CRYOGENIC ENGINEERING

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Lecture No - 33
Earlier Topics

• Introduction to Cryogenic Engineering

• Properties of Cryogenic Fluids

• Properties of Materials at Cryogenic Temperature

• Gas Liquefaction and Refrigeration Systems

• Gas Separation

• Cryocoolers
Topic: Cryogenic Insulation

- Why Insulation?
- Different types of Cryogenic Insulations
- A comparative study
- Applications

- The current topic will be covered in 3 lectures.

- Tutorials and assignments are included at the end of each lecture.
Outline of the Lecture

Topic: Cryogenic Insulations

- Why Insulation?
- Types of Insulation
- Expanded Foam and Powder Insulations
- Radiation Fundamentals
Introduction

• Storage of a cryogen (say, LN2) is difficult, as there is a continuous boil off due to heat in leaks.

• These vessels cannot be sealed as boil off generates huge volumes of vapour, resulting in large pressure rise. This may lead to bursting.

• For example, vapor to liquid volume ratio for a general cryogen is 175 (1600 for water).

• To avoid the pressure rise, the need of insulation is vital. Insulation or a combination of insulations, minimize all these modes of heat transfer.
Consider a LN2 container as shown in the figure.

The inner vessel is housed inside an outer vessel and these vessels are separated by some form of insulation.

Also, the inner vessel is supported using lateral beams as shown.

The liquid boils off continuously due to the various modes of heat transfer.
Heat Transfer

- Different modes of heat transfer are
  - **Conduction**: The heat is conducted through lateral beams, neck and residual gas conduction.
  - **Convection**: The air between inner and outer vessels convect heat into the liquid.
  - **Radiation**: The radiation heat transfer from 300 K outer vessel to 77 K inner vessel.
Types of Insulation

- **Insulation**
  - Mass
  - Reflective
  - Vacuum
    - Cellular
    - Granular
    - Fibrous
      - Metal Foils
      - Multi Layer Insulation
Types of Insulation

- Expanded Foam – Mass
- Gas Filled Powders & Fibrous Materials – Mass
- Vacuum alone – Vacuum
- Evacuated Powders – Mass + Vacuum
- Opacified Powders – Mass + Vacuum + Reflective
- Multilayer Insulation – Vacuum + Reflective
Types of Insulation

• The choice of insulation for a particular application is a compromise between the following factors.

  • Thermal Conductivity
  • Temperature
  • Effectiveness of Insulation
  • Cost
  • Ease of application
  • Weight and reliability

• A combination of insulations is used to prevent different modes of heat transfer.
Apparent Thermal Conductivity

- As seen earlier, the different modes of heat transfer are Gas and Solid Conductions, Convection and Radiation.

- Consider an element of insulation, separated by two temperatures \( T_1 > T_2 \) as shown below.

- Let \( Q \) be net heat transferred across this element by all possible modes of heat transfer mentioned above.
Apparent Thermal Conductivity

- If $A$ and $L$ be the area of the cross section and length of the element respectively, the apparent thermal conductivity ($k_A$) is defined as

\[ k_A = \frac{QL}{A(T_1 - T_2)} \]

- In other words, this apparent thermal conductivity is calculated based on all possible modes of heat transfer.
Expanded Foams

- Expanded foam is a low density, cellular structure which is formed by evolving gases during the manufacturing process.

- Gases that are generally used are \( \text{CO}_2 \) and Freon.

- In other words, it is a solid – gas matrix with void spaces. The solid connections together with gas trapped in cellular spaces form a continuous path.

- The heat is transferred only by conduction (solid conduction). The contribution by convection and radiation are negligible.
Expanded Foams

- Examples are polyurethane foam, polystyrene foam, rubber, silica glass foam.

- $k_A$ and density are as shown below. The operating temperature is between 77 K to 300 K.

<table>
<thead>
<tr>
<th>Foam</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$k$ (mW/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyurethane</td>
<td>11</td>
<td>33</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>39</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>26</td>
</tr>
<tr>
<td>Rubber</td>
<td>80</td>
<td>36</td>
</tr>
<tr>
<td>Silica</td>
<td>160</td>
<td>55</td>
</tr>
<tr>
<td>Glass</td>
<td>140</td>
<td>35</td>
</tr>
</tbody>
</table>
Expanded Foams

- The $k_A$ of the foam depends on the type of gas used and also the temperature of the insulation.

- For a given gas, the performance of the foam is improved by varying the void size and bulk density.

- The adjacent figure shows the variation of $k_A$ with the mean cell diameter.
Expanded Foams

• With the decrease in the mean cell diameter, the solid conduction path increases in the foam insulation.

\[ k_A = \frac{QL}{A(T_1 - T_2)} \]

• From the above equation, the Q decreases and hence the \( k_A \) decreases.
Expanded Foams

• At the same time, with the decrease in the mean cell diameter, the bulk density of the foam increases.

• Therefore, $k_A$ is also a function of bulk density and it increases with the increase in bulk density.
Expanded Foams

• The major advantage of an expanded foam is that it offers an ease of fabrication.

• The foam is directly blown onto the surface of the vessel to be insulated. It forms a self supporting structure.

• The cost of this insulation is also low as compared to other types of insulations.
Expanded Foams

• Exposure of a CO$_2$ expanded foam to LN2 temperatures, increases the thermal conductivity.

• At LN2 temperature, the vapor pressure of CO$_2$ is less. As a result, most of CO$_2$ is condensed within the insulation and caters for the heat transfer.

• Also over a period of time, air, hydrogen or helium diffuse into foam from external atmosphere.

• The $k_A$ of the foam increases due to increase in the gas conduction at room temperature.
Expanded Foams

- Expanded foams have large thermal contractions, which pose a major disadvantage.

- A rigid foam has a large thermal contraction between -30°C to +30°C.

- For example, coefficients of linear expansion are:
  - $\alpha_{\text{Polystyrene Foam}} : 7.20 \times 10^{-5}/\degree C$
  - $\alpha_{\text{Carbon Steel}} : 1.15 \times 10^{-5}/\degree C$

- The foam when closely fitted around a LN2 vessel, crack due to difference in shrinkages.
Gas Filled Powder & Fibrous Insulations

• A gas filled powder or a fibrous insulation reduces or eliminates the gas convection due to the small size of voids within the material.

• This is because, the distance between the powder particles within the insulation is much smaller than the gas mean free path.

• As a result, the gaseous conduction mechanism shifts from continuum to free molecular conduction decreasing the apparent thermal conductivity, $k_A$. 
Gas Filled Powder & Fibrous Insulations

- The commonly used insulations of this type are Fiber Glass, Perlite (Silica Powder), Santocel, Rockwool, Vermichlitine.

- $k_A$ and density are as shown below. The operating temperatures are between 77 K to 300 K.

<table>
<thead>
<tr>
<th>Insulation</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$k$ (mW/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perlite</td>
<td>50</td>
<td>26</td>
</tr>
<tr>
<td>Silica Aerogel</td>
<td>80</td>
<td>19</td>
</tr>
<tr>
<td>Fiber glass</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>Rockwool</td>
<td>160</td>
<td>35</td>
</tr>
</tbody>
</table>
Gas Filled Powder & Fibrous Insulations

• The advantages of a gas filled powder are low thermal conductivity, low density and low particle distribution to minimize the vibration effects.

• The insulation can either be evacuated or non-evacuated. Heat transfer by residual gas is further minimized by low vapor pressure of the gas.

• Finely divided particulate materials make solid conduction paths disjointed and discontinuous.
Gas Filled Powder & Fibrous Insulations

• The disadvantage is that moisture and air diffuse through the material to the cold surface unless a vapor barrier is used. $\text{N}_2$ purging is used.

• Fill – gas should be unreactive and compatible with powder material.

• Powder tends to settle and packs due to vibrations, thermal contraction and expansion.

• This creates increased solid conduction.
Gas Filled Powder & Fibrous Insulations

- Nusselt & Bayer developed the following expression for $k_A$ for a gas filled powder.

$$k_A = \left( \frac{V_r}{k_s} + \left[ \frac{k_g}{(1-V_r)} + \frac{4\sigma T^3 d}{V_r} \right]^{-1} \right)^{-1}$$

- $V_r$ – Ratio of solid particulate to total volume.
- $k_s$ & $k_g$ – Thermal conductivity of Solid and Gas.
- $T$ – Mean temperature.
- $d$ – Mean diameter of fiber or powder.
At cryogenic temperatures, two assumptions are made:

- $T^3$ term is very small relative to $k_g$ term.
- $k_s >> k_g$

Therefore, the equation is:

$$k_A = \frac{k_g}{(1-V_r)}$$
\( k_A = \frac{k_g}{(1-V_r)} \)

- Therefore, as \( V_r \) tends to zero, \( k_A \) approaches \( k_g \).

- This is the lowest possible thermal conductivity of this insulation.
Radiation – Fundamentals

• Consider two flat surfaces maintained at different temperatures \((T_1 > T_2)\) as shown in the figure.

• There is continuous heat transfer between the two plates due to the radiation.

• This mode of heat transfer does not require any medium and is given by the following equation.

\[
Q = F_e F_{1 \rightarrow 2} \sigma A_1 \left( T_2^4 - T_1^4 \right)
\]
In the above equation, it is clear that for a given $A_1$, $T_1$, $T_2$, $F_{1\rightarrow 2}$, $Q$ is directly proportional to the emissivity factor $F_e$.

The $F_e$ is reduced by introducing the radiation shields in the path of radiation heat transfer as shown.

The effect of these shields is as explained in the next slide.
The effective emissivity factor $F_N$ after introduction of $N$ shields is as given below.

$$\frac{1}{F_N} = \left( \frac{1}{e_1} + \frac{1}{e_s} - 1 \right) + (N - 1) \left( \frac{2}{e_s} - 1 \right) + \left( \frac{1}{e_2} + \frac{1}{e_s} - 1 \right)$$

For the sake of understanding, let the values of $e_1$, $e_2$, and $e_s$ be 0.8, 0.8, 0.05 respectively.

Students are advised to calculate and compare $F_N$ for following cases.

- Case 1: $N=0$
- Case 2: $N=10$
Radiation Shields

- Case 1: $N=0$ – $F_N = 0.667$

- Case 2: $N=10$ – $F_N = 0.00255$

- It is clear that the $F_N$ decreases drastically with the introduction of radiation shields.

- These shields are aluminum foils with a very high reflectivity.
Summary

• Cryogenic vessels need insulation to minimize all modes of heat transfer.

• The apparent thermal conductivity is calculated based on all possible modes of heat transfer.

• Expanded foam is a low density, cellular structure. The heat is transferred only by solid conduction.

• With the decrease in the mean cell diameter, the $k_A$ decreases. With the increase in the bulk density, the $k_A$ also increases.
Summary

• A gas filled powder or a fibrous insulation reduces gas convection due to the small size of voids. The heat is transferred by free molecular conduction.

• Fill – gas should be unreactive and compatible with powder material.

• Radiation heat transfer does not require any medium. It is reduced by introduction of radiation shields.

• These shields are aluminum foils with a very high reflectivity.
• A self assessment exercise is given after this slide.

• Kindly assess yourself for this lecture.
1. The vapor to liquid volume ratio for a general cryogen is _____.
2. The liquid boils off continuously due to ______.
3. ________ is calculated based on all possible modes of heat transfer.
4. In an expanded foam, gases that are used are ___.
5. In an expanded foam, the heat is transferred only by ______.
6. With the decrease in mean cell diameter, the solid conduction path _____in the foam insulation.
7. In a Gas – Filled powder insulation, fill – gas should be ______.
8. ______ does not require any medium.
Answers

1. 175
2. Heat in leaks
3. Apparent thermal conductivity
4. CO$_2$ and Freon
5. Conduction
6. Increases
7. Unreactive
8. Radiation
Thank You!