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 \( \frac{Q_E}{(p_{\text{max}} V_T)} \) and \( \frac{W_T}{(p_{\text{max}} V_T)} \) 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
  \[ Q_{E, \text{Design}} = 3 \times Q_{E, \text{Reqd}}. \]

• In the earlier lecture, a tutorial problem was solved on Stirling cryocooler design using the Walker’s Optimization Charts.

• For a given \( Q_{E, \text{Design}} \), 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
In the earlier lecture, we have seen the classification of cryogenic refrigeration.

The closed cycle division of the same is as shown.
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.
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 whereas 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**

- Electrical Input: \( \dot{W}_0 \)
- 20 – 140 Hz
- \( \dot{Q}_0, T_0 \)
- ~ - AC
- pV work output

**G – M**

- Electrical Input: \( \dot{W}_0 \)
- 50 Hz
- \( \dot{Q}_0, T_0 \)
- -- - DC
- 1 – 2 Hz
- ~ - AC
- 50 %

**Efficiency**: 85%

**Efficiency**: 25%
<table>
<thead>
<tr>
<th><strong>Stirling</strong></th>
<th><strong>Gifford - McMahon</strong></th>
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<tbody>
<tr>
<td>20 – 150 Hz frequency.</td>
<td>1 – 5 Hz frequency.</td>
</tr>
<tr>
<td>Direct connection (Compressor – expander).</td>
<td>Valved connection (Compressor – expander).</td>
</tr>
<tr>
<td>Dry compressor.</td>
<td>Lubricated compressor.</td>
</tr>
<tr>
<td>High COP (10 W at 80 K, 350 W).</td>
<td>Low COP (100 W at 80 K, 4000 W + Q_{chill}).</td>
</tr>
<tr>
<td>Low pressure ratios.</td>
<td>High pressure ratios.</td>
</tr>
<tr>
<td>20 K using two stages.</td>
<td>4 K using two stages.</td>
</tr>
<tr>
<td>Low power compressors and compact.</td>
<td>High power compressors and bulky.</td>
</tr>
</tbody>
</table>
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.
The corresponding situation of the cold space ($V_1$), when plotted on a $pV$ diagram is as shown in the adjacent figure.
With the opening of the HP valve, the high pressures gas fills $V_1$ and $V_2$ spaces at a constant volume as shown in the figure.
The displacer moves back displacing the gas from $V_2$ to $V_1$ at a constant pressure.

The cold space volume ($V_1$) increases whereas the warm space volume ($V_2$) decreases.
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 ($V_1$).
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.
• 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\(_3\)Ni 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 + Er₃Ni.
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
  • $\text{N}_2$ 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 ($\sim 30$ K), SS mesh.

• 2 – stage ($\sim 10$ K), 1st stage: SS mesh, 2nd stage: Lead balls.

• 2 – stage ($\sim 4.2$ K), 1st stage: SS mesh + Lead balls, 2nd stage: Lead balls + Er$_3$Ni balls.

• Commercially available cryocoolers have rotary valves to control/regulate the flow.
• A self assessment exercise is given after this slide.

• Kindly assess 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.
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, \( \text{Er}_3\text{Ni} \) and Neodymium
9. Optimum
10. Rotary