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SUMMER INTERNSHIP

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Index

1. Introduction

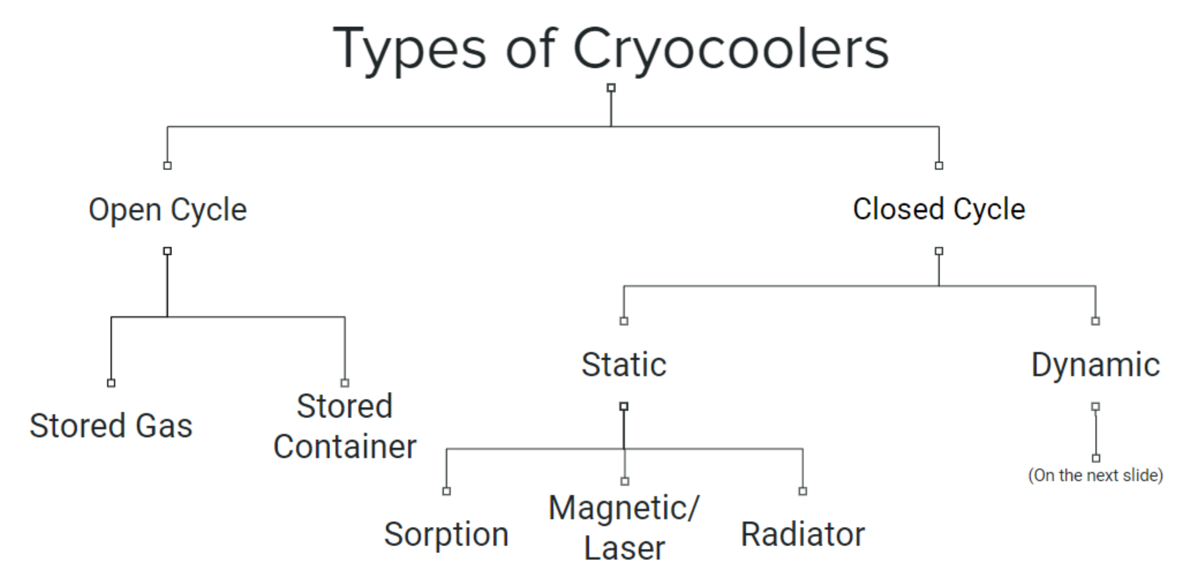
Cryogenics is the branch of science that deals with production of very low temperatures, known as cryogenic temperatures (less that 123K).

1.1 Basics of Cryocoolers

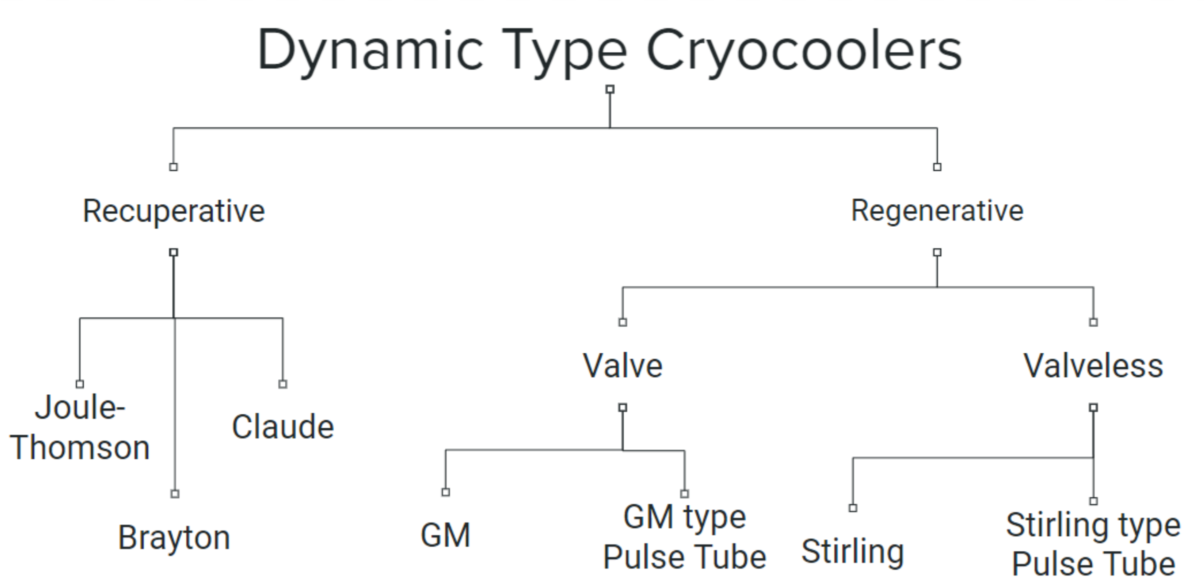
Cryocoolers are devices which generate low temperature due to compression and expansion of gas. They consist of two major components, the compressor and the cold head assembly. The compressor provides the PV power to the cold head, which is necessary for compression and expansion of the gas in the system. The initial research on cryocoolers primarily dealt with military application; development of infrared thermal imaging equipment for night vision and heat seeking missile guidance. Nowadays the application has extended to fields of space, medicine, superconducting devices and research. Cryocoolers may be used for liquefaction of gases, cryo-pumping, cooling of superconducting magnets, Infrared detectors and various other experiments in laboratories at low temperatures. Due to the several applications described, high efficiency and reliability, low vibration, long lifetime, small size and weight have become important aspects for improvement of the cryocoolers.

1.2 Types of Cryocoolers

The elemental classification of cryocoolers is as follows:



The dynamic type of cryocoolers can be further classified as:



The above distinction, that for Dynamic Type is made on the basis of the heat exchanger used: regenerative and recuperative type heat exchanger.

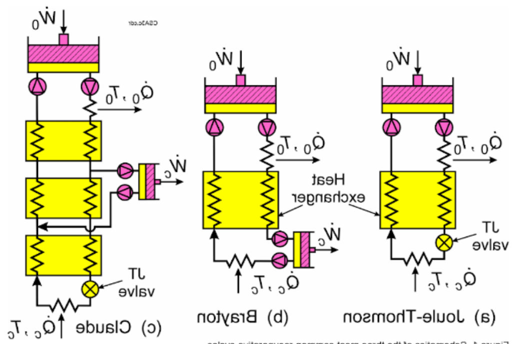


Figure 1. Schematics of the three most common recuperative cycles.

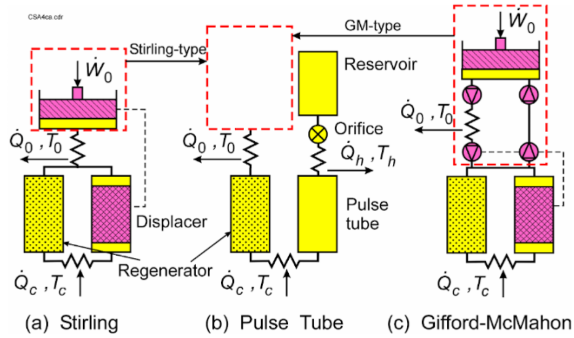


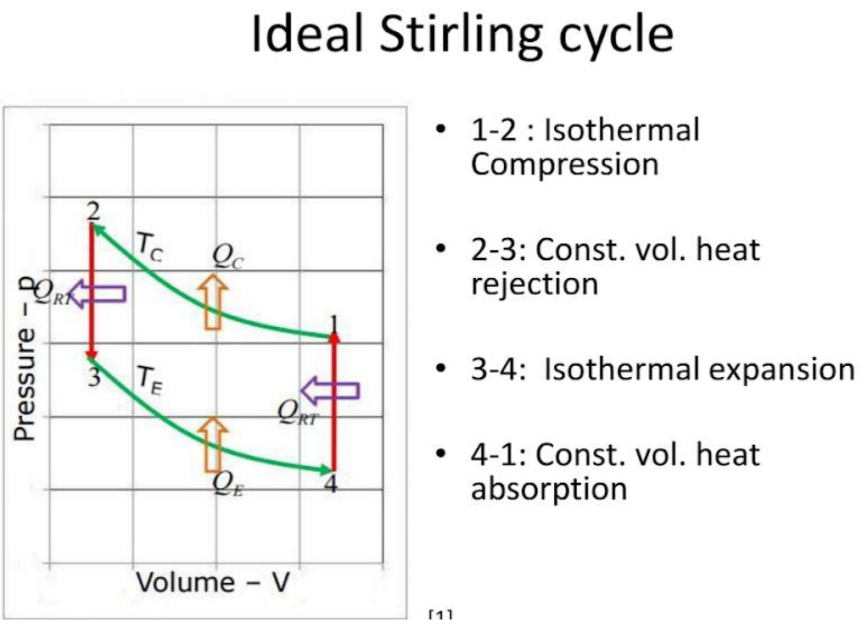
Figure 2. Schematics of the most common regenerative cycles.

The **recuperative type heat exchanger** is one where the flow of both fluids is constant and simultaneous. The 2 fluids are separated by a solid boundary.

The **regenerative type heat exchanger** is one where flow is periodic in nature, alternating between hot and cold fluids across the matrix. When the hot fluid flows, the matrix stores energy cooling the fluid; whereas when the cold fluid flows, the energy is transferred to the fluid making it hotter. This is indirect heat transfer. They have higher efficiencies due to low heat transfer losses, and hence are used more than the others. This report will focus on the regenerative cryocooler

1.2.1 Stirling Cryocooler

The Stirling cryocooler works on the reversed Stirling cycle. It consists of 2 isothermal and 2 isochoric processes as shown below.



[1]

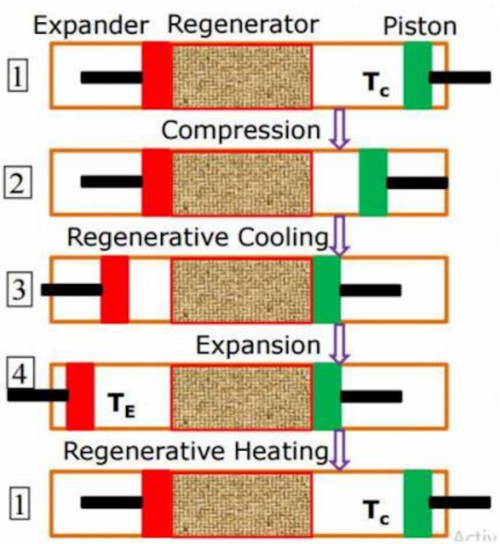
It operates between 2 temperatures: T_E and T_C. The heat of compression, Q_C, is rejected at T_C and the refrigeration effect, Q_E, is produced at T_E.

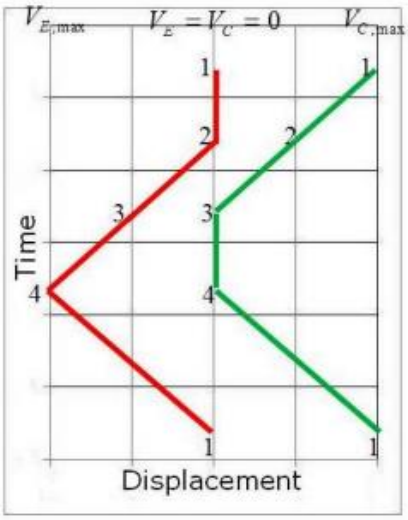
The processes in detail can be explained as:

- **Isothermal Compression Process (1-2)**: During compression, the compressor piston moves towards the inner dead centre and the expander piston is stationary. The gas is compressed in the compression space and thus the pressure increases. The temperature is maintained constant at T_C while the heat of compression Q_C is discharged from the compression space to the surroundings.

- **Isochoric Cooling Process (2-3):** Both the pistons move simultaneously so that the volume between them remains constant. Therefore, the gas is transferred through the regenerator from the compression space to the expansion space. In passing through the regenerator, the gas transfers heat QR to the regenerator matrix and cools down from TC to TE.
- **Isothermal Expansion Process (3-4)**: The expander moves away from the regenerator towards the outer dead centre while the compression piston remains stationary at inner dead centre. The working gas expands in the expansion space at a constant temperature TE as heat QE is absorbed from the surrounding space or the material to be cooled.
- **Isochoric Heating Process (4-1)**: Both the pistons move simultaneously to transfer the working fluid from the expansion space to the compression space through the regenerator at constant volume. Heat QR is retrieved by the working gas from the regenerator matrix so that the gas temperature increases from TE to TC. The ideal Stirling cycle has the COP equal to Carnot COP. Thus, the cryocoolers working on Stirling cycle have a high efficiency of 30-40%.

The movement of the two pistons (displacer and expander) is achieved in the way shown below, along with the time-displacement curve for the same.





The ideal Stirling cycle has the COP equal to Carnot COP. Thus, the cryocoolers working on Stirling cycle have a **high efficiency** of around 85%.

In actual practice, the discontinuous motion as shown in the time-displacement curve, cannot be achieved; and so, a sinusoidal wave form is implemented. The actual Stirling cycle will also account for the effects of void volume, ineffectiveness of heat transfer in regenerator and non-isothermal processes.

The Stirling cryocoolers operate at a **high frequency** (20-150 Hz) and are therefore **very compact** as compared to GM type cryocoolers. This makes them an obvious choice for the space applications like IR cooling. However, the pressure ratio available in Stirling type cryocooler is very low (1.25 to 1.5) as compared to that for the G-M cryocoolers (4 to 5). In addition, it is difficult to achieve temperatures below 4 K with Stirling type cryocoolers as opposed to G-M cryocoolers.

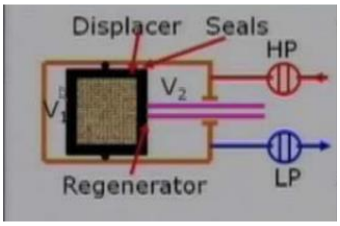
The compressors of Stirling cryocoolers do not consist of any valve. So, the operating frequency of the compressor is also the operating frequency of the cryocooler. They provide **wear free operation** without any lubrication and **no maintenance** is necessary. Furthermore, they can operate in **any orientation.**

1.2.2 Gifford-McMahon (GM) Cryocooler

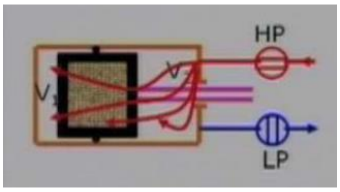
The GM cryocooler is also a regenerative type cryocooler. The imperative components are compressor (scroll/reciprocating type), flex line (low-pressure and high-pressure lines), displacer-regenerator, valve mechanism (rotary/solenoid), aftercooler. The main point of difference from the Stirling cooler is the presence of valve mechanism.

The compressor and the cold head are connected through valves. The two volumes, one to the left(V_1) and the other to the right(V_2) of the displacer can be varied from zero to maximum; total volume remains constant. The two volumes are connected through a regenerator, integral with the displacer. They are also connected to the gas supply which consists of a compressor, inlet (HP) and outlet (LP) valves and the surge volumes. An aftercooler is placed downstream of the gas compressor to take the heat of compression. The pressure above and below the displacer is same except for a small pressure drop across the regenerator. The pressure in the system increases or decreases depending on the opening of inlet or outlet valves, generating the desired pressure waveform. The displacer has a rubbing seal that prevents leakages past the displacer from one space to the other.

The movement of the displacer-regenerator is shown below:



(1)



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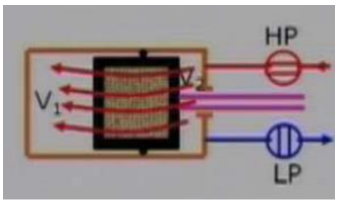

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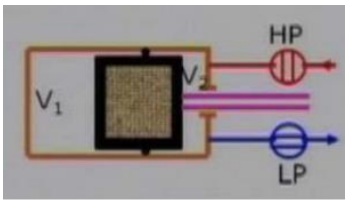


(4)

The processes in detail are as follows:

- **Initial Condition (1):** Both the valves are closed. Displacer is at $V_{1, min}$ (to the left)
- **Pressure Build-up (1-2):** HP valve open opens and HP gas fills V_2 & V_1 at constant volume. This increases the pressure in the system.
- **Intake Stroke (2-3):** The displacer moves from $V_{1, min}$ to $V_{1, max}$ (left to right) at constant pressure, ensuing the gas to flow from V_2 to V_1 through the regenerator.
- **Expansion (3-4):** The HP valve closed whereas the LP valve opens. This causes expansion of gas, producing the required cooling effect in V_1.

- **Exhaust (4-1):** The displacer moves back to the initial position. As the gas flows back through the regenerator, it is heated by the matrix to almost ambient temperature, cooling the matrix for the next cycle.

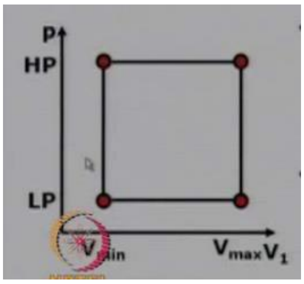
The PV diagram is as shown:

1-2: isochoric

2-3: isobaric

3-4: isochoric

4-1: isobaric



This cycle continues to lower and lower temperature until the regenerator cannot store more heat.

The GM cryocooler has **flexibility in flow control and timing** as it uses a valve for flow regulation. The compressor and the displacer are connected by a rotary valve so that the compressor can run at a frequency of 50 or 60 Hz while the cold head can run at **lower frequency** (1-5 Hz). Due to this, **temperatures below 4 K** can be achieved without much difficulty.

During the opening and closing of the valves, irreversible processes take place which induces losses (**lower efficiency** of around 25%). These valves lead to high noise and vibrations. This reduces the life of the machine and **increases maintenance**. The compressor uses oil as the lubricant. This oil may sometimes leak to the regenerator and contaminates the regenerator and may further reach up to the cold end, where it may get solidified and block the passage of the working gas. Therefore, GM cryocooler requires regular maintenance schedules.

GM coolers are usually used in MRI, NRM machines, cryopumps and N2 liquifaction.

2. Pulse Tube Cryocooler (PTC)

There exist cold moving parts (mechanical expander-displacer systems) in the Stirling and GM coolers. These cause motion induced vibrations and noise, and thus higher maintenance.

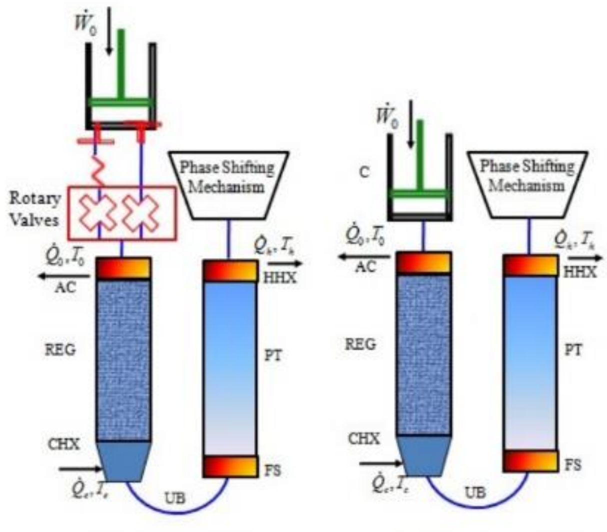
The Pulse Tube Cryocooler is designed to overcome these issues by eliminating the moving parts. The expander-displacer is replaced by a gas column i.e., a thin-walled simple tube filled with gas. This tube is subjected to alternate pressurization and de-pressurization to obtain cooling effect. A phase shift mechanism (PSM) is also introduced to improve the performance. The components categorized broadly are compressor, heat exchangers, regenerator, pulse tube and PSM.

2.1 Types of PTC

The pulse tube cryocoolers are mainly of two types, 1) G-M type pulse tube cryocooler and 2) Stirling type pulse tube cryocooler.

GM Type PTC

The GM type PTC consists of valves of rotary type. The GM type PTCs are the modification of G-M type cryocoolers where the displacer is absent. The GM type PTCs operates at low frequencies (1-5 Hz) as in the GM cooler. The efficiency of these PTCs is generally low due to presence of valves but by using these cryocoolers, lower temperatures near 2.5 K can be achieved.



(a) G-M type PTC (b) Stirling type PTC

Stirling type PTC

The Stirling type PTC does not have valves. These PTCs are the modifications of Stirling cryocoolers without the displacer. These PTCs operate at a high frequency (20-150 Hz), as in the Stirling cooler.

2.2 Components of PTC

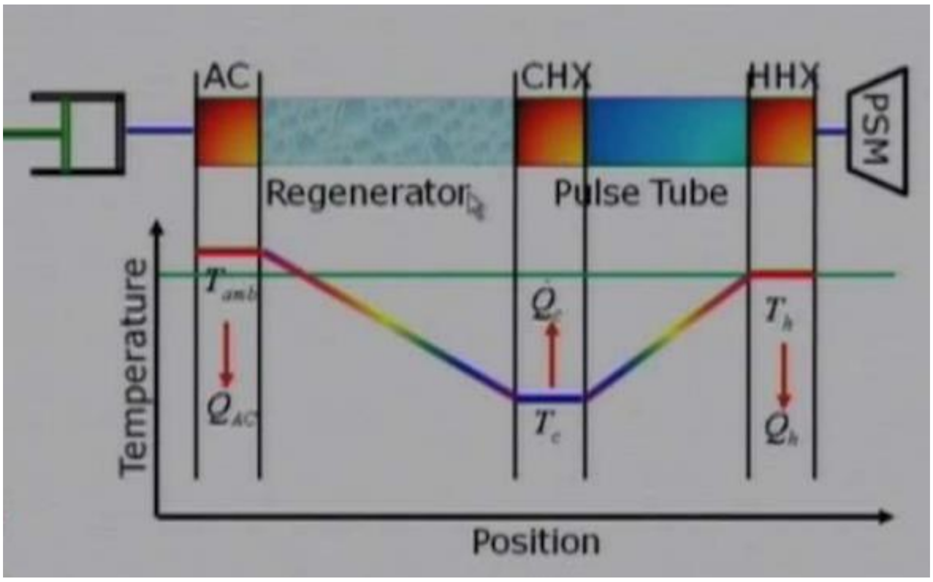
The pulse tube cryocooler consists mainly of a linear compressor, aftercooler (AC), cold end heat exchanger (CHX), pulse tube (PT), hot end heat exchanger (HHX), orifice valve / inertance tube and a reservoir.

- **Linear Compressor**
  This generates oscillating pressure. Electrical energy is converted to mechanical energy resulting in sinusoidal waves.
  There are 2 pistons connected to linear reciprocating motors. The motors cause the pistons to alternately compress and expand the gas in the front volume (volume between the 2 pistons). The motors are enclosed by a back volume. The gas in the front and back volume acts as a gas spring.
  Flexure bearings are used to support the piston, and allow movement in only axial direction. The piston rods and flexure bearings are rigidly attached to each to each other, possessing no need for lubrication.
- **Aftercooler (AC)**
  This is a recuperative type heat exchanger used to extract the heat of compression of the gas before it enters the main system. Water or air is used as the cooling medium.
  The HX uses either copper fins or wire mesh on the gas side.
- **Regenerator**
  It is the most vital part of the Cryocooler. Fundamentally a regenerative type HX, it is used to absorb the heat from incoming hot gas during pressurization and deliver the same to the cold gas during depressurization. It generates as effect of pre-cooling before the gas undergoes expansion. Ideally, there shouldn’t be a pressure drop across it.
  Regenerators are basically hollow tubes filled with wire meshes known as the regenerator matrix. The matrix material should offer higher heat transfer area, low pressure drops. High heat capacity and low thermal conductivity.
- **Cold Heat Exchanger (CHX)**
  This is also a recuperative heat exchanger, which is to be coupled to the object that needs to be cooled and hence obtain the desired refrigeration effect.
  The HX uses either copper fins or wire mesh on the gas side.

- **Pulse Tube (PT)**
  This is also an important part of the PTC. This is where the expansion and compression of gas takes place (alternating pressurization and de-pressurization of gas). It carries the heat from its cold end (connected to the CHX) to its hot end (connected to the HHX) by enthalpy flow. Physically, it is a hollow thin-walled stainless steel tube.
- **Hot Heat Exchanger (HHX)**
  The gas in the pulse tube rejects heat to the surrounding air or circulating water in the HHX, in order to maintain the hot end of the pulse tube at ambient temperature. It is a recuperative heat exchanger having fins or a copper wire mesh on the gas side.
- **Phase Shifting Mechanism (PSM)**
  It is introduced at the hot end of the PT, in order to optimize the phase shift between the pressure pulse and the mass flow rate at the cold end of the PT.
  It uses an orifice or an inertance tube connected to a gas reservoir.

2.3 Working of PTC

During pressurization (i.e., pistons move towards each other), the AC takes the heat of compression from the gas entering the regenerator. This gas is pre-cooled in the regenerator (giving heat to the regenerator matrix) to the cold end temperature T_c. As it enters the pulse tube through the CHX, it compresses the gas already present in the pulse tube. Hence, the gas acts as a 'Gas Piston'. This gas piston does two things: first, it compresses the gas in the tube almost adiabatically, as a result the temperature of this gas increases, and second, it pushes this gas to the hot end of the pulse tube. The temperature at the hot end of the pulse tube is maintained at room temperature by circulation of water in the HHX. During de-pressurisation (i.e., pistons move away from each other), the gas expands to a lower temperature (at the cold end) than the temperature at which it enters. This temperature difference produces refrigerating effect. When the gas passes through the regenerator again, it absorbs the heat from the matrix, preparing for pre-cooling in the succeeding cycle.



The diagram above shows the working of inline configuration of PTC.

Advantages of PTC

- Elimination of cold moving parts.
- No rubbing seals and rubbing forces due to replacement of displacer.
- High reliability, longevity and better vibration characteristics.

Disadvantages of PTC

- Energy dissipation in phase shifting mechanism reduces the COP.
- The performance of PTC is affected by the orientation of pulse tube.

Uses of PTC

- Extremely low temperatures produced by PTCs are widely used in cooling of infrared sensors
- Absence of moving parts at the cold end and reliability caters the needs in space applications.
- Re-condensing of LHe and LN2 in Magnetic Resonance Imaging (MRI) and Nuclear Magnetic Resonance (NMR) machines.
- Storage of biological cells and specimen

2.4 Classification of PTC

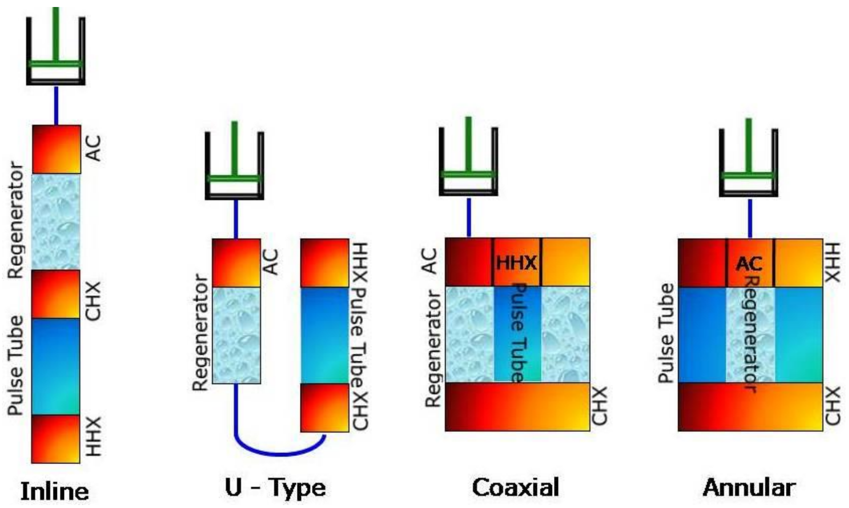
Pulse tubes cryocoolers are broadly classified on the following basis: 1) Based on Valves 2) Based on Frequency 3) Based on Geometry 4) Based on arrangement of Phase Shift 5) Based on Number of Stage

Classification based on Valves

PTCs can be classified based on presence of valve. The PTC with a valve operates at a low frequency. This frequency of operation of the valve is equal to the frequency of the PTC. A PTC without a valve operates at high frequency, which is the operating frequency of the linear compressor.

The GM type PTC consists of a valve between the compressor and the cold head, whereas the Stirling type PTC does not have any valve between the compressor and the cold head as discussed earlier. At high frequency the PTC system becomes compact, however the available refrigeration effect reduces.

Classification based on Geometry



In the inline, gas doesn't have to change direction of flow, reducing the pressure losses. It is the most efficient. It is less compact because of the length. Another disadvantage is the presence of the CHX at the centre, making it less accessible.

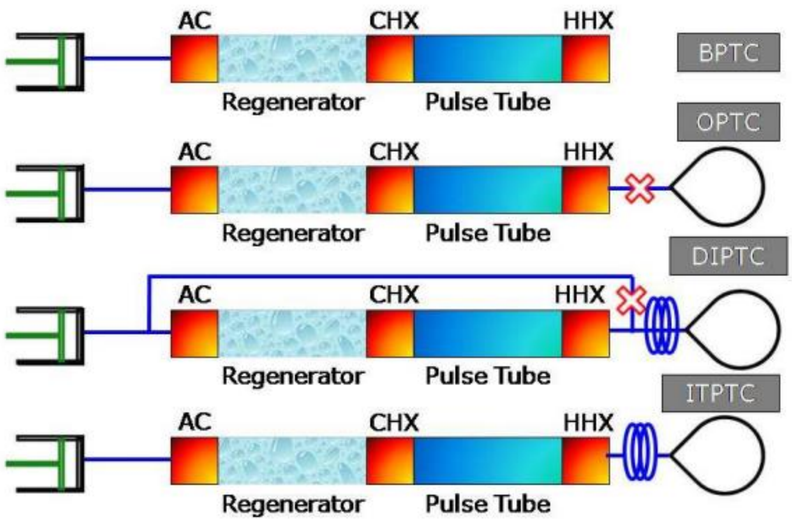
In the U-type, gas has to undergo a 180degree direction change, which increases the pressure drop. It is more compact and has the CHX exposed for use.

In the coaxial as well as the annular, the pressure drop is very high due to the sharp change in flow direction. They are the most compact, along with accessible CHXs. They are low in efficiency due to the heat transfer between the gas in regenerator and pulse tube.

Classification based on Frequency

Low frequency (<30Hz), High frequency (30-80Hz) and Very High frequency (>80Hz)

Classification based on arrangement of Phase Shifting Mechanism



In a Basic PTC (BPTC), there is no phase shift mechanism. Hence, a very low refrigeration effect is obtained at a relatively high temperature. This makes the basic pulse tube cryocooler redundant.

In Orifice PTC (OPTC), an orifice and a reservoir are connected to the hot end of the pulse tube. This variation enhanced the enthalpy flow from the cold end of the pulse tube to its hot end, thereby increasing the efficiency of the cryocooler.

In Inertance Tube PTC (ITPTC), the orifice is replaced by a long length thin tube known as the inertance Tube. The phase difference between the pressure pulse and the mass flow rate at the cold end changes with the change in length and diameter of the inertance tube. An inertance tube PTC gives better refrigeration effect in practice for a Stirling type PTC.

The Double Inlet PTC (DIPTC) is a modification of the low frequency OPTC obtained by connecting the compressor to the hot end of the pulse tube with the use of a Double Inlet/Bypass Valve. This modification allows less gas to pass through the regenerator to avoid losses and hence gives improved performance in terms of increased refrigeration load per unit of input power. Although the performance of the PTC improves, an additional work input is required with the DIPTC mechanism. The double inlet valve bypasses some part of the gas, which would otherwise flow in to the regenerator, directly to the pulse tube. This increases the pressure ratio in the pulse tube.

Classification based on Number of Stages

Multi-staging is essential in order to reach the lowest possible temperatures for a Stirling type PTC. The simple geometry and the absence of moving parts make the multi-staging of PTC relatively easy. The cooling effect produced by the preceding stage is transferred to the succeeding stage either by gas coupling or by thermal coupling.

The stages can be operated independently by use of independent compressors for each stage. Any change in design and operating parameters of one stage does not affect the performance of the other stage. Hence, it is relatively easy to optimize each of the stages. However, some cooling effect is lost during its transfer from one stage to the other.

3. Analysis of PTC

Based on the complexity and accuracy of the analysis, they can be categorized into three orders.

- First Order Analysis
- Second Order Analysis
- Third Order Analysis

3.1 First Order- Phasor Analysis

Phasor diagram is a vectorial representation of the mass flow rate, pressure and temperature at different locations of the PTC as a function of time. The phasor analysis based on these diagrams gives an idea regarding underlying complex phenomena of the PTC.

The phasor analysis assumes ideal conditions like an ideal working fluid, no pressure drop in the cooler, sinusoidal piston movement and a perfect regenerator with 100% effectiveness with isothermal compression and expansion process.

Pressure and temperature in the pulse tube is given by

$$P = P_o + P_1 \cos(\omega t) \qquad (2.1)$$

$$T = T_o + T_1 \cos(\omega t) \qquad (2.2)$$

Mass flow rate at the cold end the Pulse Tube is expressed in terms of mass flow rate at its hot end and mass flow rate due to pressurization of the gas, which is given by

$$\dot{m}_c = \frac{\omega V_{pt}}{RT_c} P_1 \sin(\omega + \frac{\pi}{2}) + \frac{T_h}{T_c} \cos(\omega t) \qquad (2.3)$$

Applying the first law of thermodynamics for time-averaged enthalpy flow and assuming perfect regeneration, we get,

$$Q = \langle \dot{H} \rangle = \frac{C_p}{\tau} \int_0^{\tau} \dot{m}_c t dt \qquad (2.4)$$

Finally, the refrigeration effect obtained in terms of the mass flow rate at the cold end of the pulse tube, and the phase difference between mass flow rate and pressure is given by,

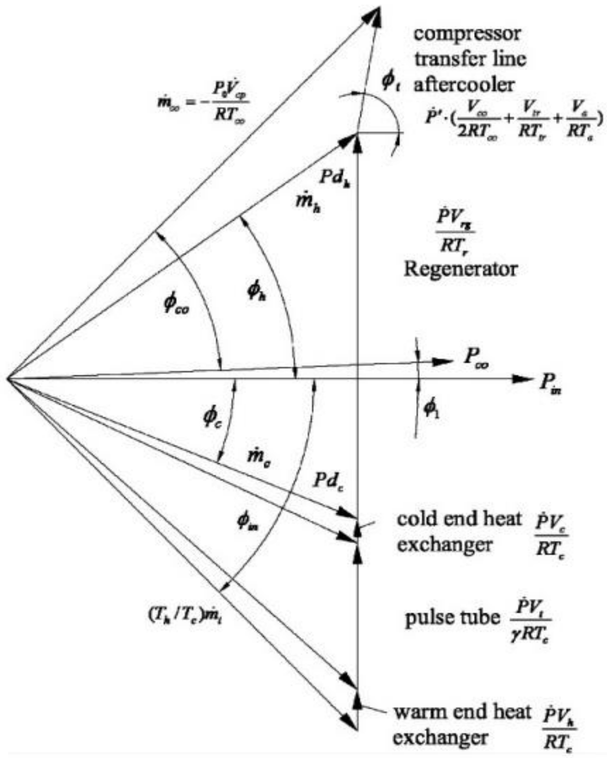
$$Q = \frac{1}{2} RT_c \frac{P_1}{P_0} |\dot{m}_c| \cos(\theta) \qquad (2.5)$$

where θ is the phase difference between mass flow rate at cold end and the pressure wave, which is given by,

$$\cos(\theta) = \frac{|\dot{m}_h|}{|\dot{m}_c|} \frac{T_0}{T_c} \qquad (2.6)$$

It may be noted from equation 2.5 that the cooling effect obtained at the cold end of pulse tube, depends on the cold end temperature, pressure ratio, mass flow rate at the cold end and the angle between the pressure pulse and the mass flow rate at the cold end of the pulse tube. The refrigeration effect increases with an increase in the pressure ratio and mass flow rate at the cold end of the pulse tube. However, it decreases with an increase in angle θ. The mass flow rate at the cold end of the pulse tube is given by the equation 2.3, can be represented by the Phasor diagram.

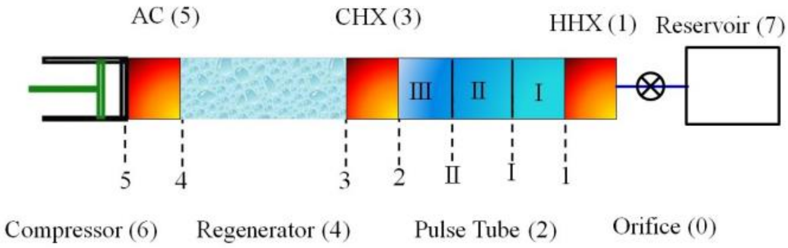
Since the experiment at hand deals with the inertance type PTC, phasor diagram for the same shall be discussed.



The optimum phase relationship between the mass flow rate and the pressure pulse is achieved when both the parameters are in phase, somewhere near the midpoint of the regenerator as shown in Figure. The regenerator losses are minimum when the flow lags the pressure by 30°.

3.2 Second Order- Isothermal Model

In this model, the interior of the pulse tube is divided in three parts (I, II and III). One of the major assumptions is that the middle part of the gas is adiabatic and the gas in other parts of the PTC is isothermal.



Assumptions

- The cold part of the gas that flows from the regenerator and expands to produce work is defined as part-III, whereas the hot part of the gas, which flows to the reservoir through orifice and absorbs work is defined as part-I. The middle part (part-II) never flows out of the pulse tube.
- The gas in part-II is adiabatic, whereas gas in other parts of the pulse tube is isothermal.
- The pressure at all points in the system remains the same at any instant. • There is no gas leakage through the piston seals.
- The orifice is an ideal jet.
- There is no fluid resistance.
- The gas is an ideal gas.
- Temperature variation across the regenerator is linear.

3.3 Third Order- SAGE Modelling

Sage software is used to model and optimize Stirling cycle engines and coolers, pulse tube cryocoolers and low temperature coolers. It allows component dimensions specification, optimization of parameters and prediction of the performance, all within a graphical user interface. Sage allows creating a model by graphically selecting component parts from a palette, dropping them into a window and connecting them together using boundary connections. It supports optimization of input variables subject to constraints, if any, with an objective function to be minimized or maximized.

The equations used are designed specifically for one dimensional internal flow with space and time variable flow area. The starting point is the general Navier-Stokes equations. The equations are the Continuity Equation, Momentum Equation and the Energy Equation in differential form. They are discretized over a grid of points.

Setting up of the PTC model and detailed usage of Sage will be discussed in a later section.

4. Experimentation

Before looking into the experimental results, a study of the components, their assembly and the equipments used for measurement is of essence.

4.1 Assembly

- The regenerator is filled with the required mesh
- The aftercooler and the HHX are assembled in the respective grooves in the cold head (The sensors for measurement of temperature, pressure and load are added using a thermal tape)
- Multi-layer insulation is wrapped over the cold head to reduce radiation losses
- The top flange is clamped on the vacuum jacket
- The inertance tube and reservoir form a phase shift mechanism of the PTC which is connected at the hot end of the pulse tube.

- The linear compressor is connected to the cold head assembly by a connecting tube

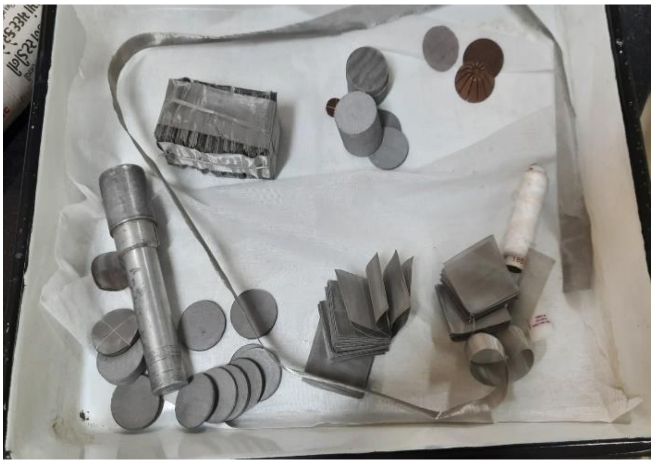


(1) (2) (3)

(1) is the linear compressor with the bottom flange

(2) is the cold head consisting of the AC, regenerator, CHX, PT, HHX (from bottom to top)

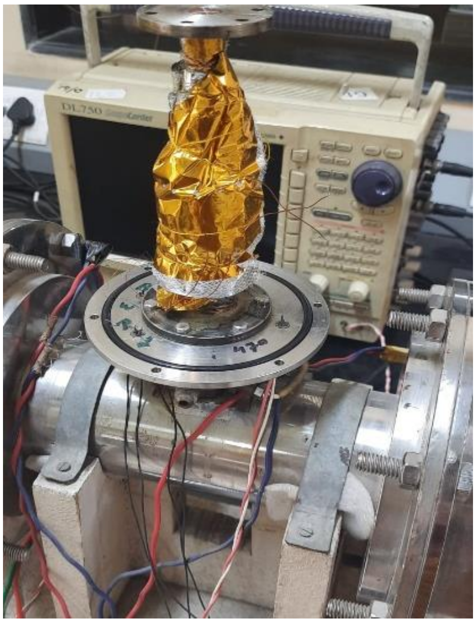
(3) is the cold head after being covered with multi layer insulation




(4) (5)

(4) shows the meshes available (loose and sintered)

(5) shows the botton view of the cold head where first the meshes are entered, and sealed off with the copper AC



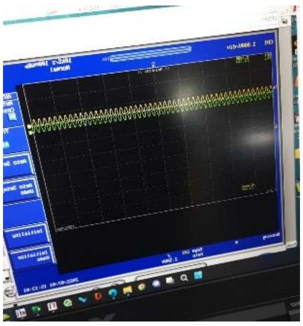
(6) (7)

(6) is the cold head assembled on the linear compressor

(7) is the complere assembly with vacuum jacket, inertance tube and reservoir

The instruments used for measurement and sensing are as follows:

- **Oscilloscope**: Used to measure pressure variation. The output signal from the pressure sensor is given to the signal conditioner to remove noise and add amplication. This is then given to the oscilloscope, which displayes the waveform and gives other required data. It is used to calculate the pressure ratio at the inlet and outlet and hence understand the pressure drop. (8)
- **Temperature Indicator**: Silicon diodes are attached to the CHX to measure the temperature. Th signal is given to the indicaor which displays the temperature at a resolution of 0.001 Kelvin. (9)
- **Vacuum Pump:** It is ued to create and maintain vacuum inside the vacuum jacket. A diffusion pump is used to create the higher vacuum. (10)
- **Heat load:** A nichrome wire heater us mounted at the CHX to find the cooling effect of the PTC.
- **Input Power Supply:** This is used to give Input power to the system, contolled using the dimmerstat. (11)



(8) (9) (10) (11)

4.2 Set Up

The final set up is as shown below.

The cold head is fitted in the vacuum jacket. This vacuum jacket is further connected to vacuum pump. A linear compressor is used to generate a pressure wave in the PTC system. The PTC system consists of various temperature and pressure measuring devices. Temperature at the cold end is measured using Silicon diode. All leads related to temperature and heat load measurement are taken out using sealed feedthroughs. Pressure is measured using pressure sensors, amplified by a signal conditioner, and finally measured on a Yokogawa make oscilloscope.

4.3 Procedure

- A vacuum pump is used to evacuate the PTC system up to 10−5 mbar. This cleans the system and remove water vapor and dust particles, if any.
- The system is purged at 10-12 bar repetitively for 2-3 times. This is done by charging the system with helium gas, and then opening the charging valve suddenly so as to flush out the gas at a fast rate.
- Helium gas is charged to the desired operating pressure.
- The water supplied to the aftercooler and the HHX to cool the gas.
- The vacuum jacket is evacuated using a vacuum pump. The experiment is started after achieving a vacuum of the order of 10−5 mbar. The power is supplied in the steps of 100 W to the compressor up to 300 W.
- The time and temperature are recorded till steady state is obtained.
- The dynamic pressure is recorded using an oscilloscope.

5. Regenerator Mesh

Selection of regenerator meshes is critical for obtaining low temperatures and expected functioning of the cryocooler. This segment will delve into detail about the same.

5.1 Properties

Meshes are inserted in the regenerator as the matrix. The meshes must have high porosity. The material used to make the meshes should possess certain thermal properties to behave successfully as a regenerative heat exchanger.

The working temperature decides the material to be used, but the general properties required are:

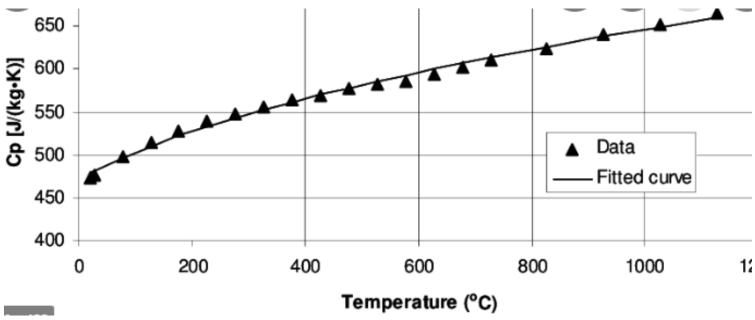
- **Higher heat transfer area**
- **High heat capacity (C_p)**
  This is the most important property, Heat exchanged between the working gas and matrix is directly dependant on it
- **low thermal conductivity**
  To prevent HT by conduction in the meshes

These properties should persist at cryogenic temperature as well.

5.2 Materials

Stainless steel (SS) meets the criterion for temperatures as low as 30K. For temperatures between 10K and 30K (i.e., when using a 2-stage cryocooler), SS in the first stage and Lead in the second stage may be used. For achieving temperatures as low as 4.2K (i.e., when using a 2-stage cryocooler), the first stage can be a combination of SS and lead and the second stage can be of rare earth metals. This is just one combination of materials used, numerous others are possible.

Since the analysis in this report is for a single stage PTC, the material used will be Stainless Steel. The C_p of SS decreases with decreasing temperature, but doesn't get very low. The general trend is:



For this experiment, the changes in temperature generation are compared for SS200 and SS400 varieties of stainless steel.

5.2.1 SS200

It is an austenitic alloy. The constituents are chromium, manganese, nitrogen and nickel. It has higher tensile and yield strength, impact resistance and toughness.

It has lower heat capacity at lower temperatures. The diameter of the mesh wire is also larger, providing less heat transfer area.

5.2.2 SS400

It is ferritic and martensitic stainless steel. The constituents are chromium, manganese and nickel. It has high corrosion and wear resistance. It is magnetic in nature.

It has <u>higher heat capacity</u> at lower temperatures. The wire <u>diameter</u> is <u>smaller</u> providing higher heat tranter area.

The meshes are thin circular sheets of crossed wires. Bundles of 100 meshes are made, which are inserted into the regenerator. The process of cutting, bundling and inserting loose meshed becomes tedious and time consuming. The number of meshes to be inserted gets left to the hands of the operator and how much he compresses them. Also, since the meshes have to be inserted by hand, a perfect fit between the mesh and the regenerator isn't possible, there will exist a significant amount of clearance.

5.3 Sintering of Meshes

To eliminate the aforementioned issues, the meshed were sintered in a hot furnace at 2000 degrees, staggered increasing of temperature. Staggered increase is necessary so that the heat spreads uniformly to the entire surface area, especially the core, before the temperature is increased. Then, they were subjected to air cooling. This got us a cylinder comprising of the meshes.

{Sintering is the process of forming a solid mass of material through heat and pressure without melting to the point of liquefaction. This process involves the atoms in materials diffusing across the particle boundaries and fusing together into one piece.)

This cylinder was turned to a dimension equal to the inner diameter of the regenerator. Shrink fitting was done to insert it in the regenerator. The cylinder was dropped in liquid nitrogen, which caused it to shrink. This allowed the cylinder to be transferred into the regenerator. When brough to room temperature, the cylinder expanded and assumed a near perfect fit in the regenerator, having negligible clearance as desired. After which it was cleaned with petroleum and placed in a heater to remove all moisture. Hence, the sintered mesh was ready.

The sintering was done for SS200 as well as SS400.

5.4 Experimentation

The experimental procedure was carried out on a **Stirling Type Inline PTC with inertance tube** for all the four mesh types: Loose and Sintered SS200, Loose and Sintered SS400.

For SS200, 450 loose meshes were used and 520 meshes were sintered.

For SS400, 720 loose meshes were used and 850 meshes were sintered.

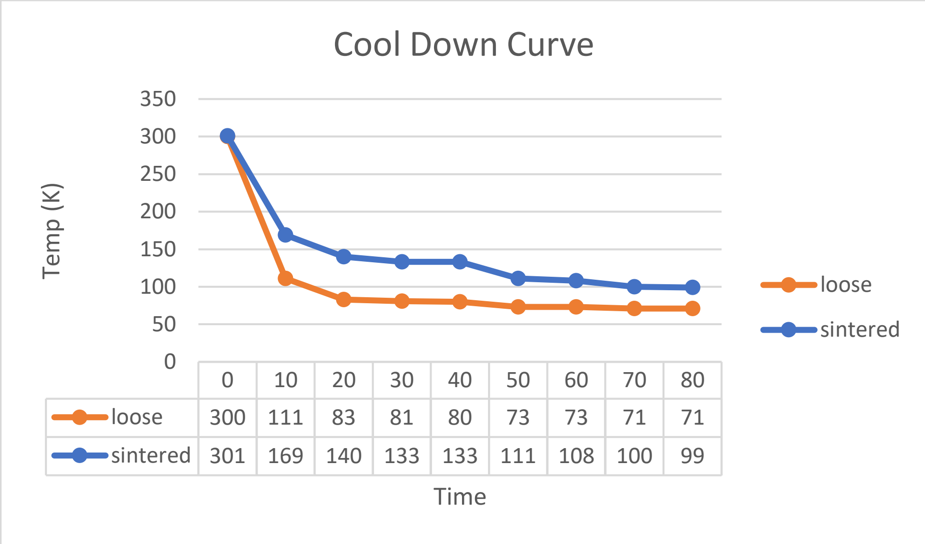
The number of meshes being higher in sintering is attributed to the mesh stack occupying less space due to high compression when heated.

During experimentation, all the other conditions were kept the same, so as to obtain a fair comparison of the mesh dependencies. The charging pressure was **16 Bar** and the frequency was **50Hz**.

5.5 Results

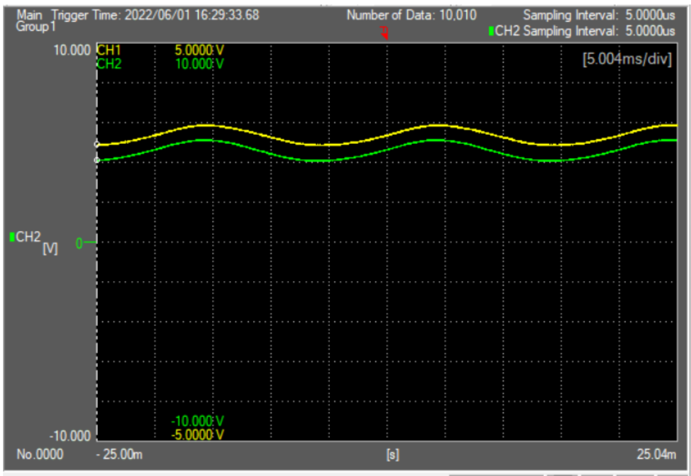
The results will demonstrate the Temperature-time and Sinusoidal pressure curves.

5.5.1 SS200

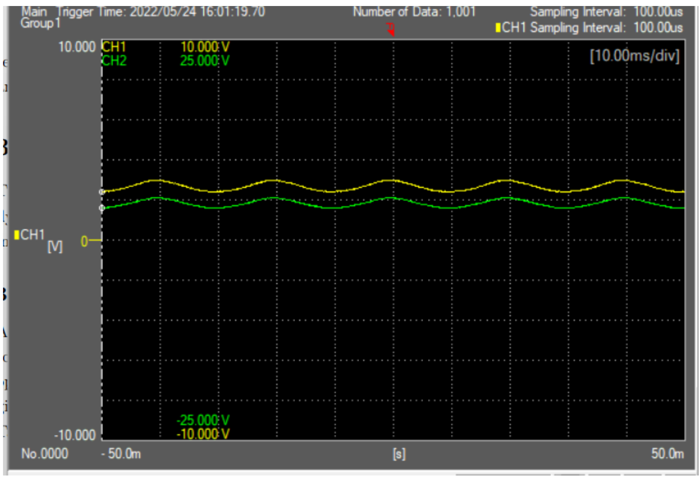


	0	10	20	30	40	50	60	70	80
loose	300	111	83	81	80	73	73	71	71
sintered	301	169	140	133	133	111	108	100	99

Cool Down curve on increasing the input power from 100W to 300W. (0-40 mins: 100W, 40-60 mins: 200W, 60-80 mins: 300W) We can see that lower temperature is obtained in case of Loose mesh.



This is the pressure pulse of Loose SS200 mesh. The yellow represents the AC whereas the green represents the CHX. This is a capture of 50ms.



This is the pressure pulse of sintered SS200 mesh. Capture of 100ms.

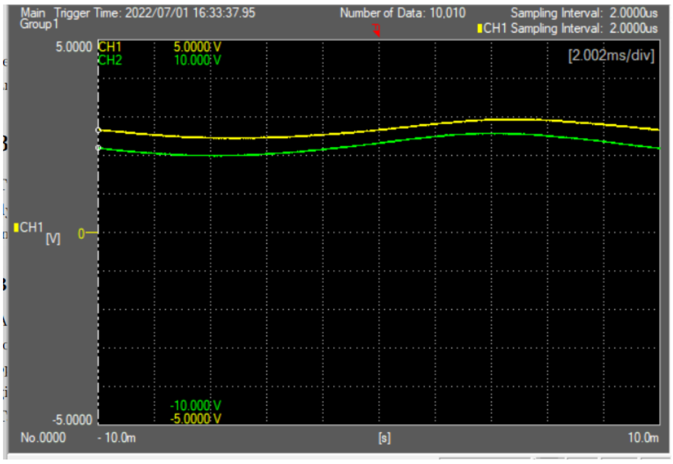
	PR AC	PR CHX
loose	1.25	1.22
sintered	1.32	1.24

PR AC stands for the pressure ratio at the AC and PR CHX for that at the CHX. We can see that the pressure drop across the regenerator, which is situated between the AC and CHX, is higher in case of the sintered mesh. Higher pressure drop is not desired, it reduces the ability of the machine to generate lower temperature since the effect of pressurization and depressurization reaching the PT is less.

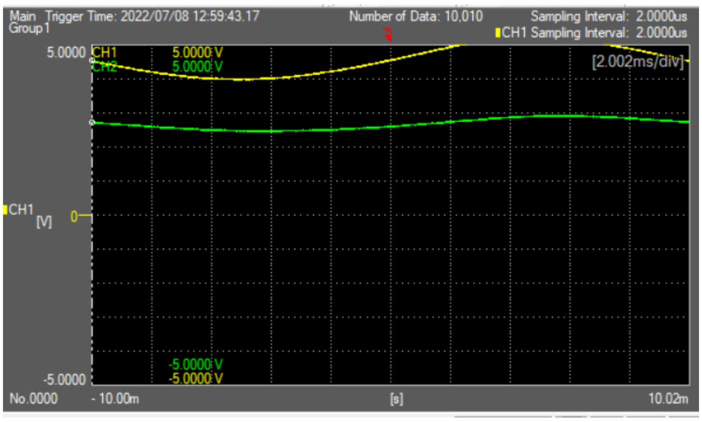
All the above are at an input power of 300W.

5.5.2 SS400

Cool Down curve on increasing the input power from 100W to 300W. (0-50 mins: 100W, 50-70 mins: 200W, 70-80 mins: 300W) We can see that lower temperature is obtained in case of Loose mesh.



This is the pressure pulse of Loose SS400 mesh. The yellow represents the AC whereas the green represents the CHX. This tells us the pressure drop across the regenerator. The screen is a capture of 20ms (since the frequency is 50Hz, 20ms corresponds to 1 cycle)



This is the pressure pulse of sintered SS200 mesh. The capture is of 20ms.

	PR AC	PR CHX
loose	1.26	1.19
sintered	1.33	1.19

PR AC stands for the pressure ratio at the AC and PR CHX for that at the CHX. We can see that the pressure drop across the regenerator, which is situated between the AC and CHX, is higher in case of the sintered mesh. Higher pressure drop is not desired, it reduces the ability of the machine to generate lower temperature since the effect of pressurization and depressurization reaching the PT is less.

All the 3 above are at an input power of 300W.

The interpretations will be discussed in a latter segment of the report.

6. Modelling the PTC on Sage

The PTC consists of sub-assemblies made up of different components, which have already been discussed in the previously. These sub-assemblies are: the linear compressor, the cold head, and the phase shifter assemblies.

The modelling henceforth is going to be based on the **Isothermal Model** described in the report above.

Linear Compressor - creates the pressure oscillation in the PTC system and is composed of:

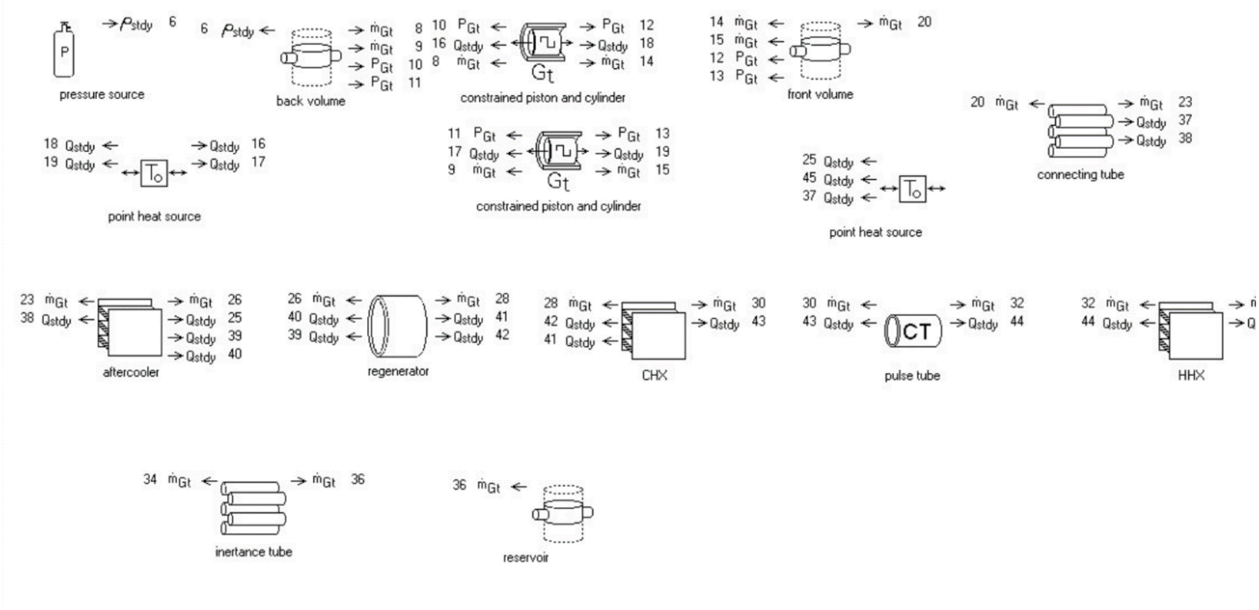
- Linear motor
- Piston Cylinder

Cold head -fitted in the vacuum jacket and consists of:

- Aftercooler
- Regenerator
- Cold end heat exchanger
- Pulse tube
- Hot end heat exchanger

Phase shifter - creates the required phase shift between pressure and mass flow oscillations, composed of:

- Inertance tube
- Reservoir



This is the overall modelling on Sage. The numbers correspond to the connections made, i.e., the arrows with the same number are how the components are related to one another.

The first 2 rows represent the Linear Compressor Assembly, the 3rd the Cold Head Assembly and the last the Phase Shifter Assembly.

6.1 Components and conditions

1. Linear Compressor

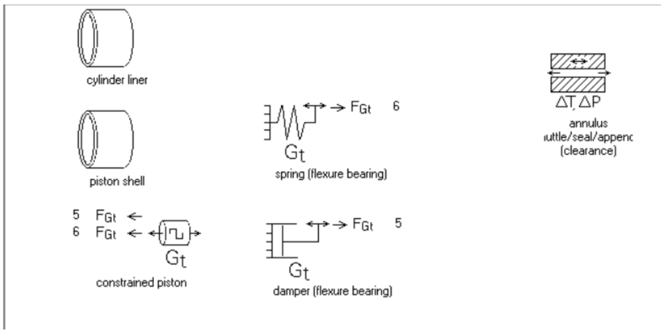
This Assembly is at ambient temperature and charging pressure initially as defined by the pressure source and the point heat source.

- **Linear motor**

The linear motor is not modelled by Sage. The linear motor efficiency is estimated and is then applied to the PV power (predicted by Sage) in order to calculate the electrical power input to the compressor.

- **Piston/Cylinder and compression Space**

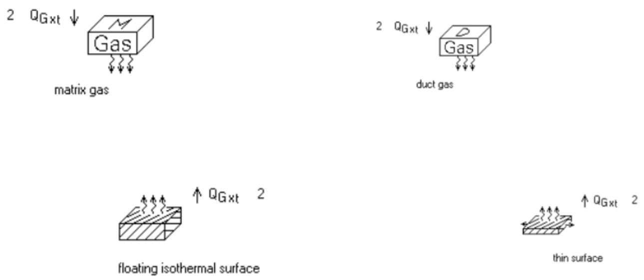
A linear compressor consists of a charging port, two piston and cylinders, compression space or the front volume, i.e., volume facing the pistons and back volume, i.e., volume behind the pistons. This linear compressor, which has two opposite pistons reciprocating inside their respective cylinder liners, is modelled using Sage.
The piston/cylinder and compression space model are created in Sage using: two constrained piston-cylinder and two generic cylinders (renamed as back and front volume) from the ’Basic tab’. A connecting tube between the compressor and the cold head is treated as a part of the compressor assembly. The charge pressure (pressure source) is introduced with an inbuilt attachment (ρ_{stdy}) and the value of charge pressure of the system is assigned to these components. Amongst all the parent level components, only this has an inbuilt attachment (ρ_{stdy}). The other components consist of sub-components or child components which must be added for the mass and heat flow connections.



Piston and Cylinder

Constrained piston means that the motion of the piston, i.e., phase, is defined by displacement, The other sub-components or child components like the annulus gap and spring components are added to this child level. The constrained piston at the child level defines the piston mass and its stroke, cylinder loner and piston shell are used to give the actual dimensions and materials of the same. the other child components ’Spring’ defines the stiffness of flexure bearing, ‘damper’ defines the damping coefficient while the annulus seal defines the actual clearance between the piston and the cylinder in a linear compressor.

Children components are as shown:



Of Annulus Seal Of Connecting tube

The gas flows back and forth through the clearance (annulus) seal and exchanges heat with the piston and the cylinder liner. To model this gas flow, the annulus seal component is provided with child components, i.e., matrix gas and floating isothermal surface as shown.

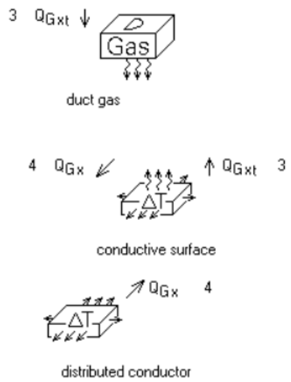
Each of these components have inbuilt heat flow connections Q_{Gxt} to model the thermal interaction between the gas and solid boundary. In Sage, the isothermal surfaces do not have any child components. The connecting tube has similar child components as the annulus seal model. However, the gas domain is labelled as ’M’ in annulus seal component, as opposed to the gas domain is labelled as ’D’ in connecting tube as shown. ’M’ stands for the matrix gas domain and ’D’ stands for the duct gas domain. The duct gas domain is used within relatively short flow ducts with not so tiny hydraulic diameters.

2. Cold Head

This assembly is connected to the linear compressor using the connecting tube which we considered to be a part of the latter.

- **Heat Exchangers**

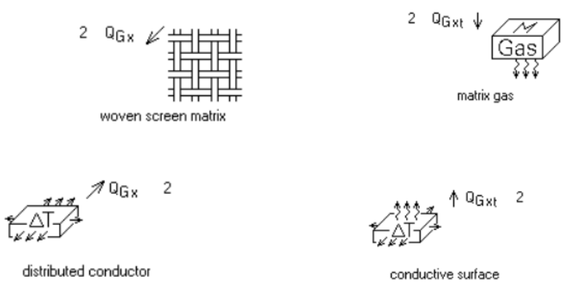
The aftercooler, the cold end heat exchanger (CHX) and the hot end heat exchanger (HHX) are the heat exchangers that transfer heat to and from an external heat source or sink. They are all at the parent level and are formed by selecting rectangular fins from the ’Heat Exchanger’ tab. As they are all modelled as rectangular fins, the child components within them are identical, of which the first child level is as shown. In these heat exchangers, the gas transfers its heat to the fins which transfer it to their surroundings, which could be water or air. This heat exchange between gas and the fins is modelled using a child component known as a ’conductive surface’ in Sage. The heat transfer between the fins and its surroundings is modelled by using a child component known as a ’distributed conductor’. The duct gas domain is used to simulate the mass flow of the gas through the fins. The duct gas components have positive and negative gas inlets that are exported up to the parent level.



Child components in HX

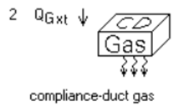
- **Regenerator**

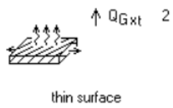
The regenerator consists of SS meshes with a mesh size of 400/200. The tubular canister (renamed as Regenerator) from the ’Canister’ tab forms the parent level. The length of tube, wall thickness and material are defined in this tab. Woven screen 70 matrix from the ’Matrices’ tab (a child component of ’Canister’ tab) is used to model the regenerator meshes that are filled in the regenerator tube. The wire thickness and the porosity of mesh are also defined in this tab. The matrix gas, conductive surface (the child components of ’Matrices’ tab) model the heat exchange between SS meshes and helium gas. The connections of the matrix gas component, and conductive surface component are exported to the parent level.
The child components of the regenerator and the woven screen matrix respectively are shown below.



- **Pulse Tube**

Pulse tube or compliance tube is treated as a special component of the PTC system in Sage; wherein the empty tube interacts with the gas molecules and also exchanges heat within the gas itself based on the flow regime. The modelling of such a component is treated in a special way. The child components of the compliance tube are shown. The compliance-duct gas (CD Gas) domain addresses the convective losses in the wall boundary layer, which are caused due to the presence of the axial temperature gradient. It accounts for the molecular and turbulent conduction, the free convection and the boundary and streaming convection. This 'CD Gas' is a child component that belongs only to the 'Compliance tube' component, which takes care of all possible losses in the pulse tube.





Child components of PT

3. Phase Shifter

The HHX is connected to the inertance tube.

- **Inertance Tube**

The inertance tube is modelled similar to the connecting pipe with their child components; i.e., the duct gas domain and isothermal surface, as discussed earlier

- **Reservoir**

The reservoir is modelled in the same way as the back and front volumes. The phase shifter assembly ends at the reservoir and thus there is only a negative gas inlet to the reservoir.

Each component also requires a specification of the number of special cells it should be divided into (discretization)

This completes the modelling of the PTC. The exact definitions and method of solving are specified in the User Manual of Sage.

6.2 Simulation

For simulating the cryocooler, the model is constructed as above. At each of the components (parent as well as child), the input values are specified.

The boundary conditions of pressure, heat flow and mass flow rate are also specified in the model above. They are easy to physically understand because of the GUI of Sage.

To solve the model, an objective function must be defined. In this case, we want to achieve minimum temperature at the CHX. Thus, this becomes our objective function.

6.3 Results

On Solving for the conditions of Loose SS400 Mesh, the minimum temperature obtained is 47.29Kelvin*

*The result hasn't converged.

7. Comparison between SAGE and Experimental Results

Since the Sage model was only solved for Loose SS400 meshes, it will be the one compared with the experimental results.

The experiment provided us with a minimum temperature of 57K while the Sage model that of 47.29K. This difference of can be attributed to numerous reasons, stated:

Usage of Ideal Helium in Sage

Exact boundary connections in Sage

Loss of heat due to radiation in the experiment (imperfect insulation)

Imperfect heat exchanges in the experiment

Attaching of sensors on the cold head in the experiment

Blockages in the meshes in the experiment

Other unaccounted errors

8. Conclusions

Conclusions from the experiment are as follows:

1. Using a single stage Stirling type Inline PTC with Inertance tube can result in temperatures as low as 57 Kelvin at an input power of 300W (With a charging pressure of !6 Bar, Operating frequency of 50Hz and CHX of type 3 used)
2. Input powers higher than 300W are not suitable since they heat up the compressor and may lead to damage or failure of the system.
3. Variation of pressures, frequencies, input powers, matrix material and HXs used will cause a significant variation in the temperature obtained.
4. SS400 is better than SS200 as a regenerator matrix. This is thought of to be due to smaller wire diameter (i.e., higher area for heat transfer) and higher heat capacity at cryogenic temperatures in case of SS400
5. Loose meshes generate lower temperature as compared to sintered meshes in both SS200 and SS400. This is due to higher pressure drop observed in the sintered mesh. Higher pressure drop decreases the effect of pressurization and depressurization in the pulse tube, in turn decreasing the compression and expansion; hence developing into a reason for non-achievement of lower temperatures.
6. Higher pressure drop in the sintered mesh for both can be attributed to a higher number of meshes since the meshes are also a source of resistance. Other reasons for the same can be improper shrink fitting or blockages in the mesh highlighted due to sintering.

Future Scope

- Elimination of the possible errors mentioned in case of sintered matrix and higher pressure drop
- Comparison using other matrix materials
- Development of an accurate and running Sage Model
- CFD analysis of the PTC
- Experimentation with more than one stage of PTC

Thank you.