CRYOGENIC ENGINEERING

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Lecture No - 35

Earlier Lecture

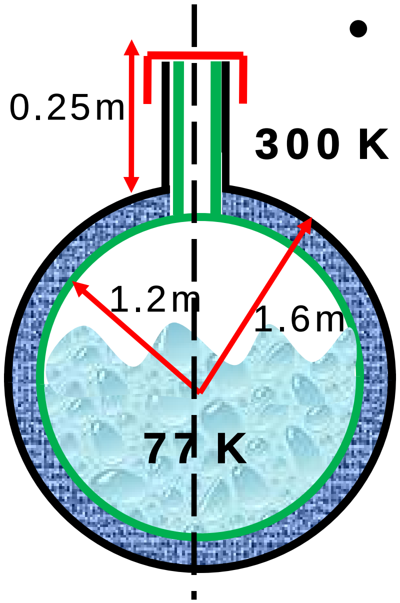
- In the earlier lecture, we have seen that radiation is dominant mode of heat transfer in vacuum.
- Evacuated powders are superior in performance than vacuum alone, in **300 K – 77 K**, as radiation heat transfer is comparatively less.
- In an opacified powder, radiation heat transfer is minimized by addition of reflective flakes.
- A tutorial problem is solved to compare the different types of insulations, so far discussed.

Outline of the Lecture

Topic : Cryogenic Insulation (contd)

- Multilayer Insulation
- Tutorial
- Conclusion

Introduction



- In the earlier lecture, we have solved the following tutorial.

A spherical **LN2** vessel (**e**=0.8) is as shown. The inner and outer radii are 1.2m and 1.6m respectively. Compare and comment on the heat in leak for the following cases.

- Perlite, Less Vacuum (1.5mPa), Vacuum alone, Vacuum + 10 shields, Evacuated Fine Perlite, 50/50 Cu – Santocel.

Introduction

Heat in leak (Q)	
Perlite	349.7 W
Less Vacuum (1.5mPa)	Q_r=2648 W Q_{gc}=0.356 W
Vacuum alone	2648 W
Vacuum + 10 shields	11.02 W
Evacuated Fine Perlite	12.7 W
50/50 Cu – Santocel	4.41 W

- It is clear that opacified powder is the best insulation.
- A heat in leak of 4.41 W to **LN2** would vaporize 2.36 Lit/day as shown in the next slide.

Introduction

- Latent heat of LN2 = 200 kJ/Kg, Density of LN2 = 807 kg/m^3.
- 1m^3 = 1000 Lit and a day has 24 hours.
- 1 Lit/hr boil off of LN2 is equivalent to $\frac{(807)(200)(10^3)}{(10^3)(3600)}$

$$= 44.83W$$

- Hence, 4.41 W of heat vaporizes 0.098 Lit/hr.
- Therefore, the total boil off in 1 day is 2.36 Lit.

Introduction

- Different types of insulations discussed in the earlier lectures are applicable only to **300 K** to **77 K** temperature range.
- Given that, latent heat of LHe = 20.2kJ/Kg and density of LHe = 124.8 kg/m^3, 1 Lit/hr boil off of LHe is equivalent to 0.7 W.
- The same amount of heat in leak, that is 4.41 W, would vaporize 151.1 Lit of LHe in one day.
- Therefore, there is a need to develop better insulations for **77 K** to **4 K** temperature range.

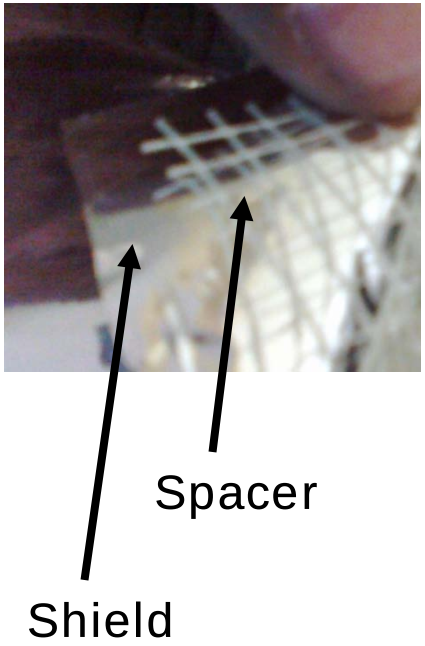
Types of Insulation

- 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

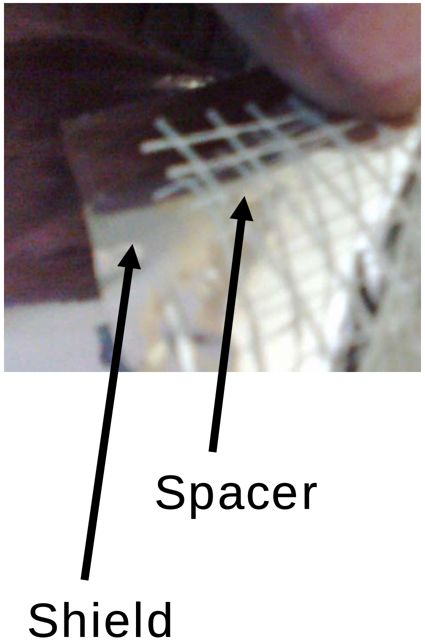
Multilayer Insulation

- Multilayer Insulation (MLI) was first developed by Petersen of Sweden in the year 1951.

- It consists of alternate layers of
  - High reflecting shields or foils
  - Separated by low conductivity spacers
  - And a very good vacuum.

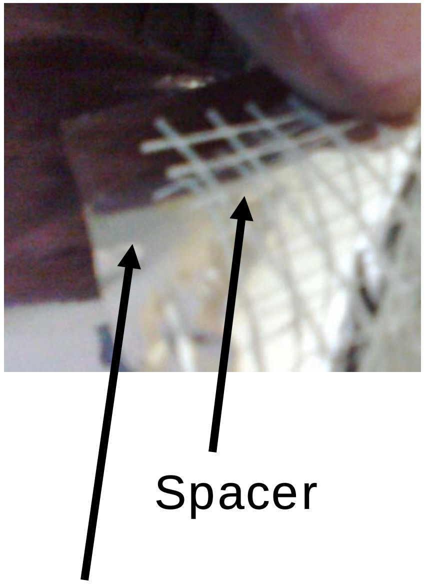


Multilayer Insulation



- The high reflecting shields are generally made of either Al, Cu or Aluminized Mylar.
- Aluminum sheet of 6μm thickness is commonly used at low temperatures.
- In order to improve mechanical strength and ease of application, plastic materials like Mylar and Kapton are coated with aluminum.

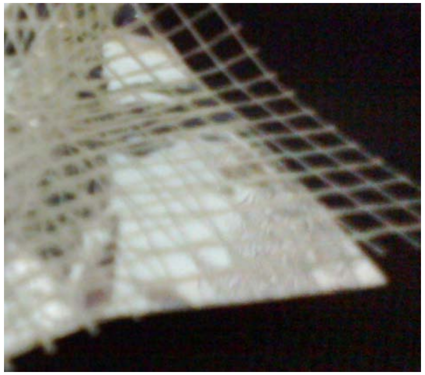
Multilayer Insulation



- Low conductivity spacers are made of coarse silk or nylon net.
- Very often, substances like glass fiber, silica fiber, low density foam or fiber glass mat are also used.
- Most common materials among fibers are Dexiglas and Tissuglas.
- One layer of MLI is defined as one sheet of reflective shield + one sheet of spacer material.

Multilayer Insulation

- Each component of this insulation is designed for a particular function.



- Radiation shields – Foils with high reflectivity reduce radiant heat transfer.
- Spacers – Nylon spacers with very low thermal conductivity reduce conduction.
- Vacuum – Residual gas conduction, convection are minimized using vacuum.

Types of MLI

- MLIs are classified according to the type of spacers used.

→ Multiple Resistance Spacers: Fibers are arranged in a parallel fashion to minimize contact area.

→ Point Contact Spacers: A grid of nylon spheres is used to separate adjacent radiation shields.

Types of MLI

- Continuing further, we have

→ Single Component MLI: Reflective shields are crinkled or embossed to minimize contact area. These MLI do not use any spacer material.

→ Composite Spacers: Few spacers consist of two or more materials. Each material has a specific function to perform.

Multilayer Insulation

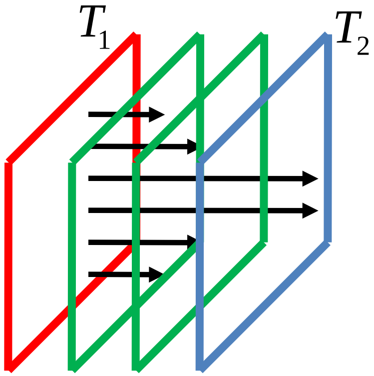
- Typically, thickness of each layer is 6 μm.

- Residual gas conduction inside an insulation depends on residual pressure of the gas.

- For an optimum performance, the usual levels of vacuum, that is maintained around an MLI, are in the range of **7.5×10^{-5}** torr.

Applications

- For an optimum performance, MLI is placed perpendicular to direction of heat flow.

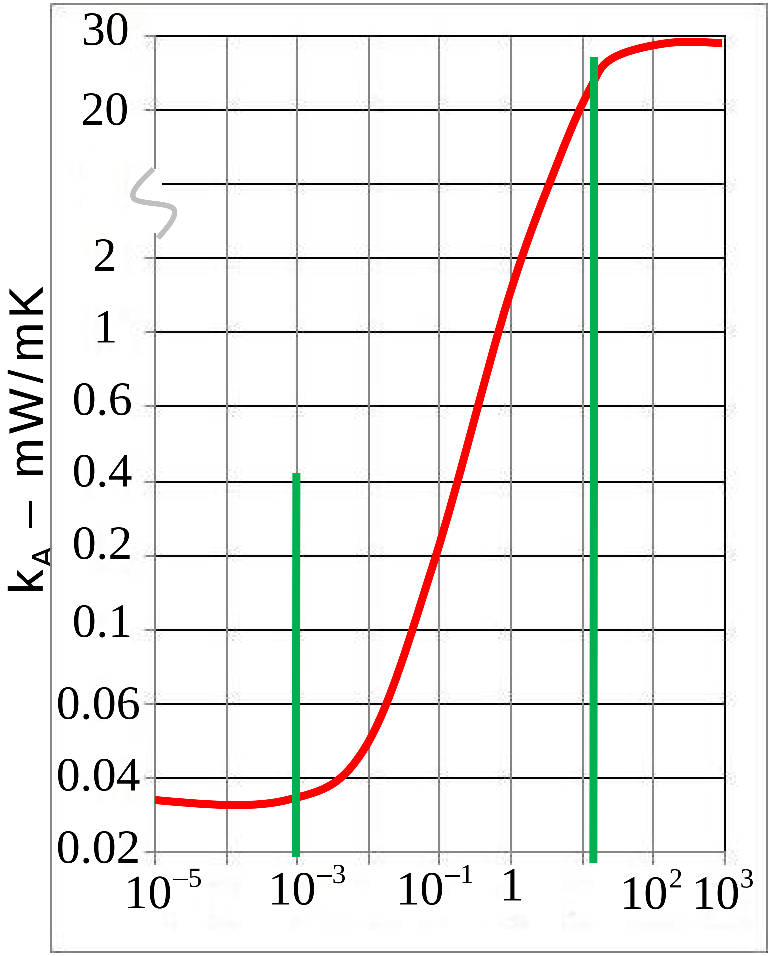


- The insulation performance is a function of following parameters.
  - Applied compressive load
  - Number of shields
  - Gas type and its pressure
  - Size and number of perforations
  - Operating temperature

Applications

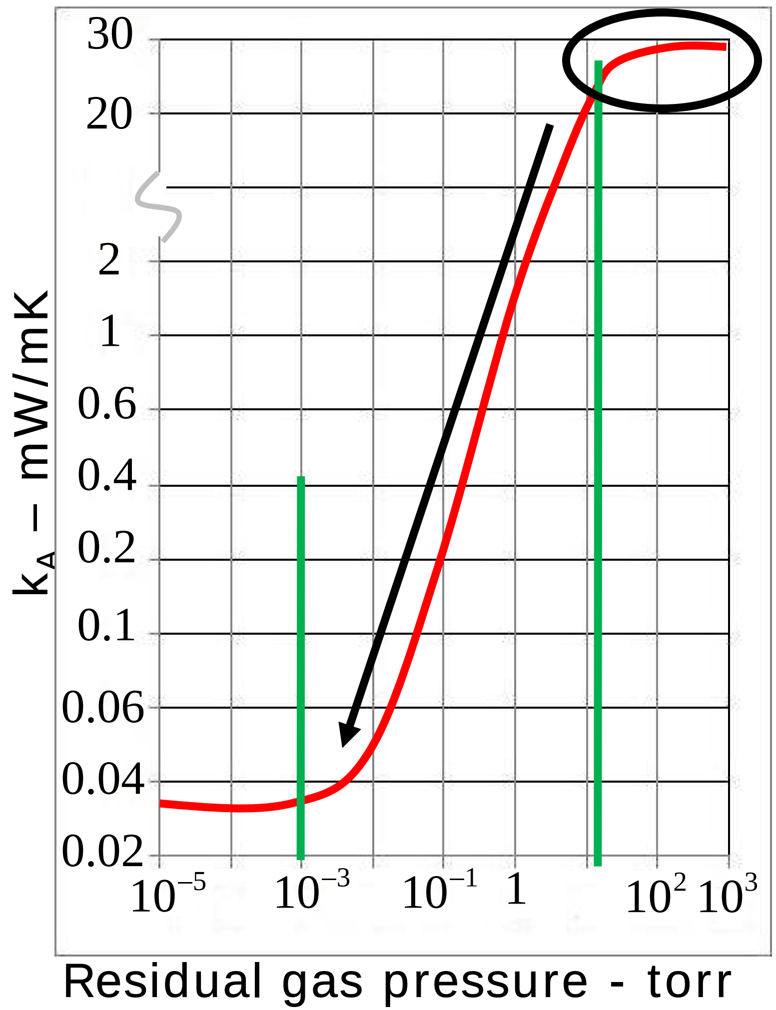
Courtesy: TIFR, Mumbai

Multilayer Insulation



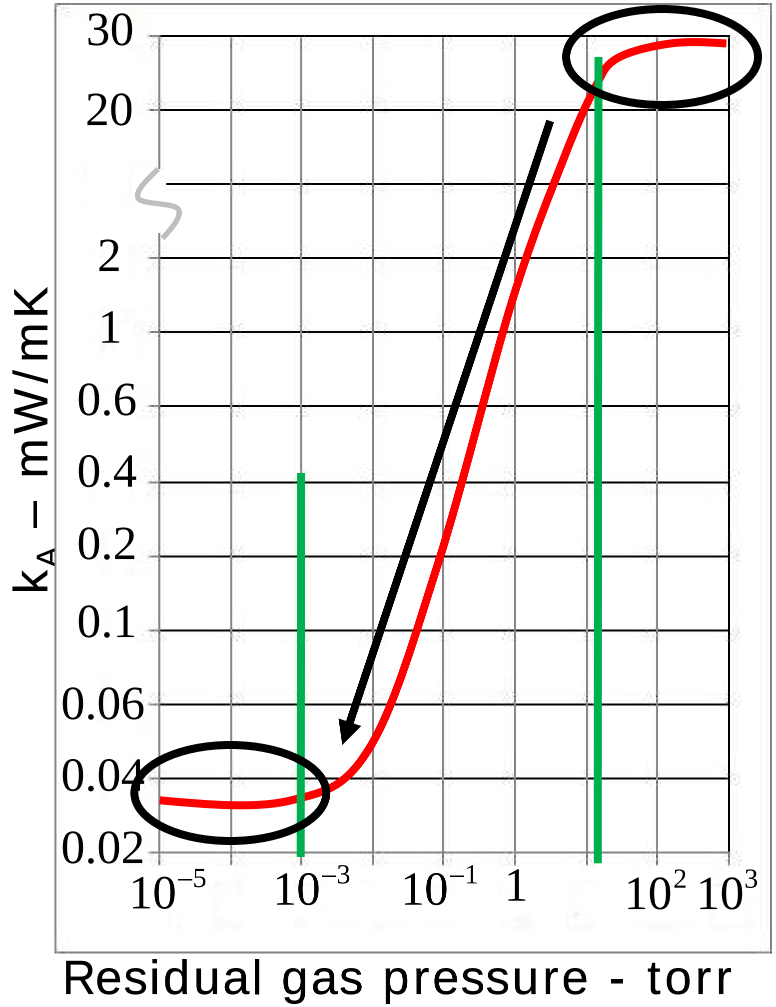
- The adjacent figure shows variation of $\mathbf{k_A}$ with residual gas pressure for a typical Multilayer Insulation.
- Insulation layer density is 24 layers/cm with boundary temperatures maintained at 300 K and 90 K.

Multilayer Insulation



- It is clear that, $\mathbf{k_A}$ is independent of residual gas pressure between atmospheric and 15 torr.
- With lowering of pressure, $\mathbf{k_A}$ is directly proportional to residual gas pressure.
- The variation is almost linear on a logarithmic chart as shown in the figure.

Multilayer Insulation



- The mode of heat transfer in this regime is mainly due to free molecular conduction or residual gas conduction.
- With further lowering of pressures, that is less than $\mathbf{10^{-3}}$ torr, $\mathbf{k_A}$ remains fairly constant.

Multilayer Insulation

- MLI bulk density (**ρ_a**) is an important parameter of the insulation. It depends on
  - Thickness of each reflective shield – **t_r**
  - Density of each reflective shield – **ρ_r**
  - Mass per unit area of the spacer – **S_s**
  - Layer density per unit thickness – **$N / \Delta x$**

- The total mass per unit area is given by $\left(S_s + \rho_r t_r\right)$

- Density being mass per unit volume, for **N** layers, **ρ_a** is given by

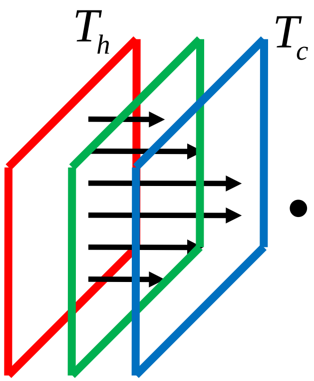
$$\rho_a = \left(S_s + \rho_r t_r\right)\frac{N}{\Delta x}$$

Multilayer Insulation

- The apparent thermal conductivity (μW/mK) and layer density (layer/cm) of few commonly used MLI are as shown. Residual gas pressure is 10^{-5} torr with end temperatures as **77 K** and **300 K**.

Insulation	N / Δx	k_A (μW / mK)
0.006mm Al foil+0.15mm Fiberglass	20	37
0.006mm Al foil+2mm mesh rayon net	10	78
0.006mm NRC-2 crinkled Al Mylar film	35	42

Apparent Thermal Cond.



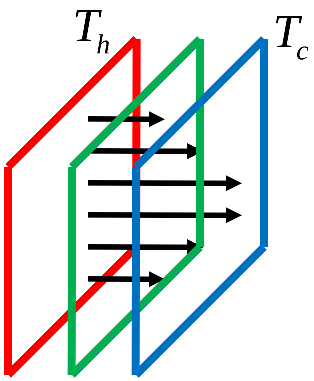
- For an evacuated MLI, heat is transferred by radiation and solid conduction.
- For 1 layer, net heat transferred (**Q_{net}**) is

$$Q_{net} = Q_{Rad} + Q_{Solid\,Cond}$$

$$Q_{net} = F_e F_{1\rightarrow 2}\sigma A\left(T_h^4 - T_c^4\right) + \frac{k_c A\left(T_h - T_c\right)}{\Delta x}$$

- **F_e** – Effective emissivity of the Shields
- **$F_{1\rightarrow 2}$** – Shape factor
- **A, Δx** – Contact area and Width
- **k_c** – Effective thermal conductivity

Apparent Thermal Cond.



$$Q_{net} = F_e F_{1\to2} \sigma A\left(T_h^4 - T_c^4\right) + \frac{k_c A\left(T_h - T_c\right)}{\Delta x}$$

$$\frac{1}{F_e} = \left(\frac{2-e}{e}\right) \qquad F_{1\to2} = 1 \qquad h_c = \frac{k_c}{\Delta x}$$

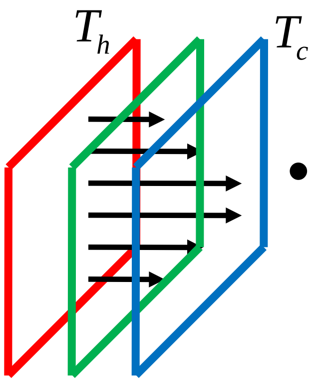
- Combining above equations, we have

$$Q_{net} = \sigma\left(\frac{e}{2-e}\right)A\left(T_h^4 - T_c^4\right) + h_c A\left(T_h - T_c\right)$$

- **e** – Emissivity of the shield
- **h_c** – Thermal conductance per unit area

Apparent Thermal Cond.

$$Q_{net} = \sigma\left(\frac{e}{2-e}\right)A\left(T_h^4 - T_c^4\right) + h_c A\left(T_h - T_c\right)$$



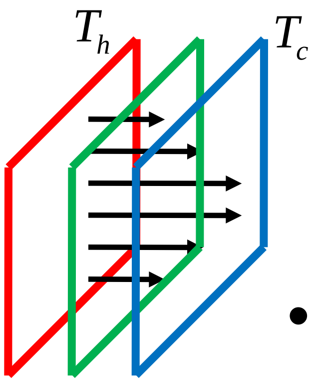
- Let $\mathbf{k_A}$ be apparent thermal conductivity of insulation. Therefore, $\mathbf{Q_{net}}$ is

$$Q_{net} = \frac{k_A A\left(T_h - T_c\right)}{\Delta x}$$

- Equating above two equations and rearranging, we have

$$\frac{k_A A\left(T_h - T_c\right)}{\Delta x} = A\left(T_h - T_c\right)\left(\sigma\left(T_h^2 + T_c^2\right)\left(T_h + T_c\right)\left(\frac{e}{2-e}\right) + h_c\right)$$

Apparent Thermal Cond.



- The apparent thermal conductivity (**k_A**) is

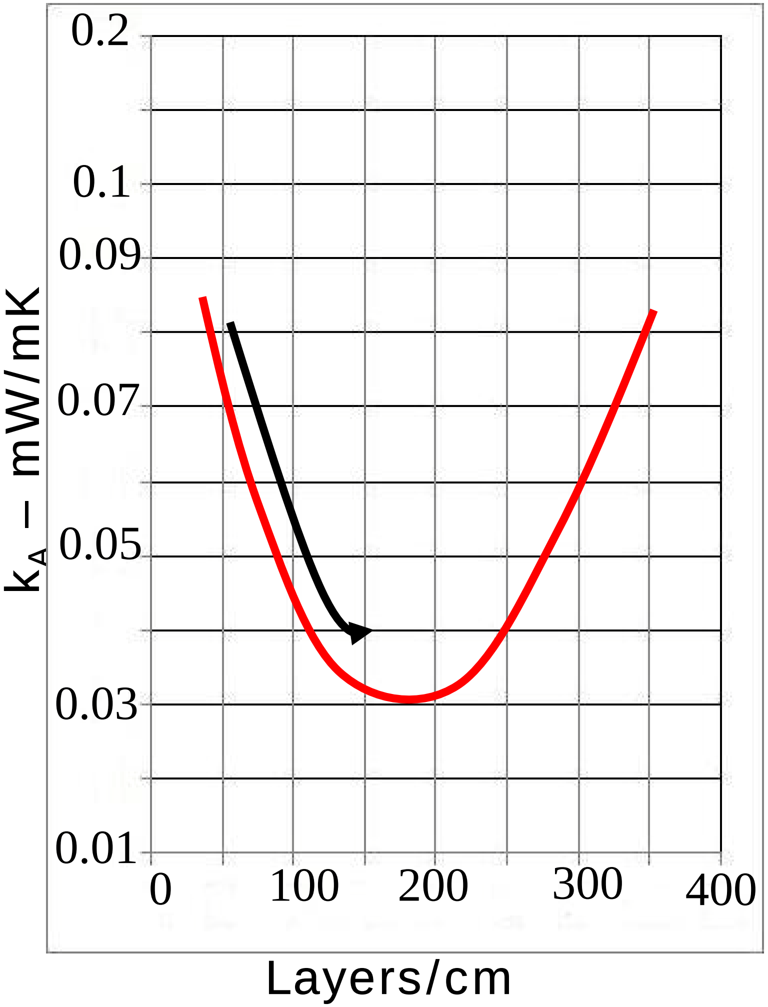
$$k_A = \Delta x \left(\sigma \left(T_h^2 + T_c^2 \right) \left(T_h + T_c \right) \left(\frac{e}{2-e} \right) + h_c \right)$$

- For **N** layers, we have

$$k_A = \frac{\Delta x}{N} \left(\sigma \left(T_h^2 + T_c^2 \right) \left(T_h + T_c \right) \left(\frac{e}{2-e} \right) + h_c \right)$$

- where,
  - **T_h, T_c** – Boundary temperatures
  - **N / Δx** – Layer density

Apparent Thermal Cond.

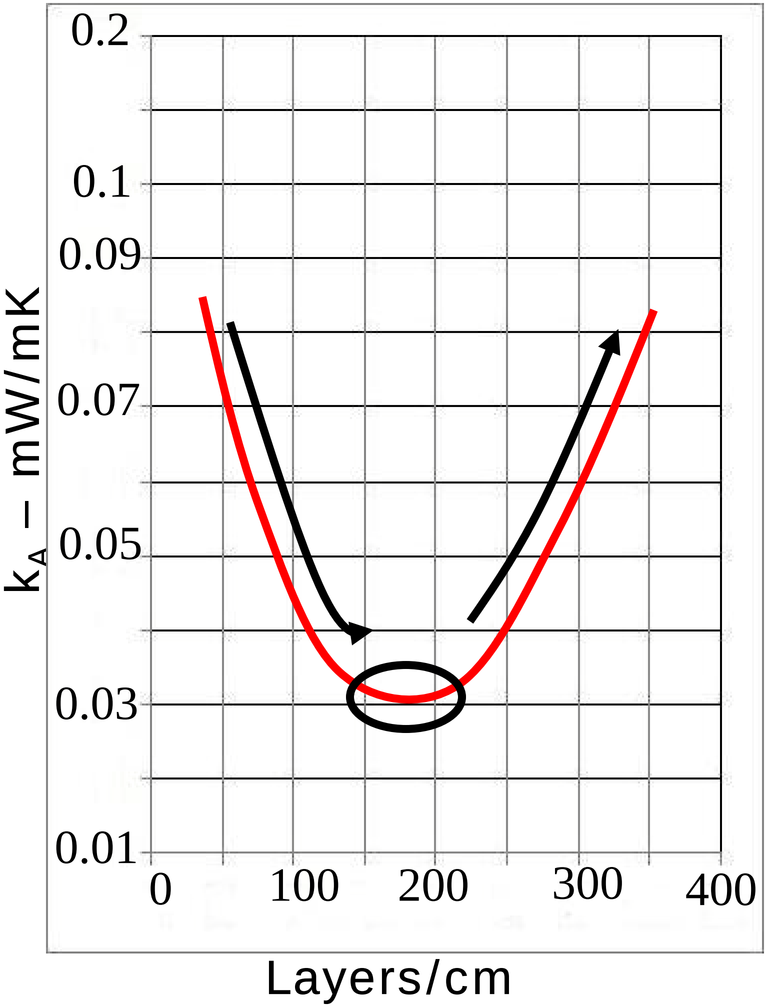


$$Q_{net} = Q_{Rad} + Q_{Solid\,Cond}$$

- With an initial increase in layer density, the decrease in radiation heat transfer is more than the increase in solid conduction.

- Hence, $\mathbf{k_A}$ of the insulation decreases.

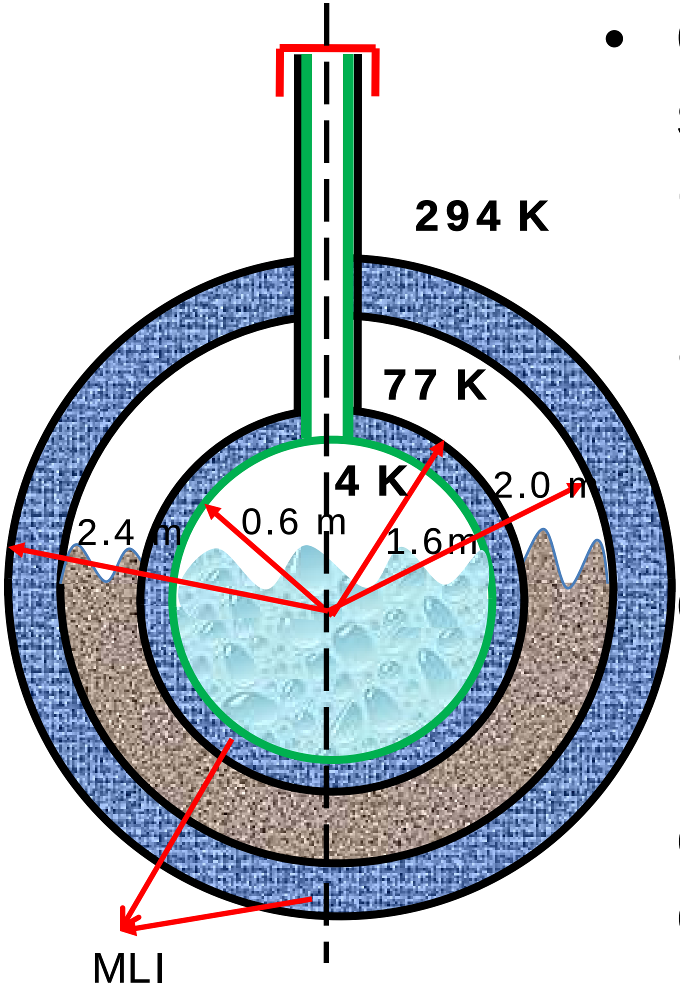
Apparent Thermal Cond.



- With further increase in layer density, $\mathbf{k_A}$ increases due to an increase in solid conduction ($\mathbf{h_c}$).

- Therefore, $\mathbf{k_A}$ goes through a minima and then rises as shown in the figure.

Tutorial



- Consider a spherical **LHe** vessel shielded with **LN2** bath. The radii of the spherical shells are as shown in the figure. MLI (24 layers/cm) is applied at each stage. Calculate the boil off/day of LN2 and LHe.

Given that emissivity of shield is 0.05. Solid conductance of spacer is 0.0851 W/m^{2}K (assumed constant). Also, neglect neck conduction.

Tutorial

Given	
Multi Layer Insulation	
Operating Temperature	LN_2 boil off : 294 K to 77 K LHe boil off : 77 K to 4 K
Emissivity of Shield : 0.05	
Number of layers : 24/cm	
Solid conductance : 0.0851 W/m^2K	

Calculate
Boil off of LN_2 and LHe on per day basis.

Tutorial

Calculation of $\mathbf{k_A}$ for LN2 (294 K to 77 K)

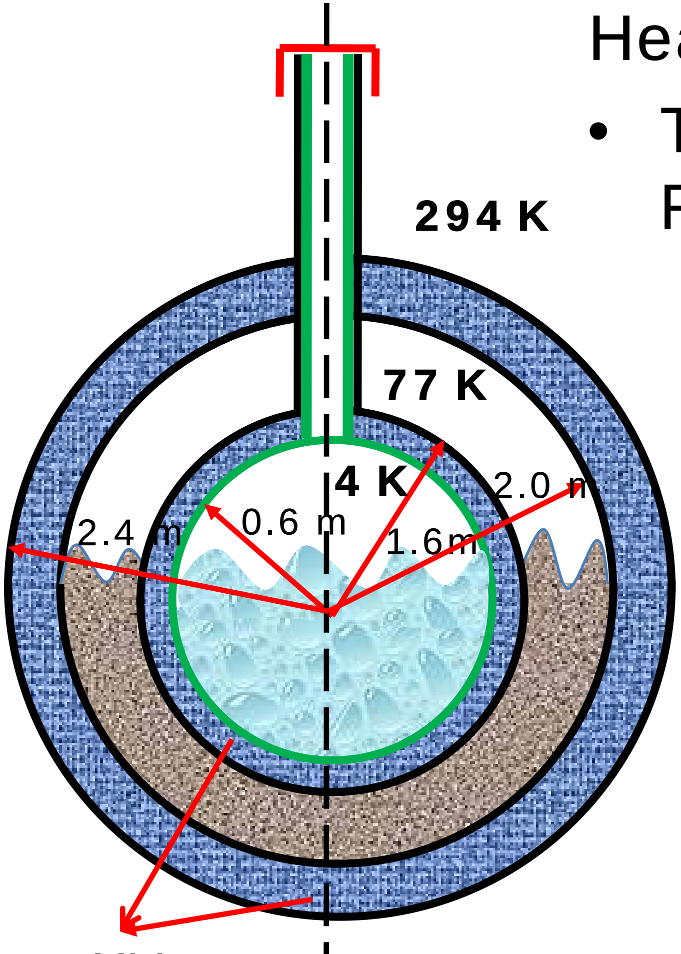
- $\Delta x/N=(1/2400)$, $h_c=0.0851$, $e=0.05$, T_h, T_c.

$$k_A=\left(\frac{\Delta x}{N}\right)\left(h_c+\sigma e\left(T_h^2+T_c^2\right)\left(\frac{T_h+T_c}{2-e}\right)\right)$$

$$k_A=\left(\frac{1}{2400}\right)\left(0.0851+\frac{(5.669)\left(10^{-8}\right)(0.05)(92365)(371)}{(2-0.05)}\right)$$

$$k_A=56.2\mu W/mK$$

Tutorial



Heat in leak for LN2 (294 K to 77 K)

- T_h, T_c, k_A = 56.2µW/mK, R_1=2.4m, R_2=2.0m, ΔT=(294-77)=217.

$$Q = \frac{4\pi k_A R_1 R_2 \Delta T}{(R_2 - R_1)}$$

$$Q = \frac{4\pi(56.2)(10^{-6})(2.4)(2.0)(217)}{(2.4-2.0)}$$

$$Q = 1.84W$$

Tutorial

Boil off of LN2 (294 K to 77 K)

- Latent heat of LN2 = 200 kJ/Kg, Density of LN2 = 807 kg/m^3.
- 1 Lit/hr of LN2 is equivalent to 44.83 W.
- Hence, 1.84 W of heat vaporizes 0.041 Lit/hr.
- Therefore, the total boil off of LN2 in 1 day is 0.985 Lit.

Tutorial

Calculation of $\mathbf{k_A}$ for LHe (77 K to 4 K)

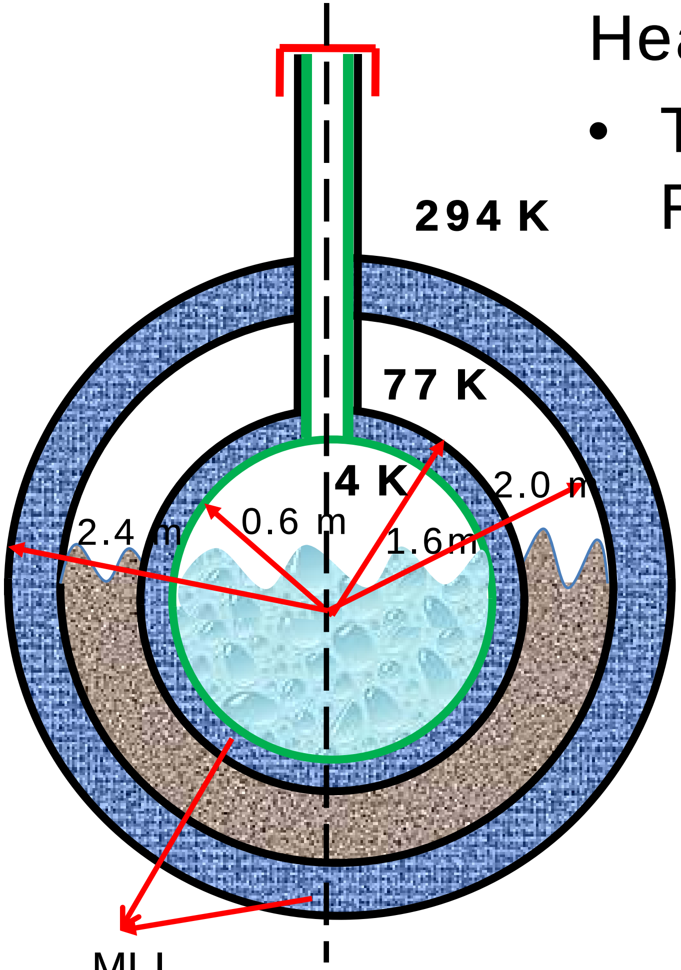
- $\Delta x/N=(1/2400)$, $h_c=0.0851$, $e=0.05$, T_h, T_c.

$$k_A = \left(\frac{\Delta x}{N}\right)\left(h_c + \sigma e\left(T_h^2 + T_c^2\right)\left(\frac{T_h + T_c}{2-e}\right)\right)$$

$$k_A = \left(\frac{1}{2400}\right)\left(0.0851 + \frac{(5.669)\left(10^{-8}\right)(0.05)(5945)(81)}{(2-0.05)}\right)$$

$$k_A = 35.7\,\mu W/mK$$

Tutorial



Heat in leak for LHe (77 K to 4 K)

- T_h, T_c, k_A = 35.7µW/mK, R_1=1.6m, R_2=0.6m, ΔT=(77-4)=73.

$$Q = \frac{4\pi k_A R_1 R_2 \Delta T}{\left(R_2 - R_1\right)}$$

$$Q = \frac{4\pi(35.7)\left(10^{-6}\right)(1.6)(0.6)(73)}{(1.6-0.6)}$$

$$Q = 0.031W$$

Tutorial

Boil off for LHe (77 K to 4 K)

- Latent heat of LHe = 20.2 kJ/Kg, Density of LHe = 124.8 kg/m^3.
- 1 Lit/hr of LHe is equivalent to 0.7W.
- Hence, 0.031 W of heat vaporizes 0.044 Lit/hr.
- Therefore, the total boil off of LHe in 1 day is 1.062 Lit.

Tutorial

Results	
LN2 boil off	LHe boil off
Working Fluid: LN2 between 294 K to 77 K	Working Fluid : LHe between 77 K to 4 K
k_A = 56.2μW/mk	k_A = 35.7μW/mk
Q = 1.84 W	Q = 0.03 W
Boil off : 0.985 Lit/day	Boil off : 1.062 Lit/day

Conclusion

- Cryogenic vessels need insulation to minimize all modes of heat transfer.
- $\mathbf{k_A}$ is calculated based on all the possible modes of heat transfer.
- In an expanded foam, heat is transferred only by solid conduction. With decrease in mean cell diameter, $\mathbf{k_A}$ decreases. With an increase in bulk density, $\mathbf{k_A}$ increases.
- In a gas filled powder or a fibrous insulation, heat is transferred by gas and solid conductions.

Conclusion

- In vacuum, radiation is the dominant mode of heat transfer. It is minimized by using radiation shields.
- In an evacuated powder, heat is transferred by free molecular conduction, solid conduction and radiation. At low pressures and temperatures, solid conduction dominates radiation.
- In an opacified powder, the radiation heat transfer is minimized by addition of reflective flakes.
- MLI consist of alternate layers of high reflecting shields and low conducting spacers.

Conclusion

- Multi Layer Insulations are more effective in **77 K** to **4 K** temperatures, when provided with a good vacuum.
- There is an optimum layer density, at which $\mathbf{k_A}$ of the insulation is minimum.

Thank You!