CRYOGENIC ENGINEERING

Prof. Milind D. Atrey

Department of Mechanical Engineering,
IIT Bombay

Lecture No - 29

Earlier Lecture

- For an optimum design of a Stirling cryocooler, a compromise between the operating and the design parameters may be sought.

- Based on Schmidt's analysis, the variation of $\mathbf{Q_E / (p_{max} V_T)}$ and $\mathbf{W_T / (p_{max} V_T)}$ for a few non – dimensional numbers was presented.

- A combined effect of parameters on performance of system as a whole, is given in **Walker's optimization charts**.

Earlier Lecture

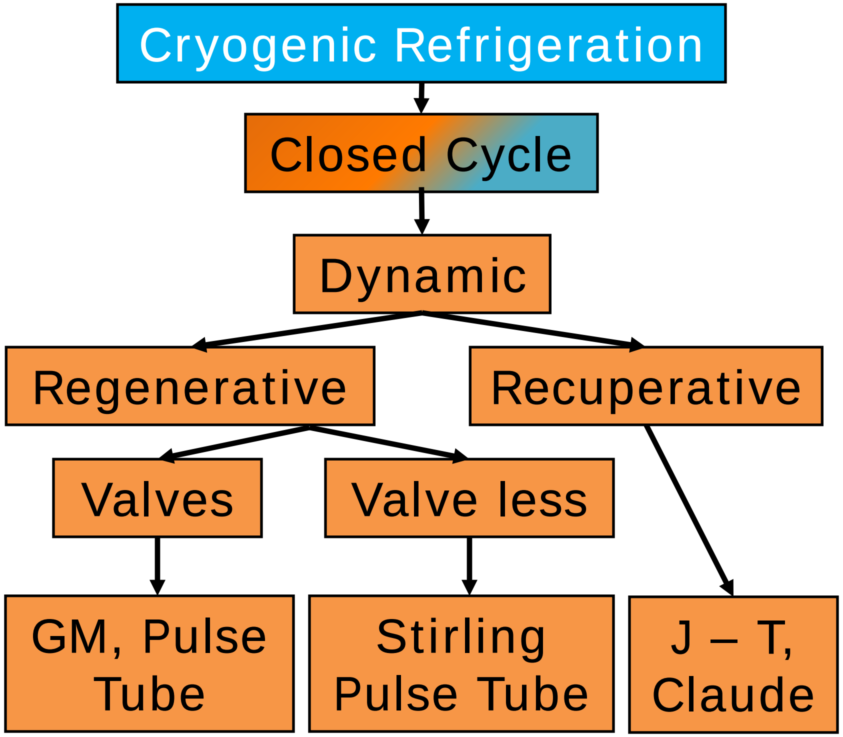
- In order to account for the various losses and to make the analysis more realistic, we have
  - $Q_{E,\ Design} = 3 \times Q_{E,\ Reqd}$.
- In the earlier lecture, a tutorial problem was solved on Stirling cryocooler design using the **Walker's Optimization Charts**.
- For a given $Q_{E,\ Design}$, if the dimensions of the piston and expander – displacer are very large, the system is designed for two cylinders or more.

Outline of the Lecture

Topic : Cryocoolers

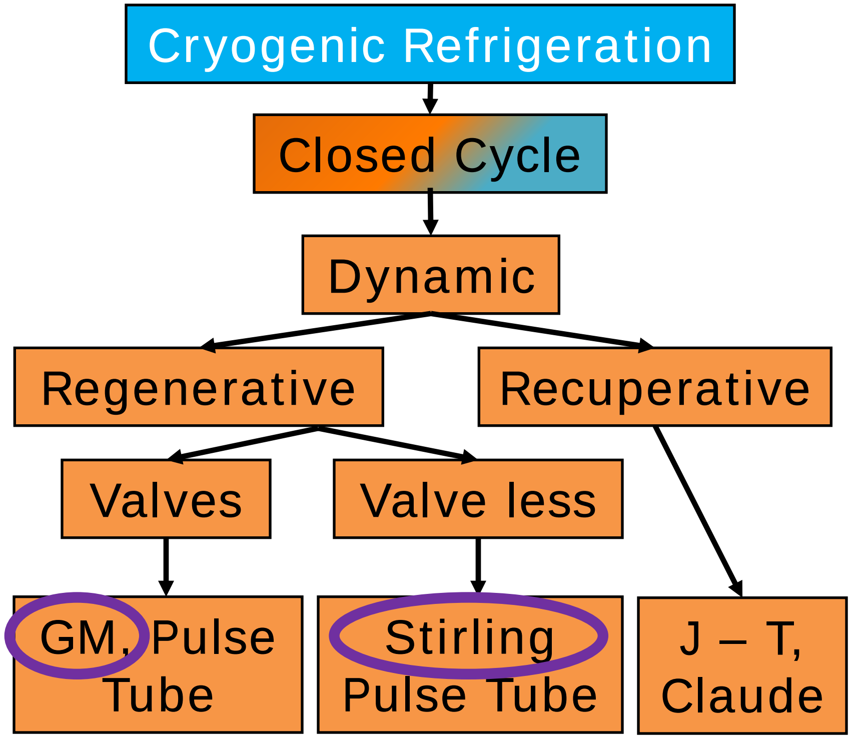
- Gifford – McMahon (GM) Cryocooler
- GM and Stirling Cryocooler – A comparison
- Working of a GM Cryocooler
- Regenerators, Valve mechanism
- Applications

Introduction



- In the earlier lecture, we have seen the classification of cryogenic refrigeration.
- The closed cycle division of the same is as shown.

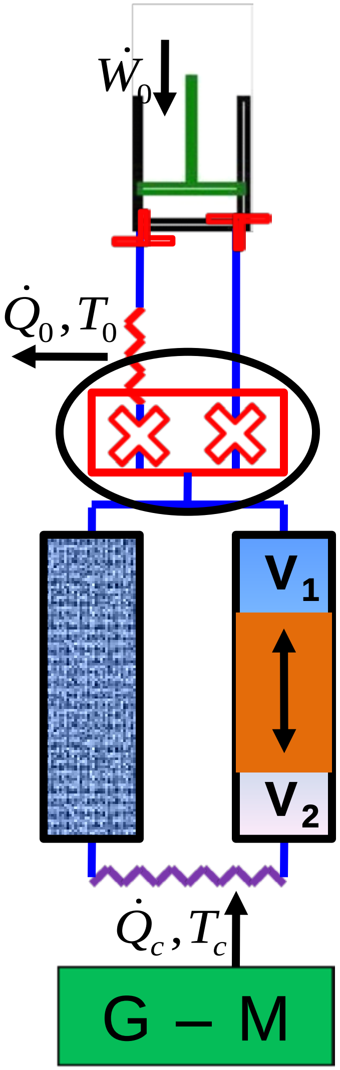
Introduction



- The working of a valve less, closed cycle, regenerative type, Stirling Cryocooler was discussed.

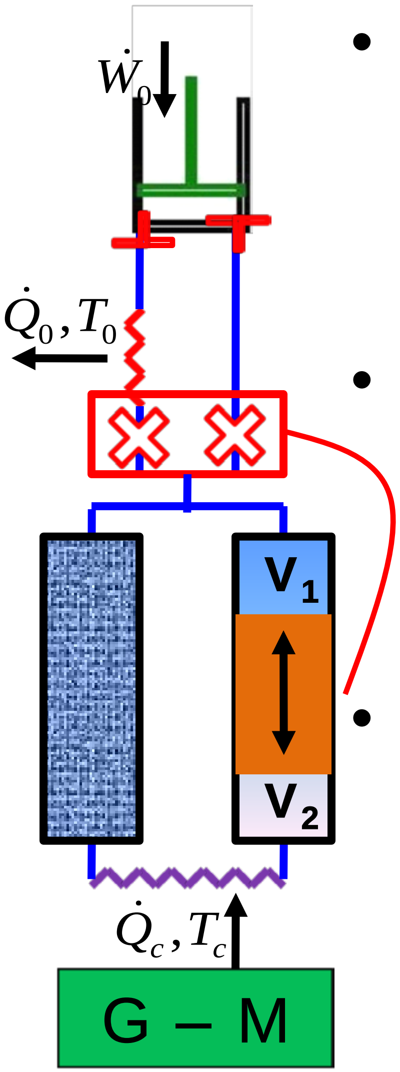
- On the other hand, the valved system under the regenerative type is the Gifford – McMahon (GM) Cryocooler.

Gifford – McMahon System



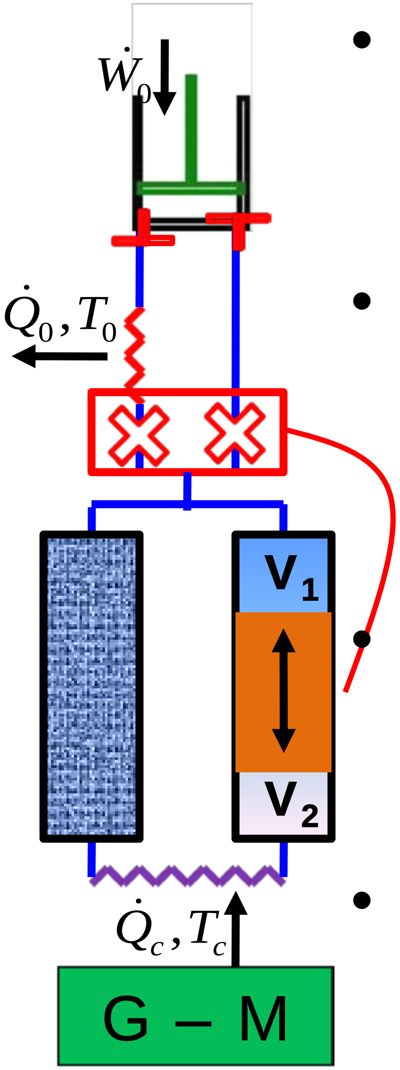
- The schematic of a Gifford – McMahon (GM) system is as shown in the figure.
- **W. E. Gifford** and **H. O. Mc Mahon** were the first to present this idea of introduction of valves in the year 1950.
- This valve mechanism is used to generate the pressure variation or the pressure pulse.
- This working cycle was later named as Gifford – McMahon cycle.

Gifford – McMahon System



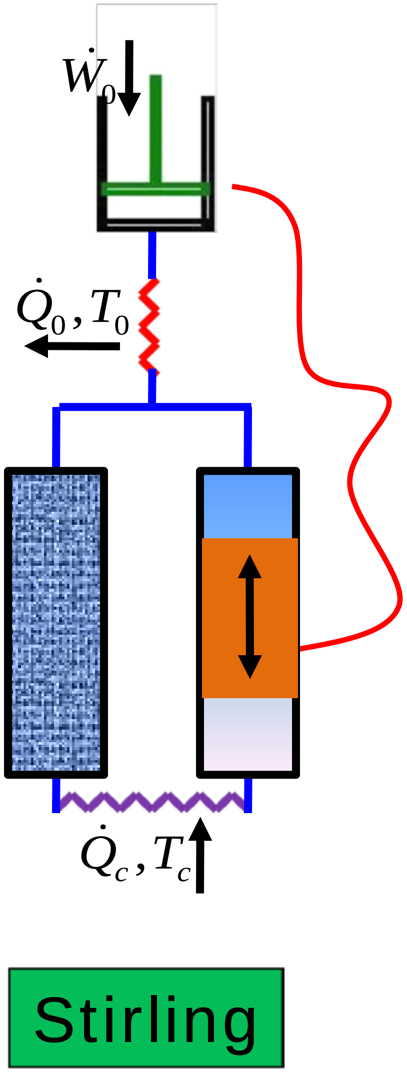
- The sequential opening and closing of these valves generate the required pressure variation or the pressure pulse.
- The timing of the valves in relation to the position of the displacer is vital for optimum operation.
- Therefore in a GM system, there is a relation between the pressure pulse generated by the valve mechanism and the expander – displacer motion.

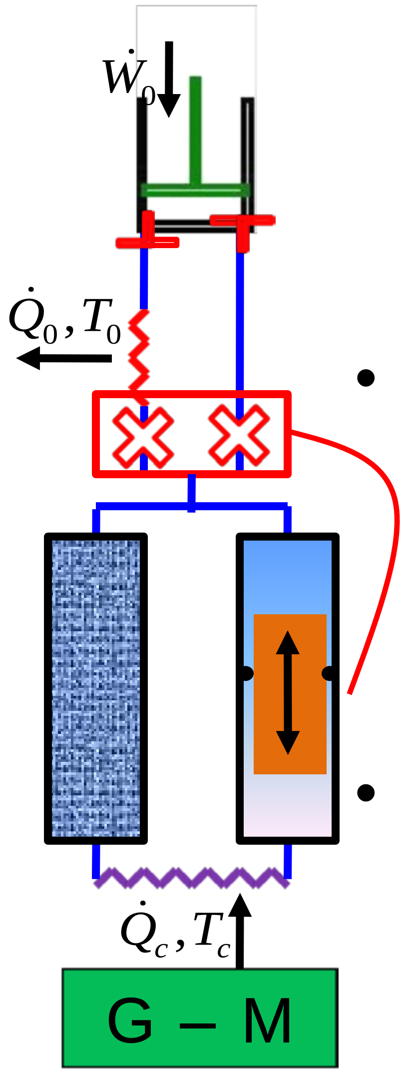
Gifford – McMahon System



- Different variations in the valve design for a GM Cryocooler are possible.
- Some of the systems may have one valve each on the high and the low pressure lines.
- Also, some of the systems may have poppet valves, solenoid valves.
- Commercially available cryocoolers have rotary valves to control or regulate the flow of the working medium.

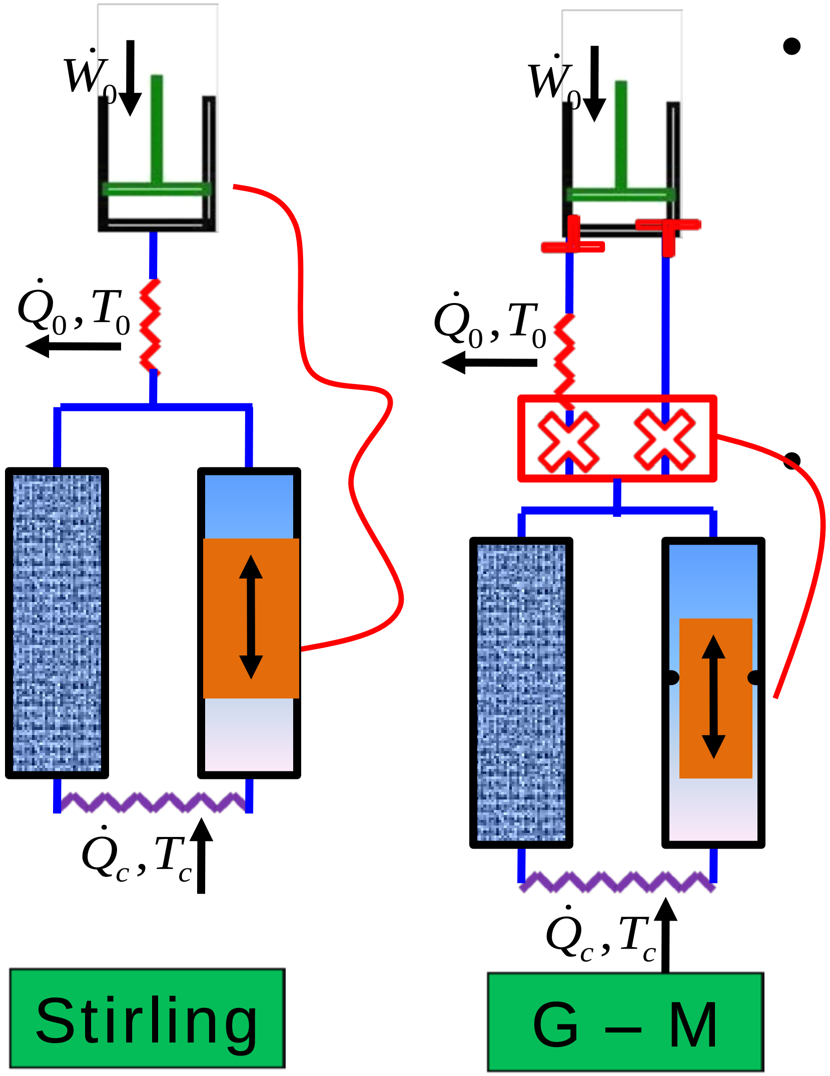
A Comparison





- At low frequencies, the rubbing seal between the displacer and the cylinder is perfect.
- The valves facilitates production of any kind of pressure wave as per the requirement of system.

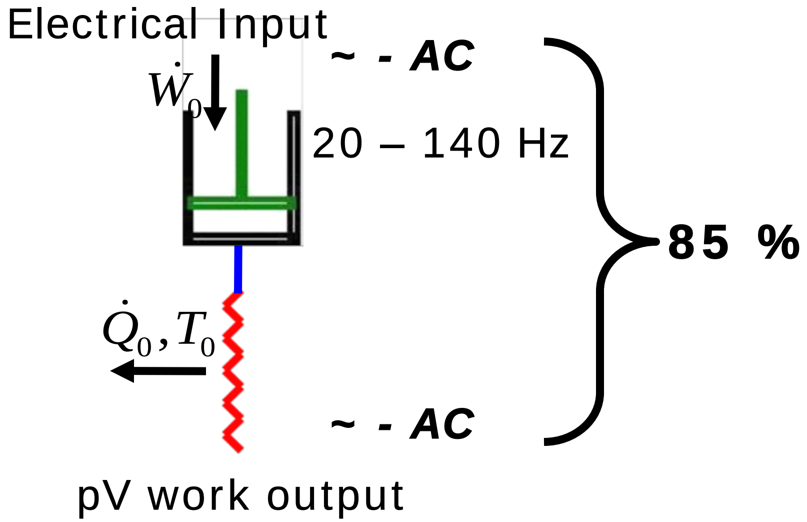
A Comparison



- Stirling cryocooler is a high frequency machine where as, a GM Cryocooler is a low frequency machine.
- Although, presence of valves deteriorates the system performance, but it is possible to reach much lower temperatures using a GM system as compared to a Stirling system.

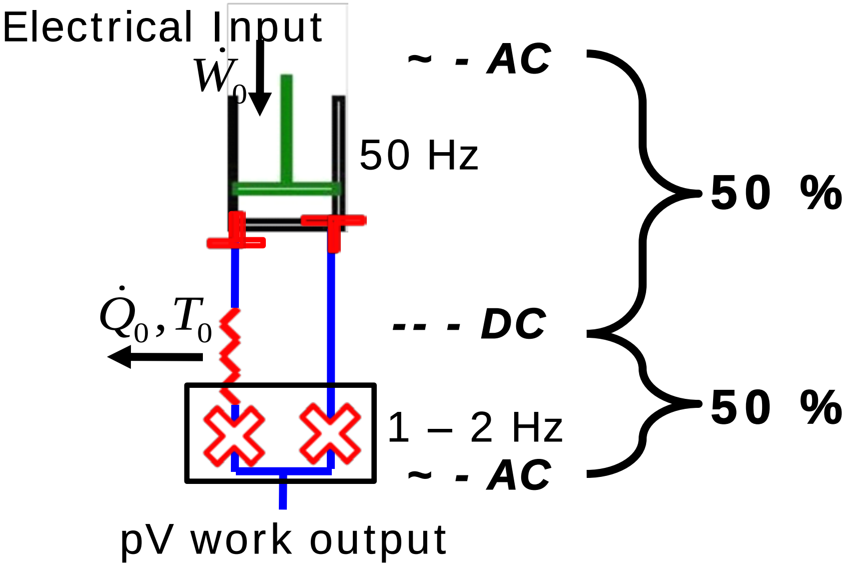
A Comparison

Stirling



Efficiency: 85%

G – M



Efficiency: 25%

A Comparison

Stirling	Gifford - McMahon
20 – 150 Hz frequency.	1 – 5 Hz frequency.
Direct connection (Compressor – expander).	Valved connection (Compressor – expander).
Dry compressor.	Lubricated compressor.
High COP (10 W at 80 K, 350 W).	Low COP (100 W at 80 K, 4000 W+Q_{chill}).
Low pressure ratios.	High pressure ratios.
20 K using two stages.	4 K using two stages.
Low power compressors and compact.	High power compressors and bulky.

A Comparison

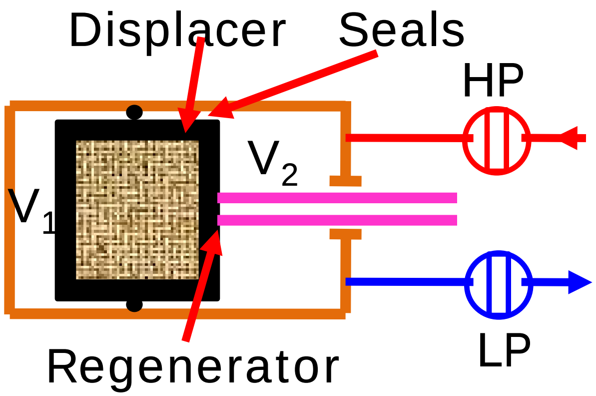
Stirling

- Miniaturization is possible due to fewer moving parts.
- Suitable for space application.

Gifford - McMahon

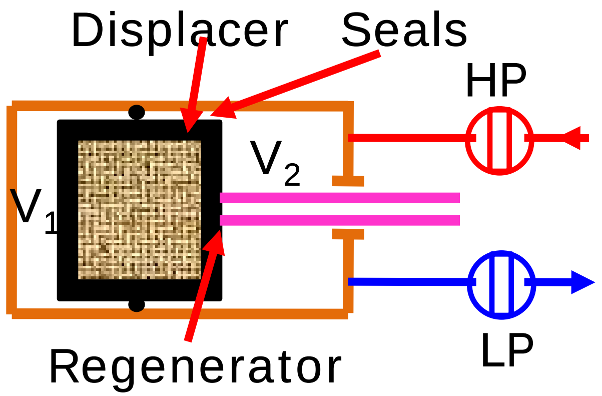
- Miniaturization is not possible due to the valves.
- Mostly, land based applications.

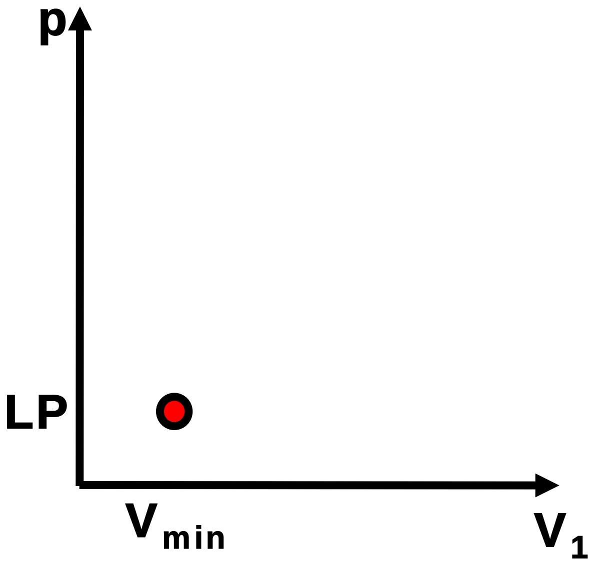
Working of GM Cryocooler



- Consider a displacer housing the regenerator, at BDC position as shown in the figure.
- The cold space (**V_1**) and the warm space (**V_2**) are as shown.
- In this schematic, both the **high (HP)** and **low (LP)** valves are in closed position.
- The seals are provided to reduce the leakage across the displacer.

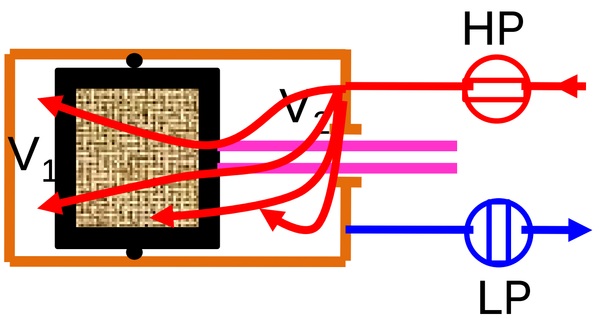
Working of GM Cryocooler

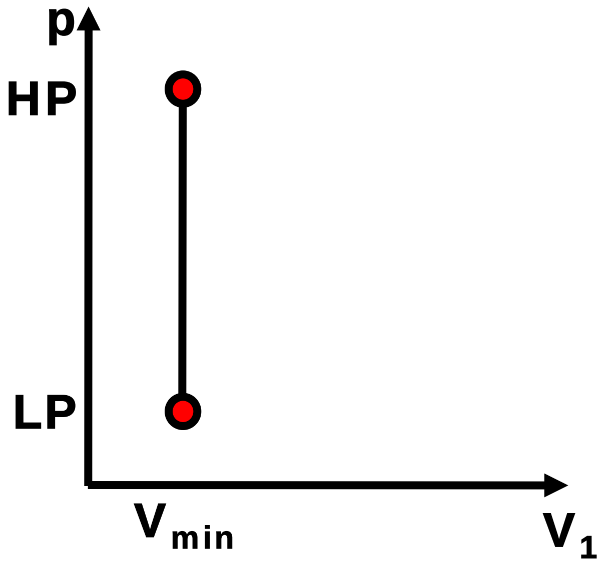




- The corresponding situation of the cold space (**V_1**), when plotted on a **pV** diagram is as shown in the adjacent figure.

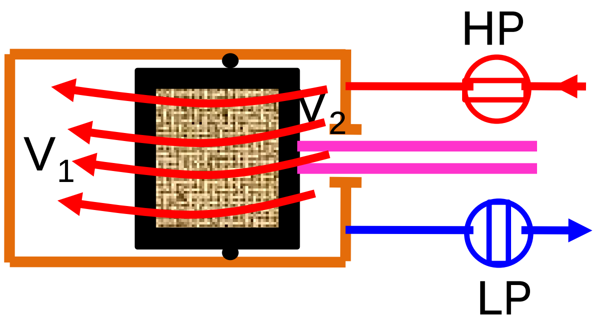
Working of GM Cryocooler

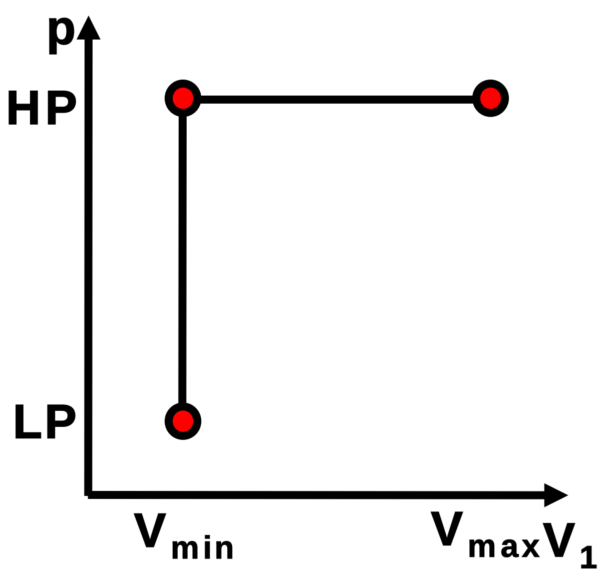




- With the opening of the **HP** valve, the high pressures gas fills $\mathbf{V_1}$ and $\mathbf{V_2}$ spaces at a constant volume as shown in the figure.

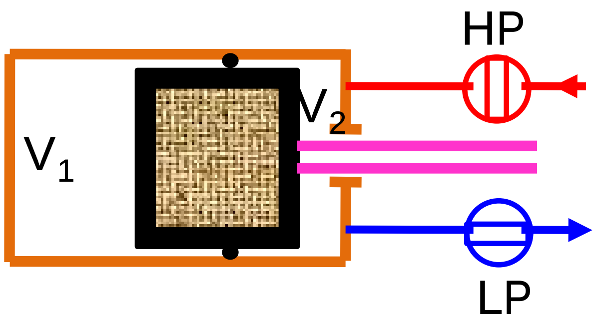
Working of GM Cryocooler

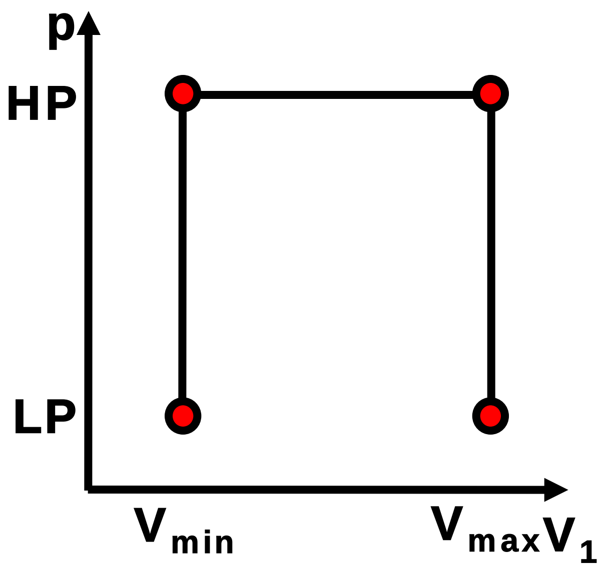




- The displacer moves back displacing the gas from $\mathbf{V_2}$ to $\mathbf{V_1}$ at a constant pressure.
- The cold space volume ($\mathbf{V_1}$) increases where as, the warm space volume ($\mathbf{V_2}$) decreases.

Working of GM Cryocooler

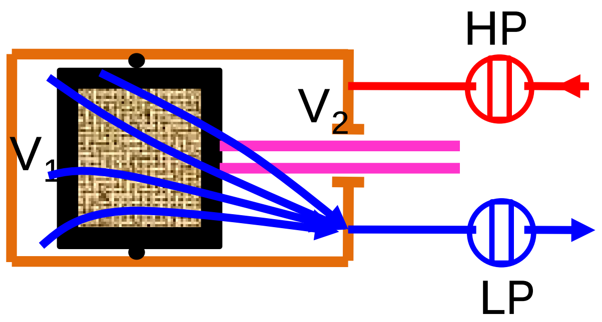


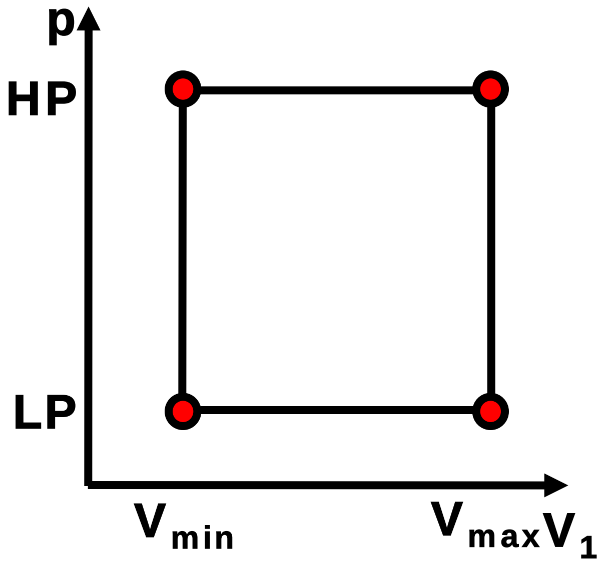


- Now, the **HP** valve is closed and **LP** valve is opened. This leads to an expansion of gas, reducing the pressure from **HP** to **LP**.

- This expansion produces cold in cold space volume ($\mathbf{V_1}$).

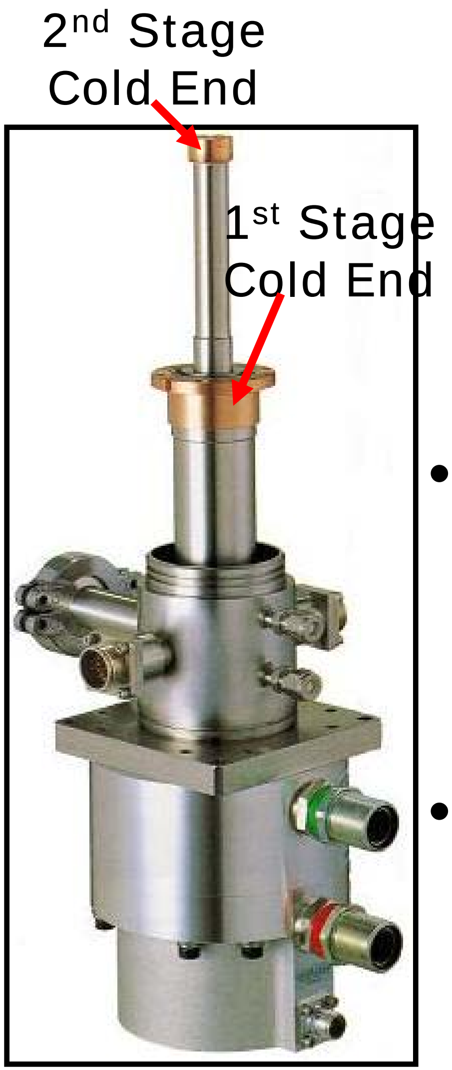
Working of GM Cryocooler





- The displacer moves back, reducing the cold space volume (**V_1**).
- The cycle continues to produce lower and lower temperatures.

Multistaging in GM Cryocooler



- A single stage GM cryocooler produces a refrigeration effect of 12 W at 80 K, for a 1.2 kW input power.
- In order to reach much lower temperatures, say, in the order of 10 K to 4.2 K, multistaging is done in these systems.

Multistaging in GM Cryocooler

- Commercially available two stage GM cryocoolers are capable of reaching temperatures lower than 4.2 K.

Components of GM Cryocooler

- Video of GM cryocooler.
- For the sake of understanding, a demo video of a GM cryocooler at **IIT Bombay** is shown.
- It is a two stage machine capable of reaching a temperature of 10 K.

Components of GM Cryocooler

- The basic components of any GM cryocooler are as listed below.
  - Helium compressor – scroll/reciprocating type.
  - Flex lines – HP line, LP line.
  - Regenerator(s) and Displacer(s).
  - Valve mechanism – rotary, solenoid, poppet.
  - Cooling arrangements – Air or water cooled.

Regenerators

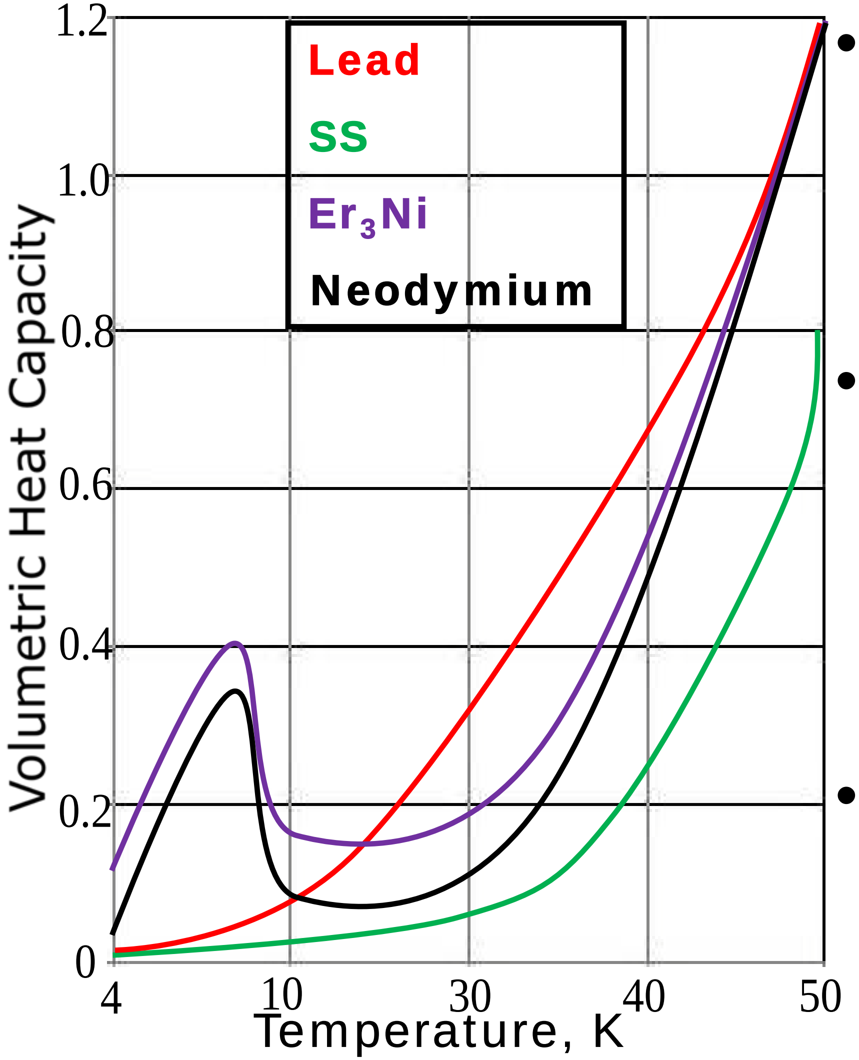
- The regenerator is the most vital component and is often called as a heart of a cryocooler.

- The major aspects of a regenerator are
  - Dimensions – length, diameter.
  - Material – Heat capacity, thermal conductivity.
  - Porosity.
  - Working temperature.
  - Heat transfer and minimum pressure drop.

Regenerators

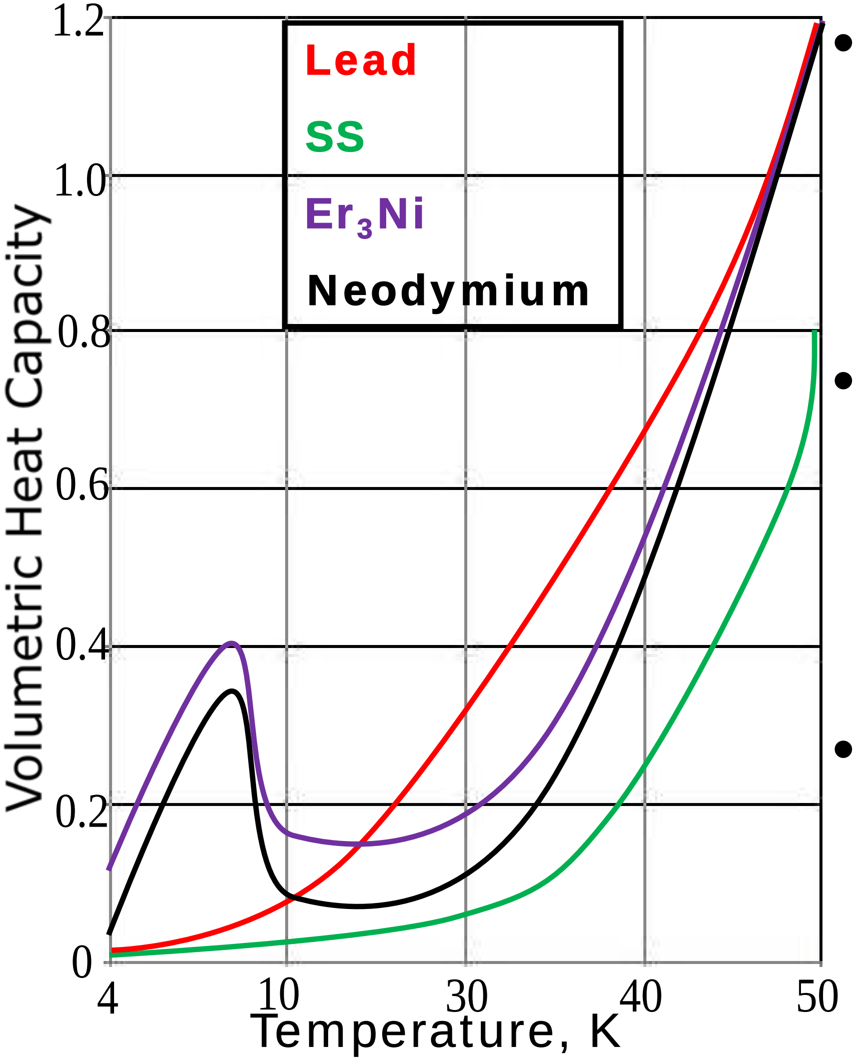
- In general, a material with high heat capacity is chosen as a regenerator material.
- This is because, the energy exchanged between the working gas and the matrix is directly dependent on the relative heat capacity.
- As seen in the earlier lectures, it is important to note that the C_P of a material decreases with the decrease in the temperature.
- Very often, a combination of various rare earth materials is used as a regenerator material.

Regenerators



- The variation of volumetric heat capacity with temperature is as shown.
- Materials like **SS** are not preferred at lower temperatures (**~ 30 K**) due to low heat capacity.
- Materials like **Lead**, **Er_3Ni** and **Neodymium** exhibit high heat capacities at lower temperatures.

Regenerators

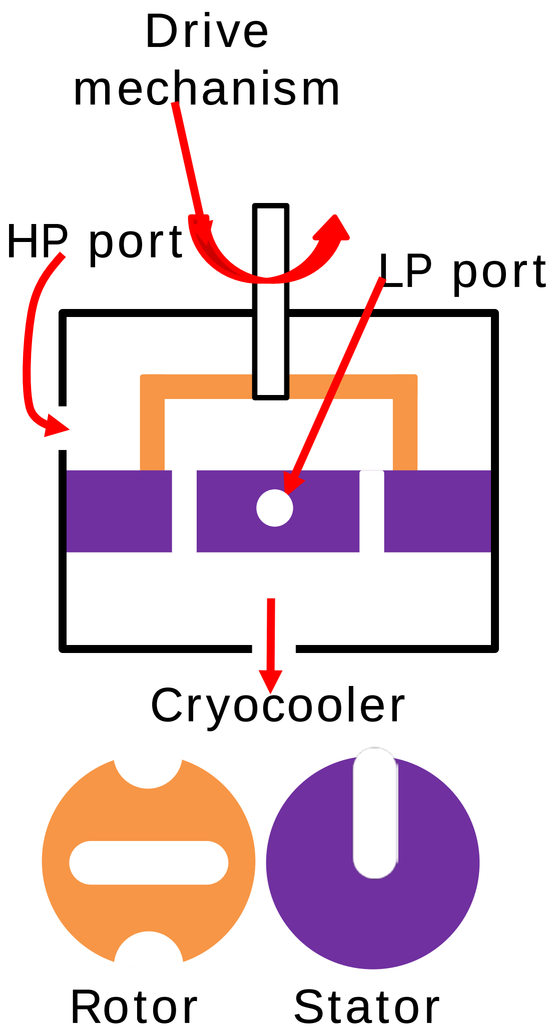


- In single stage GM systems (**~ 30 K**), **SS** meshes are used.
- Two stage (**~ 10 K**)
  - 1st stage: **SS** mesh
  - 2nd stage: **Lead** balls
- Two stage (**~ 4.2 K**)
  - 1st stage: **SS + Lead**
  - 2nd stage: **Lead + Er_3Ni**.

Valve Mechanism

- As mentioned earlier, the sequential opening and closing of the valve mechanism, generates the required pressure variation or the pressure pulse.
- The rotary valve should operate at an optimum frequency.
- The schematic and the working of a most commonly used rotary valve is explained in the next slide.

Valve Mechanism

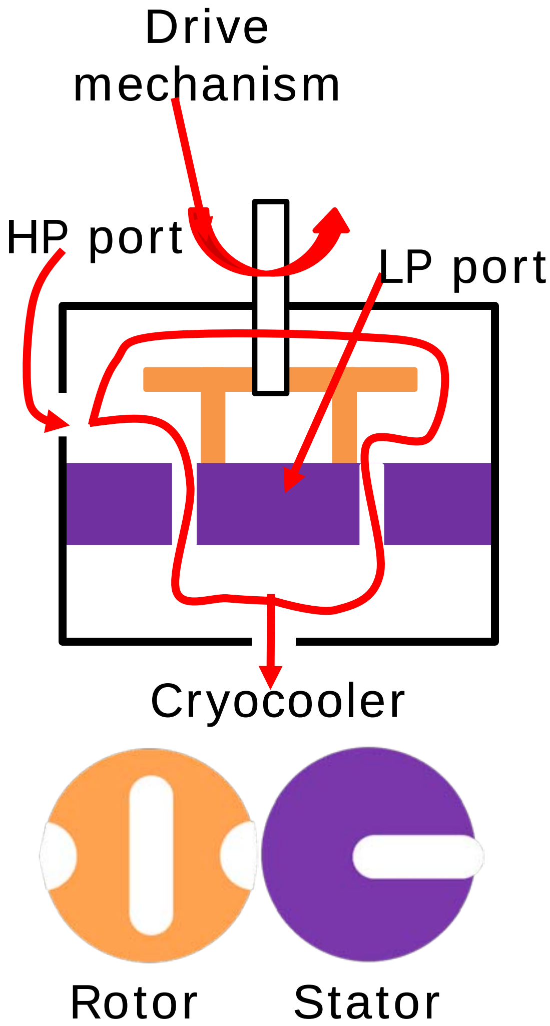


- The various parts of a rotary valve are as listed below.
  - Drive mechanism
  - HP, LP ports
  - Rotor, Stator

- The rotor is driven by a drive mechanism, maintaining a perfect seal on the stator.

- The slotted rotor and stator discs, connect the cryocooler to **HP** and **LP** lines respectively.

Valve Mechanism

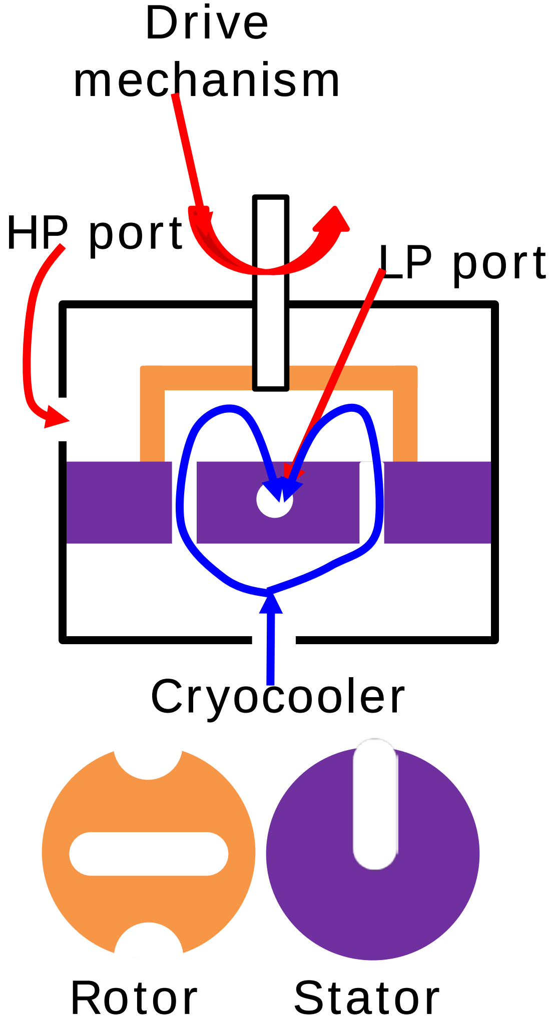


High Pressure Position

- When the slots on the rotor disc match with the stator as shown, the high pressure gas from the compressor flows to the cryocooler.

- In this position, the **LP** port is masked/closed.

Valve Mechanism



Low Pressure Position

- With the rotation of the rotor disc, at a particular instant, the slots on the rotor disc are masked/closed.
- In this position, the hole in the stator is unmasked/opened, connecting the cryocooler to the **LP** port, as shown in the figure.

Applications

- GM cryocoolers find applications in the following areas.
  - MRI machines
  - Cryo pumps
  - **N_2** liquefiers
  - Cryoprobes

- These machines also find applications in areas like **low temperature physics** and **scientific applications**.

Summary

- **W. E. Gifford** and **H. O. Mc Mahon** were the first to present this idea of introduction of valves in the year 1950.
- A GM system has a valve mechanism to control/regulate the flow between the compressor and the regenerator – displacer assembly.
- For an optimum performance, the relation between the pressure pulse generated by the valve mechanism and the expander – displacer motion is vital.

Summary

- A GM system can reach much lower temperatures as compared to a Stirling system, but may require a high powered compressor due to the inefficiency of the valves.
- Multistaging is done to reach lower temperatures (4.2 K to 10 K).
- The basic components are Helium compressor, Flex lines, Regenerator(s), Displacer(s) and Valve mechanism.

Summary

- The choice of the regenerator material is dependent on the lowest working temperature of the cryocooler.

- Single stage (**~ 30 K**), **SS** mesh.
- 2 – stage (**~ 10 K**), 1st stage: **SS** mesh, 2nd stage: **Lead** balls.
- 2 – stage (**~ 4.2 K**), 1st stage: **SS** mesh **+ Lead** balls, 2nd stage: **Lead** balls **+ Er_3Ni** balls.

- Commercially available cryocoolers have rotary valves to control/regulate the flow.

- A self assessment exercise is given after this slide.

- Kindly asses yourself for this lecture.

Self Assessment

1. ___ is used to generate the pressure variation in a GM system.
2. In a GM cycle, the relation between the pressure pulse and the ___________ is vital.
3. Rubbing seals between the displacer and the cylinder is perfect at _____ frequencies.
4. In a ___ system, miniaturization is not possible due to the valves.
5. In GM systems, ___is done in order to reach lower temperatures.
6. ___ is the most vital component and is often called as a heart of a cryocooler.
7. ___ decreases with the decrease in temperature.

Self Assessment

8. Materials like ___, ____ and ____ exhibit high heat capacities at lower temperatures.
9. Rotary valve should operate at an ___ frequency.
10. Commercially available cryocoolers have ____ types of valves to control/regulate the flow.

Answers

1. Valve mechanism
2. Expander – displacer piston.
3. Low
4. GM
5. Multistaging
6. Regenerator
7. C_P
8. Lead, Er_3Ni and Neodymium
9. Optimum
10. Rotary

Thank You!