as the pressure ratio increases from 1.5 to 3. At a pressure ratio of 3, the COP stabilizes, indicating the optimal operating point for maximum efficiency. Beyond a pressure ratio of 3, the COP starts to decline, suggesting that higher pressure ratios negatively impact the system's efficiency. As shown in Figure 5.2 (b), the net refrigeration power consistently increases with the pressure ratio from 1.5 to 4.5. This trend indicates that while higher pressure ratios may reduce efficiency as seen in the COP, they contribute to greater overall cooling capacity.

5.3.2 Effect on mass flow rate of the system

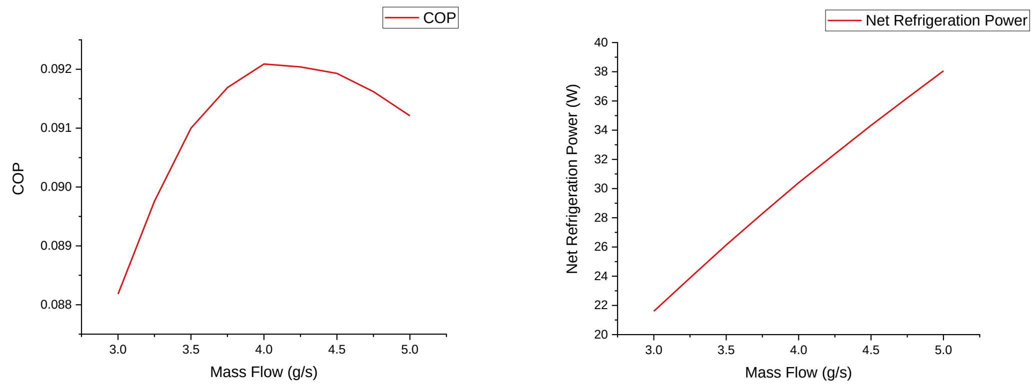


Figure 5.3 (a) shows the effect of varying the mass flow rate on the COP. Figure 4.3 (b) shows the effect of varying the mass flow rate net refrigeration power

From Figure 5.3 (a), The COP starts at 0.088 for a mass flow rate of 3 g/s, increases to 0.0915 at 4 g/s, and then decreases as the mass flow rate increases beyond this point. This indicates an optimal mass flow rate of around 4 g/s for achieving the highest efficiency. As Figure 5.3 (b) shows that the mass flow rate increases from 3 g/s to 5 g/s, the net refrigeration power rises from 0.122 W to 0.1235 W. This suggests that increasing the mass flow rate enhances the cooling capacity of the system.

5.3.3 Effect on Diameter of the Regenerator.

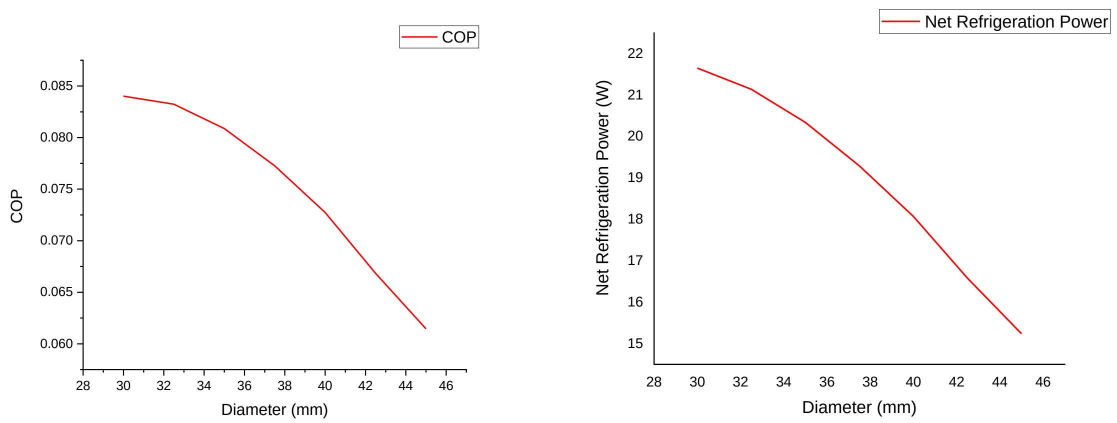


Figure 5.4 (a) shows the effect of varying the diameter of the regenerator on the COP. Figure 5.4 (b) shows the effect of varying the diameter of the regenerator on the net refrigeration power.

As shown in Figure 5.4 (a), the COP decreases from 0.085 to 0.061 as the diameter of the regenerator increases from 30mm to 45mm. This suggests that larger diameters result in decreased efficiency of the cryocooler. As shown in Figure 5.4 (b), the net refrigeration power decreases from 21.5 W to 15.3 W as the diameter of the regenerator increases from 30 to 45. This indicates that larger diameters result in decreased cooling capacity of the cryocooler.

5.3.4 Effect on Regenerator Length

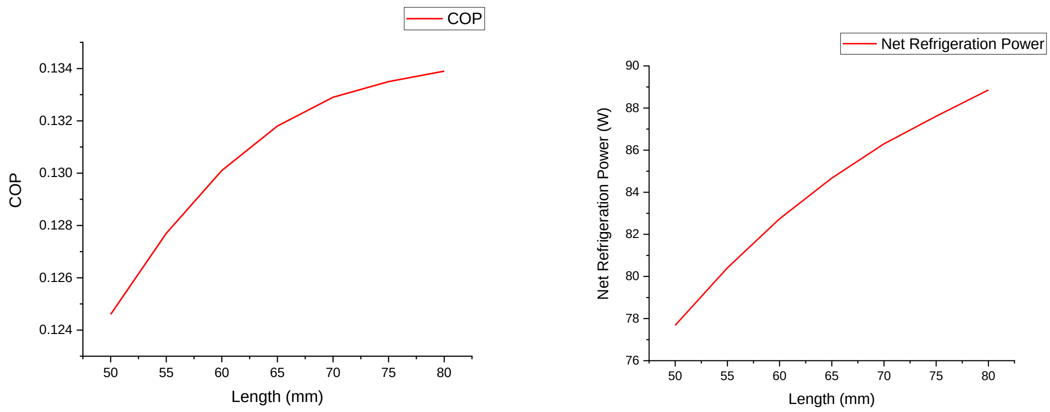


Figure 5.5 (a) shows the effect of varying the length of the regenerator from on the COP. Figure 5.5(b) shows the effect of varying the length of the regenerator on the net refrigeration power.

From figure 4.5 (a), The COP increases from 0.124 to 0.134 as the length of the regenerator increases from 50 mm to 75 mm. This indicates that longer regenerator lengths contribute to improved efficiency of the cryocooler. From figure 4.5 (b), the net refrigeration power increases from 77 W to 87 W as the length of the regenerator increases from 50 mm to 75 mm. This indicates that longer regenerator lengths contribute to greater cooling capacity of the cryocooler.

5.4 Conclusion

This chapter presents the analysis of a single-stage GM Cryocooler using the REGEN software. By systematically varying key parameters, such as pressure ratio, mass flow rate, diameter of the regenerator, and length of the regenerator, we have identified the optimal conditions for maximizing both the efficiency and the cooling capacity of the cryocooler. The results underscore the versatility and utility of REGEN in evaluating and optimizing cryogenic systems, paving the way for further experimental and theoretical studies.

CHAPTER 6

CONCLUSIONS

In this work we have indigenously designed and developed GM cryocooler. Specifically, we have tried to reverse engineer CTI model Cryodyne 350C. All the detailed dimensional drawings of the system have been prepared in particular, the regenerators of the first and second stage. The newly fabricated regenerators have been assembled in the cryocooler system and experiments have been performed with different regenerator materials. The results of these experiments have been presented in the earlier chapter along with the analysis.

The main conclusions of the present experimental studies are the following:

- Micarta originally used for both the stages of the displacers has been replaced by Bakelite, and this performing satisfactorily.
- The system performance has been quite satisfactory with the newly fabricate displacers replacing the original ones.
- The lowest temperature which can be achieved with lead as the regenerator material is ~ 10K. A temperature of 11.7K has been measured with lead as a regenerator material with 3 kW water cooled compressor.
- Although HoCu2 and ErNi regenerator materials are expected to perform better and produce temperatures close to 4K, we are not able to obtain this result in the present experimental studies. In fact, the measured temperature with the above regenerator materials is more than that of lead. This is perhaps due to the aging effects of HoCu2 and ErNi.
- Teflon seal rings are found to performs better than plastic seal rings. Perhaps the wear out of the Teflon ring is less compared to that of the plastic sealing ring.
- The Labyrinth type displacer although was expected to perform better, it did not do so. This could be due to the incorrect dimensional tolerances of the fabricated displacer.
- The performances of the GM Cryocooler are found to be better with reduced porosity of the regenerator and increased pressure ratio of the working fluid.

Scope of future work in this area

The experimental studies are currently in progress to obtain further improvements in the performances of the developed GM Cryocooler. There is considerable scope for obtaining better performances of the GM Cryocooler. Some of the future work that can be taken up in this area are the following.

1. The stroke of the displacer should be increased to have further expansion of the gas which will result in the increased cooling power of the cryocooler.
2. Better regenerator materials such as HoCu2 and ErNi can be used to lower the second stage temperature.
3. Labyrinth type displacer with correct dimensions can be used to improve the performance.
4. Indigenisation of all the different components of the GM Cryocooler should be taken up for the overall assessment of the performance.

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