Cryogenic Fluid Storage & Transfer Systems

Module 5: Cryogenic Engineering ME 467

DEWAR Vessel

- 1892, Sir James Dewar
- Vacuum-insulated double walled vessel

- Performance vary from, a complete boil off in a few hours to complete boil off in months
- Capacity vary from 1 litre to 100 thousand litre.

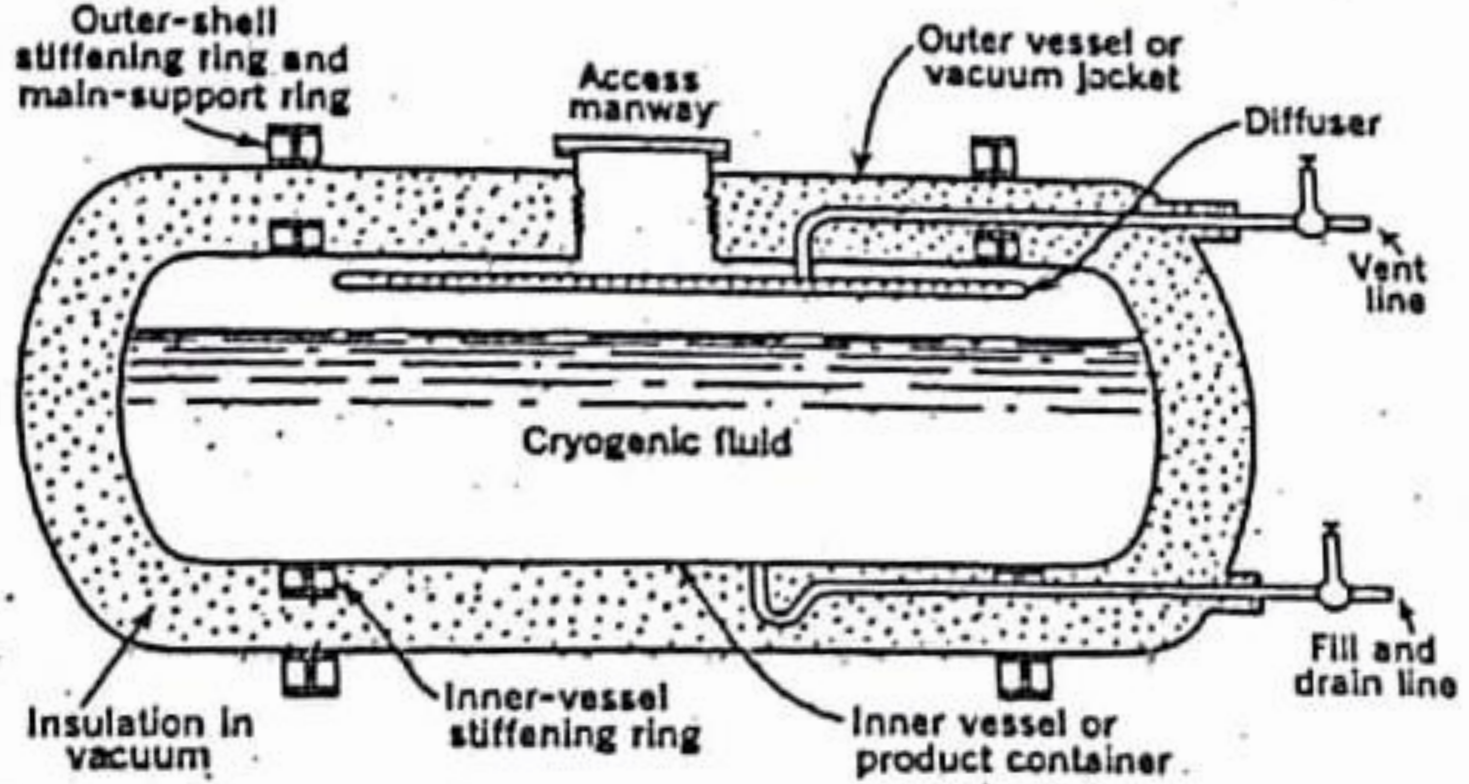
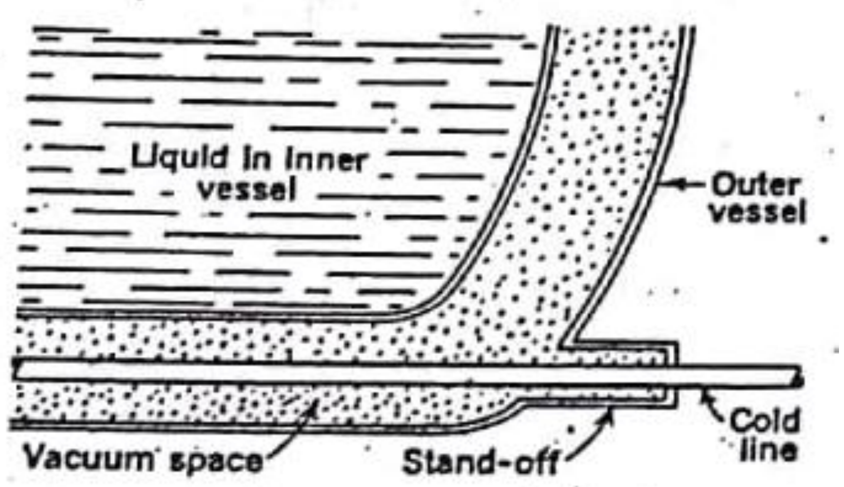


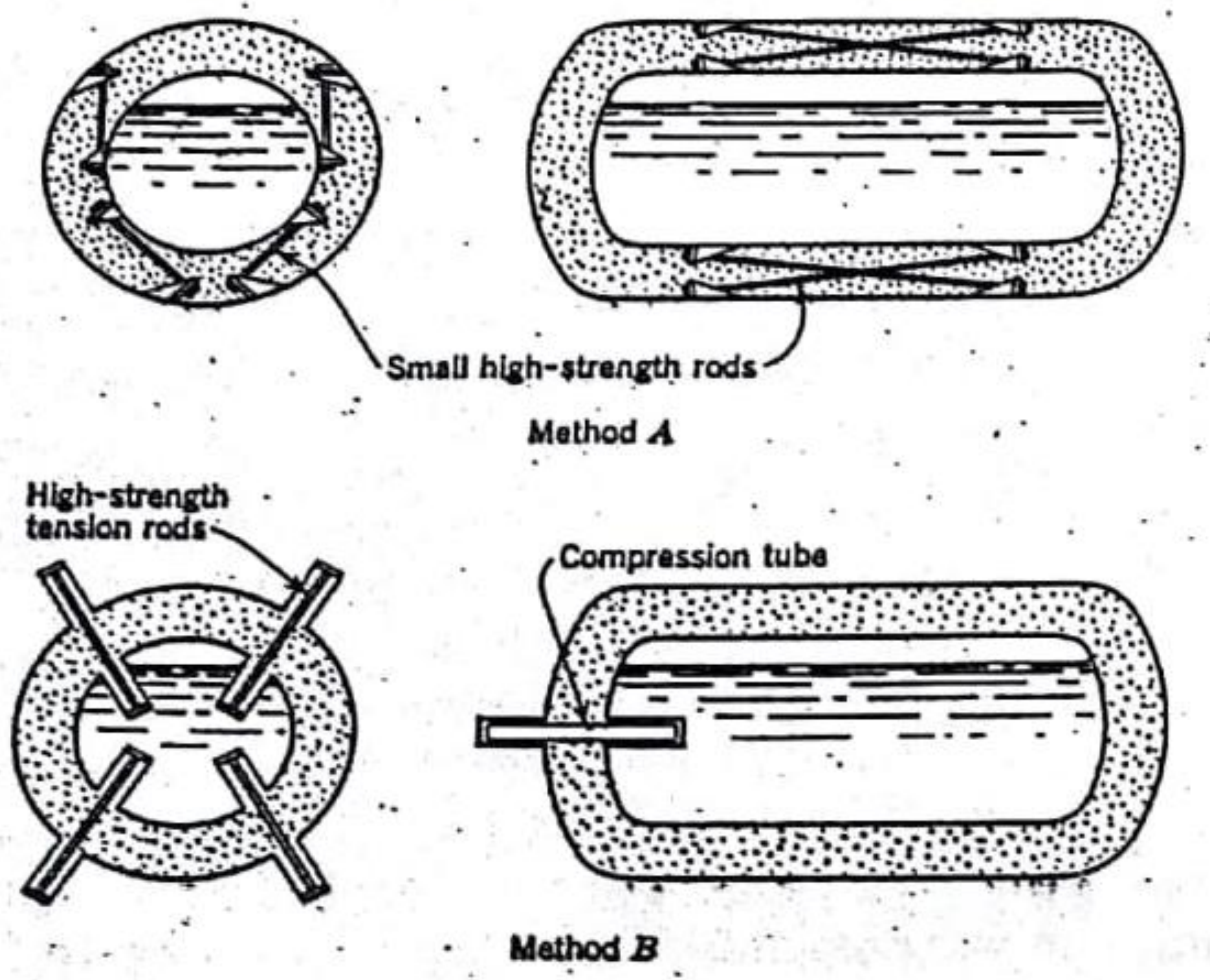
Fig. 7.1. Elements of a dewar vessel.

- Inner vessel/ Product Container
  - Must withstand the design internal pressure, the weight of the fluid and bending stresses
  - SS, Al, Monel, Cu (to withstand the very low temperature)
  - To reduce; Cost, Cool down time & thermal stresses → Thin walls are employed.
  - Stiffening rings are used to withstand weight.
- Outer Vessel/ Vacuum Jacket
  - Designed to withstand buckling under atmospheric pressure.
  - Stiffening rings are used to withstand weight.
  - Carbon steels can be used (since at ambient temperature); except for standoffs (where commonly SS is used)
  - Shape: Spherical (on-site), cylindrical with hemispherical heads (transport)



- Vacuum Space
  - The evacuated space is filled with insulation: silvered walls and high vacuum alone (small scale systems), powders, fibrous materials, multi layer insulations.
- Fill & Drain Line
  - Separate or single line.
  - Only necessary for large systems.
- Vapor Vent Line
  - To remove vapor and to avoid pressure build up.
- Ullage space(Space above liquid)
  - To arrest rapid pressure rise due to heat inleaks.
  - to avoid liquid percolation through vent tube during pressure rise.
  - Usually 10 % of total capacity.
- Vapor Diffuser/ Liquid pump
  - For removal of liquid
  - Diffuser is used to pressurize ullage space
  - Diffuser gas is directed away from liquid surface to avoid recondensation
- Antislosh Baffles
  - To damp motion during transportation
- Suspension System
  - To support product container within the vacuum jacket
  - A poor suspension system can nullify the effect of high performance insulation
  - Tension rods of high strength SS, saddle bands of metal or plastic, plastic compression blocks, stacked disks, compression tubes, wire cables or chains can be used.
  - Should withstand the weight and the dynamic loads.

Fig. 7.7. Typical methods of supporting the inner vessel within the outer vessel in a dewar.



Piping

- Necessary to remove liquid/vapor
- Causes heat leaks – conduction along pipe wall
- There for they should be made as long as possible, and as thin as possible
- Thermal contraction also must be factored in

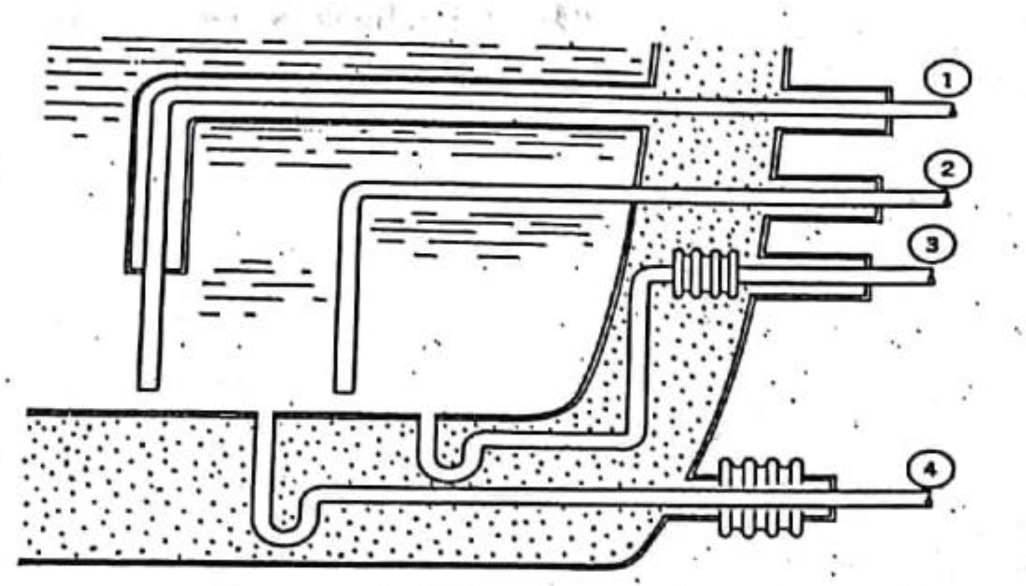
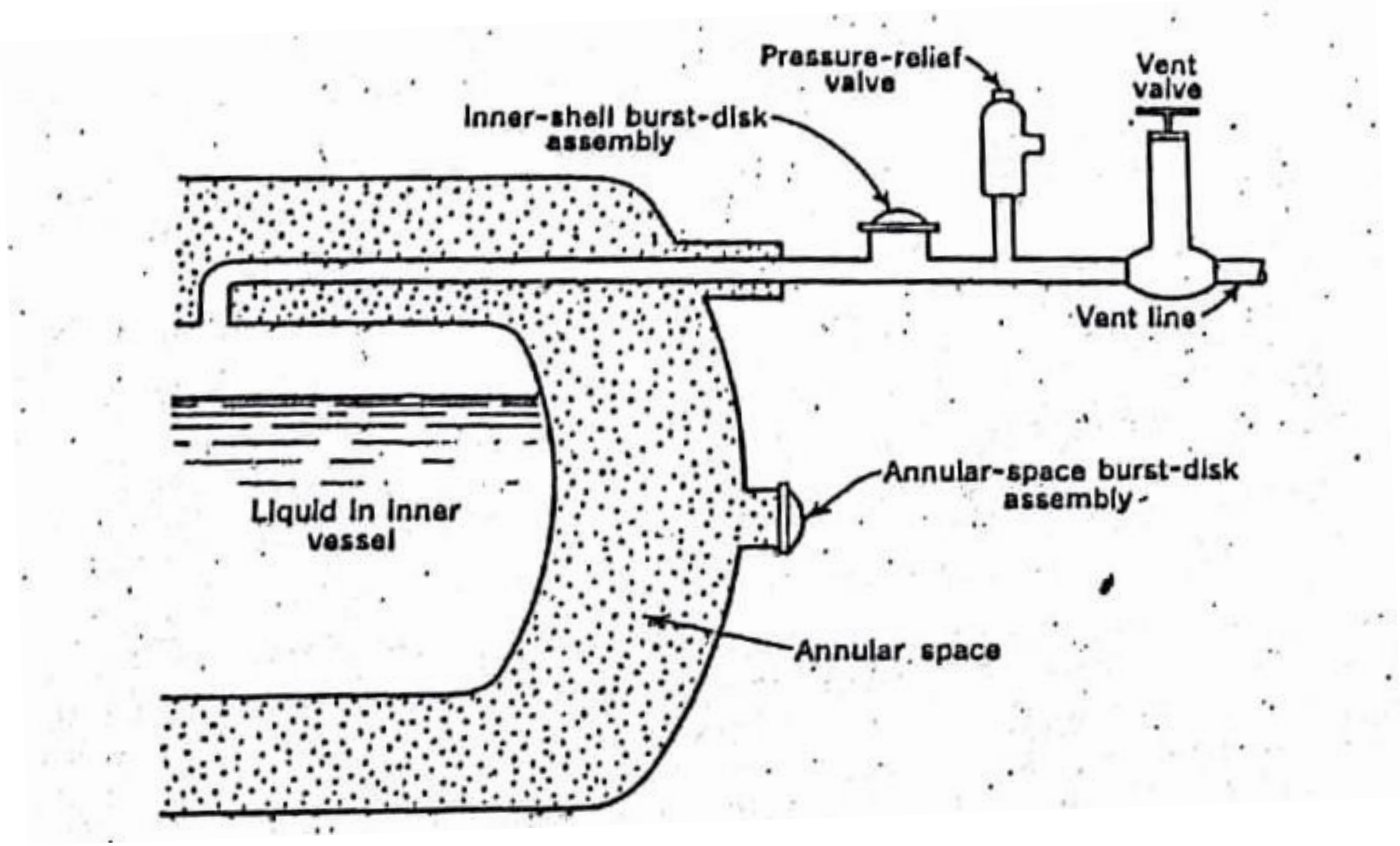


Fig. 7.10. Cryogenic-fluid storage-vessel piping arrangements.

- *(pipe 1, refer picture) Length attained by extending the vacuum space into the inner vessel. Good design. But doesn't consider thermal contraction.*
- *(pipe 2) Poor arrangement: convective loss due to the cyclic condensation and evaporation in the horizontal region (inside and outside respectively). Also doesn't consider thermal contraction.*
- *(pipe 3) Vertical rise avoids convection. But bellow position not convenient for service.*
- *(pipe 4) Better arrangement among the four.*

- Draining
  - Self Pressurization: its own vapor used.
  - External Pressurization: compressed gas.
  - Pump transfer
- Safety
  - Inner vessel pressure release valve.
  - Inner shell burst-disc assembly
  - Annular space burst-disc assembly



Insulations

In the order of increasing performance/ cost

1. Expanded foams
2. Gas-filled powders and fibrous materials
3. Vacuum alone
4. Evacuated powders and fibrous materials
5. Opacified powders
6. Multi layer insulations

Deciding Factors:

Cost, ease of application, weight, ruggedness, etc.

Expanded Foam Insulation

- Cellular structure due to evolving of gas (CO_2) during manufacturing.
- Polyurethane, polystyrene, rubber, silica, glass etc.
- Heat transfer due to radiation and conduction.
- Conductivity decreases when one side cooled to LN_2 temperatures.(CO_2 condenses).
- Conductivity increases with long exposure to atmospheric air (1.4 times) or to H_2 or He atmosphere (3 to 4 times) – as the gases diffuse into the cells.
- Due to thermal contraction, foam may crack and leakage of water vapor and air into the foam will occur, increasing the apparent conductivity – contraction joints, plastic liners can avoid this.

Gas filled powders and fibrous insulations

- Fiber glass, powdered cork, perlite, Santocel, rock wood, Vermiculite etc.
- Reduction of convection due to small size of pores
- Diffusion of moisture and air unless a vapor barrier is used or is purged by GN_2.
- Used where vacuum insulation is not economical (LNG)

Vacuum Insulation

- Small laboratory sized dewars.
- Solid conduction and gaseous convection is avoided.
- Heat is transferred by radiation and gaseous conduction.

$$\dot{Q} = F_e F_{1-2} \sigma A_1 (T_2^4 - T_1^4)$$

where F_e = emissivity factor

F_{1-2} = configuration factor

σ = Stefan-Boltzman constant

σ = 56.69 nW/m^2-K^4 = 0.1714 $\times$ 10^{-8} Btu/hr-ft^2-°R^4

A_1 = area of surface 1

T = absolute temperature

- $F_{1\text{-}2} = 1$ (completely enclosed)
- F_e for concentric spheres,

$$\frac{1}{F_e} = \frac{1}{e_1} + \frac{A_1}{A_2}\left(\frac{1}{e_2} - 1\right)$$

- Radiant heat can be reduced by interposing floating (thermally isolated) radiation shields of reflective material.
- For N shields,

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

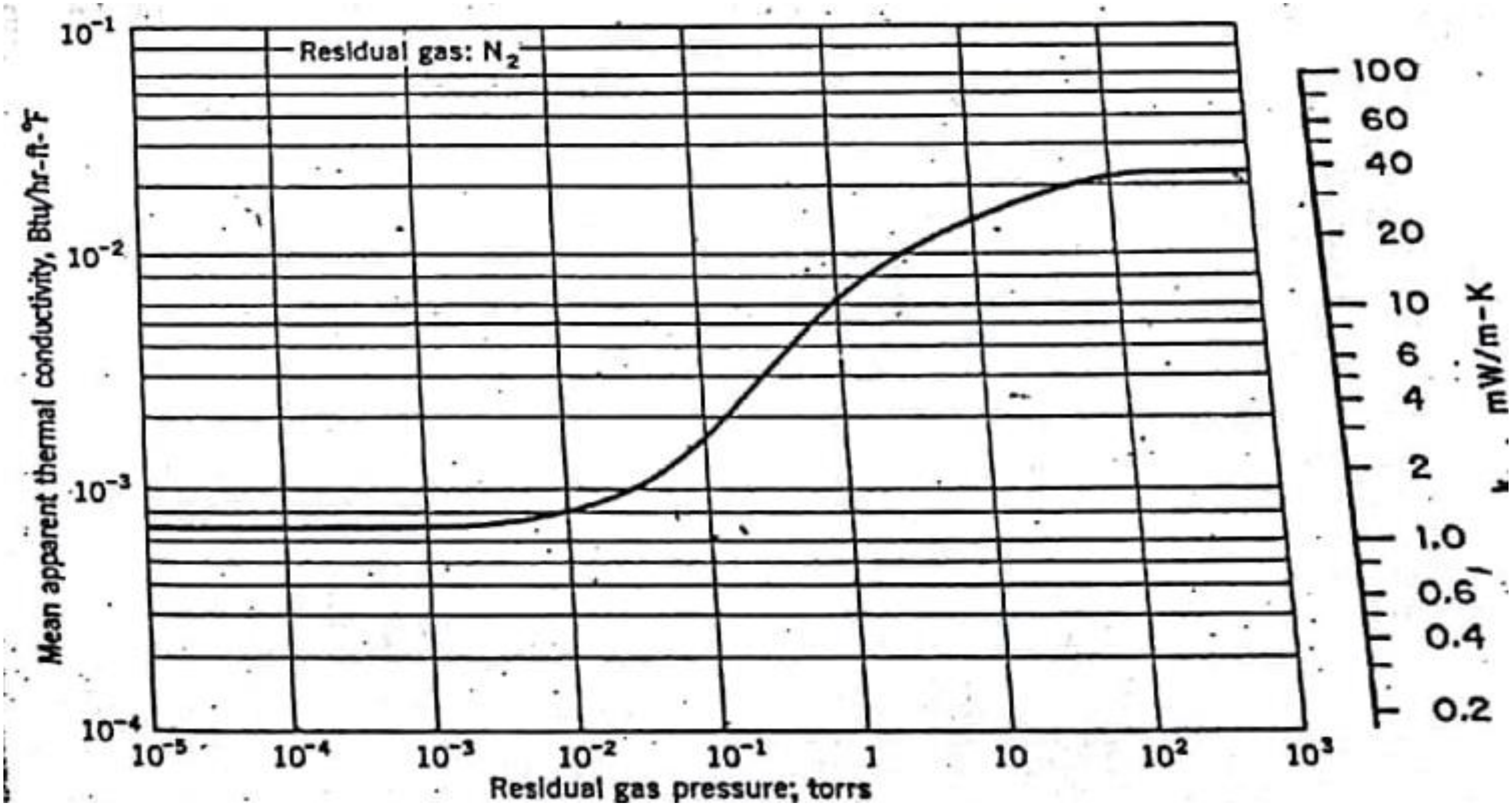
- For example, with $e_1 = e_2 = 0.8$ and 10 shields of $e_3 = 0.05$, heat transfer is reduced by a factor of 0.00383 as compared with zero shields.

- In addition to radiation, heat is also transferred by gaseous conduction (since its not perfect vacuum).
- It can be ordinary (continuum) thermal conduction with a constant thermal conductivity and linear temperature gradient, if the pressure is only moderately low.
- At very low pressures, free molecular conduction occurs.

Evacuated powder and fibrous insulations

Refer figure in the next slide:

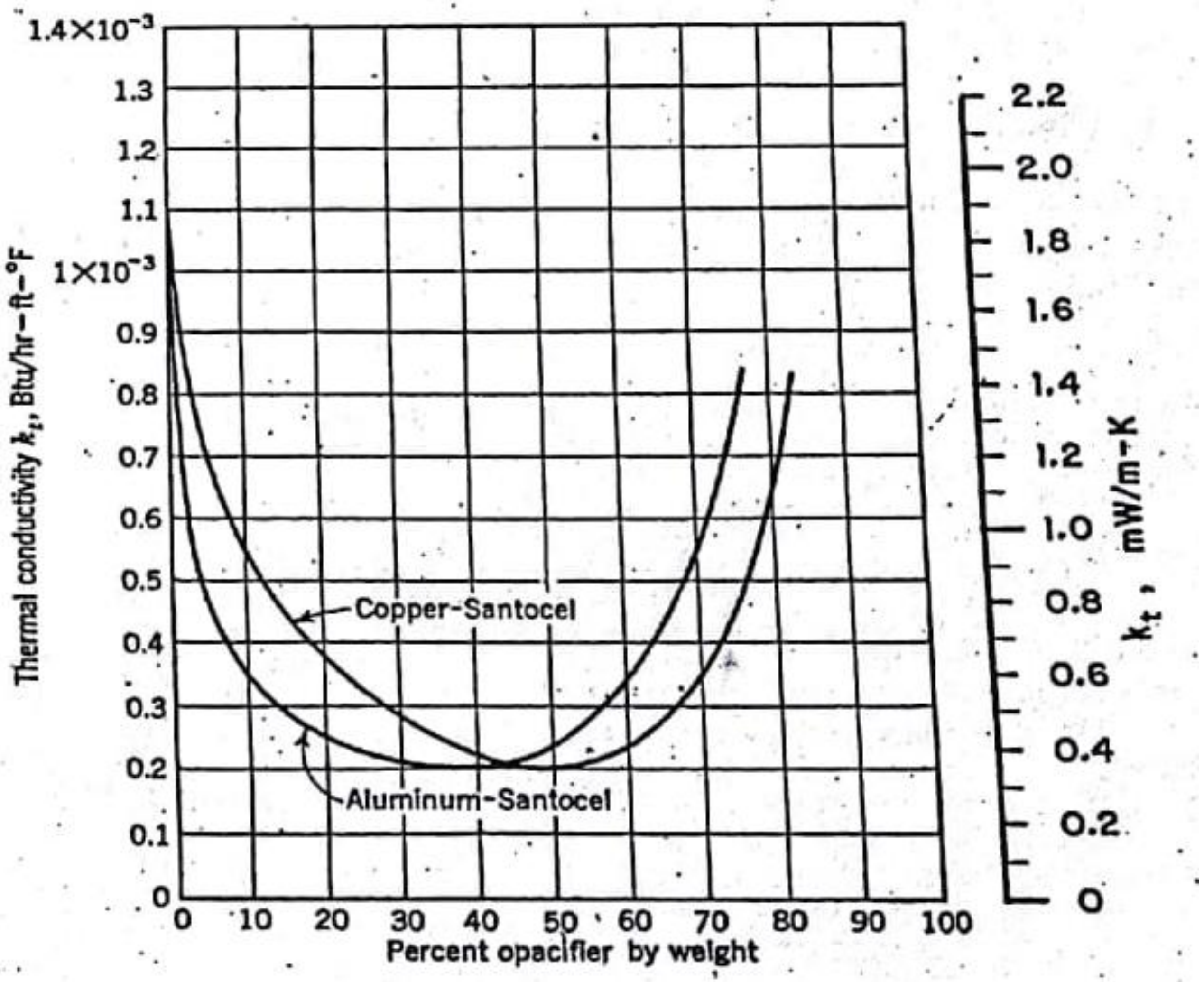
- From atmospheric pressure to around 2 kPa, there is little change in thermal conductivity of residual gas (exception: fine powders)
- At lower pressures, there is linear decrease of conductivity with pressure (free molecular conduction).
- At further lower pressures, radiation and solid conduction becomes predominant. And hence apparent conductivity remains constant.
- At temperatures below LN_2 solid conduction increases. Therefor, Vacuum alone offers better insulation.



Residual gas: N_2
Mean apparent thermal conductivity, Btu/hr-ft-°F
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
Residual gas pressure; torrs
100
60
40
20
10
6
4
2
1.0
0.6
0.4
0.2
mW/m-K

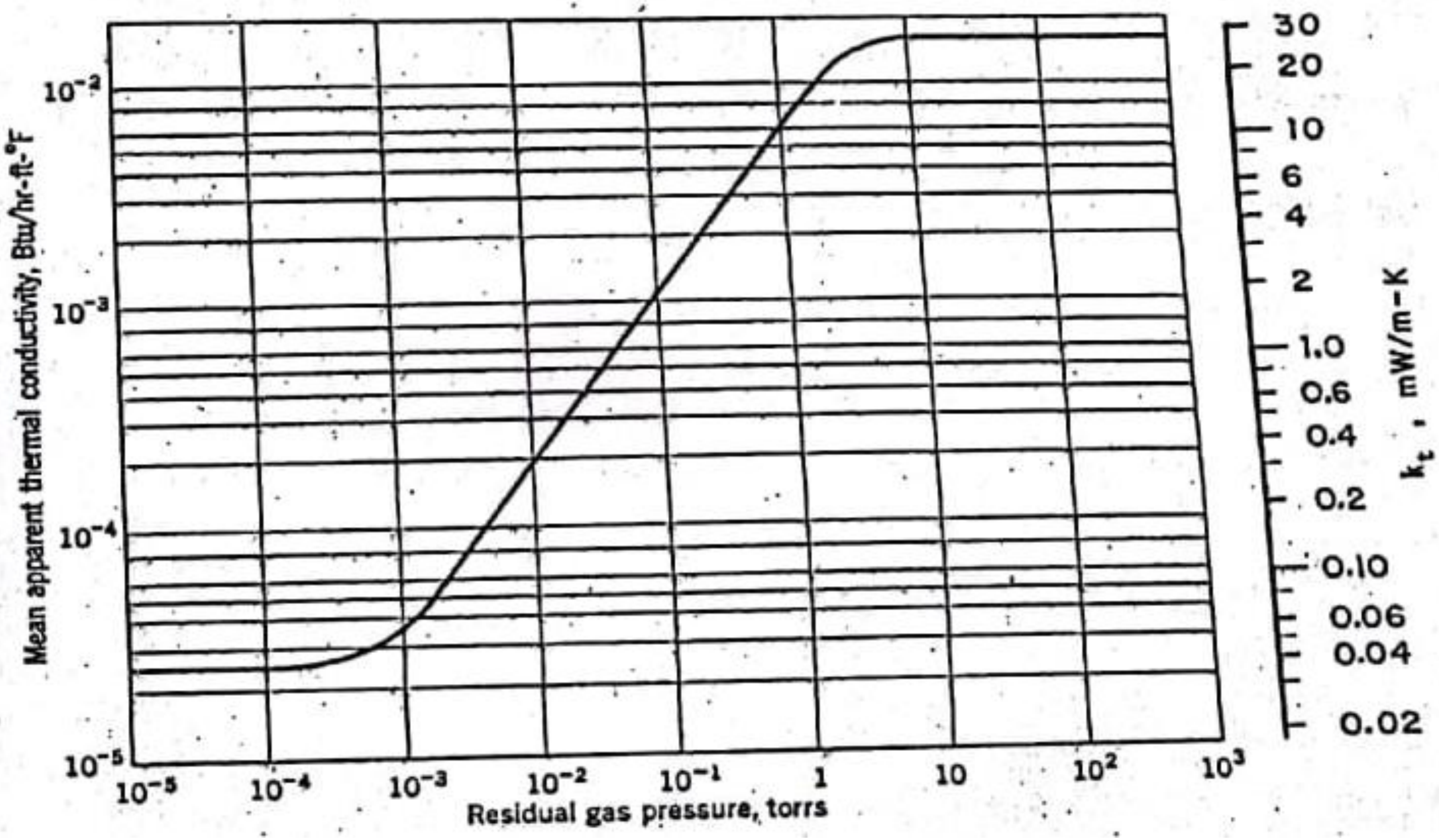
Opacified Powder Insulation

- Cu or Al Flakes added to powder insulation to decrease radiative heat transfer
- At optimum weight fraction of around 50 % the apparent thermal conductivity can be reduced by a factor of 5.
- Cu is preferred over safety issues (especially in LO_2 tanks)



Multi Layer Insulation (Super Insulation)

- Alternating layers of highly reflective materials and low conductivity spacers.
- Space is evacuated to the range of 1.3 to 10 mPa.
- Reflective layers: Al foil, Cu foil, Aluminised Mylar etc.
- Spacers: Fiber glass mat, Paper, Glass fabric, Nylon net etc.
- Embossing or crinkling of reflective layers without the use of spacers also may be used.
- All modes of heat transfer is minimised and hence this method has the lowest apparent thermal conductivity.

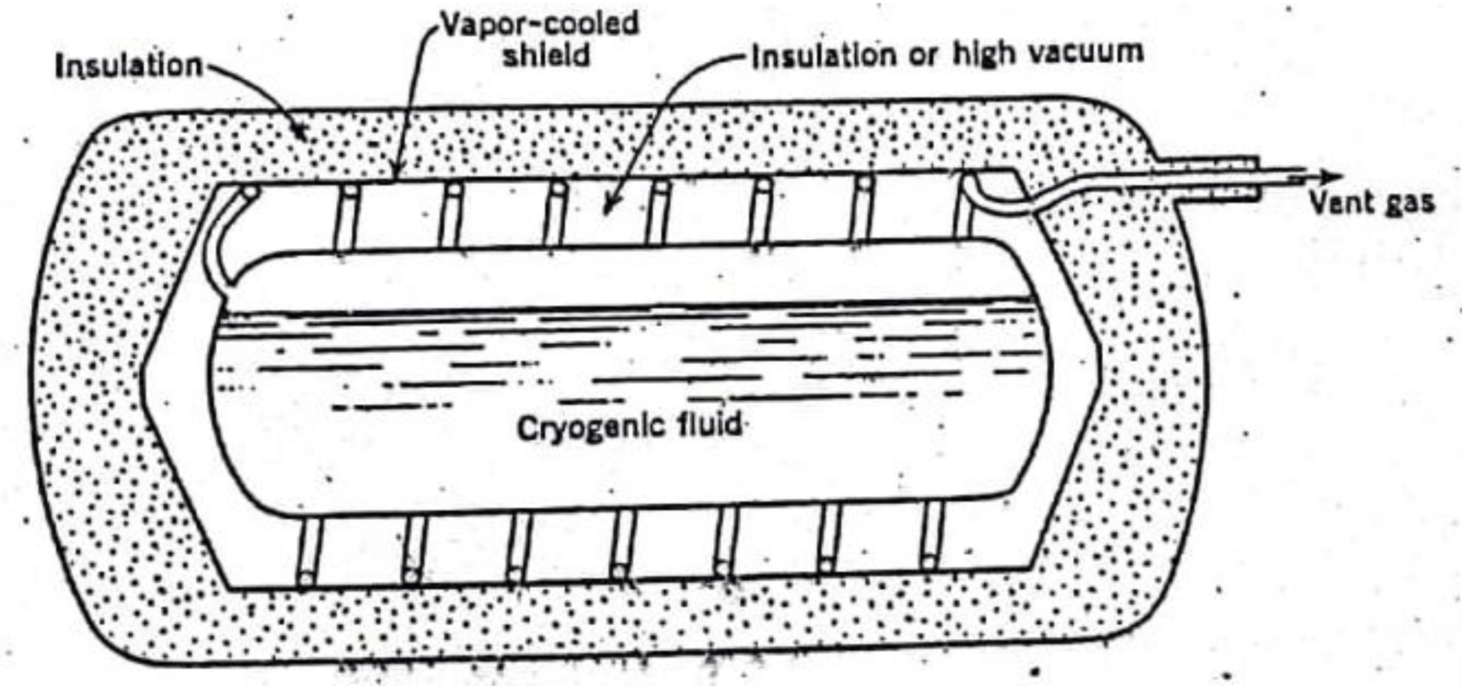


Mean apparent thermal conductivity, Btu/hr-ft-°F
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
10^3
Residual gas pressure, torrs
30
20
10
6
4
2
1.0
0.6
0.4
0.2
0.10
0.06
0.04
0.02
k_t , mW/m-K

Advantages	Disadvantages
1. *Expanded foams*	
Low cost.	High thermal contraction.
No need for rigid vacuum jacket.	Conductivity may change with time.
Good mechanical strength.	
2. *Gas-filled powders and fiberous materials*	
Low cost.	Vapor barrier is required.
Easily applied to irregular shapes.	Powder can pack and conductivity is increased.
Not flammable.	
3. *Vacuum alone*	
Complicated shapes may be easily insulated.	A permanent high vacuum is required.
Small cool-down loss.	Low-emissivity boundary surfaces needed.
Low heat flux for small thickness between inner and outer vessel.	
4. *Evacuated powders and fibrous materials*	
Vacuum level less stringent than for multilayer insulations.	May pack under vibratory loads and thermal cycling.
Complicated shapes may be easily insulated.	Vacuum filters are required. Must be protected when exposed to moist air (retains moisture).
Relatively easy to evacuate.	

5. *Opacified powders*	
Better performance than straight evacuated powders. Complicated shapes may be easily insulated. Vacuum requirement is not as stringent as for multilayer insulations and vacuum alone.	Higher cost than evacuated powders. Explosion hazards with aluminum in an oxygen atmosphere. Problems of settling of metallic flakes.
6. *Multilayer insulations*	
Best performance of all insulations. Low weight. Lower cool-down loss compared with powders. Better stability than powders.	High cost per unit volume. Difficult to apply to complicated shapes. Problems with lateral conduction. More stringent vacuum requirements than powders.

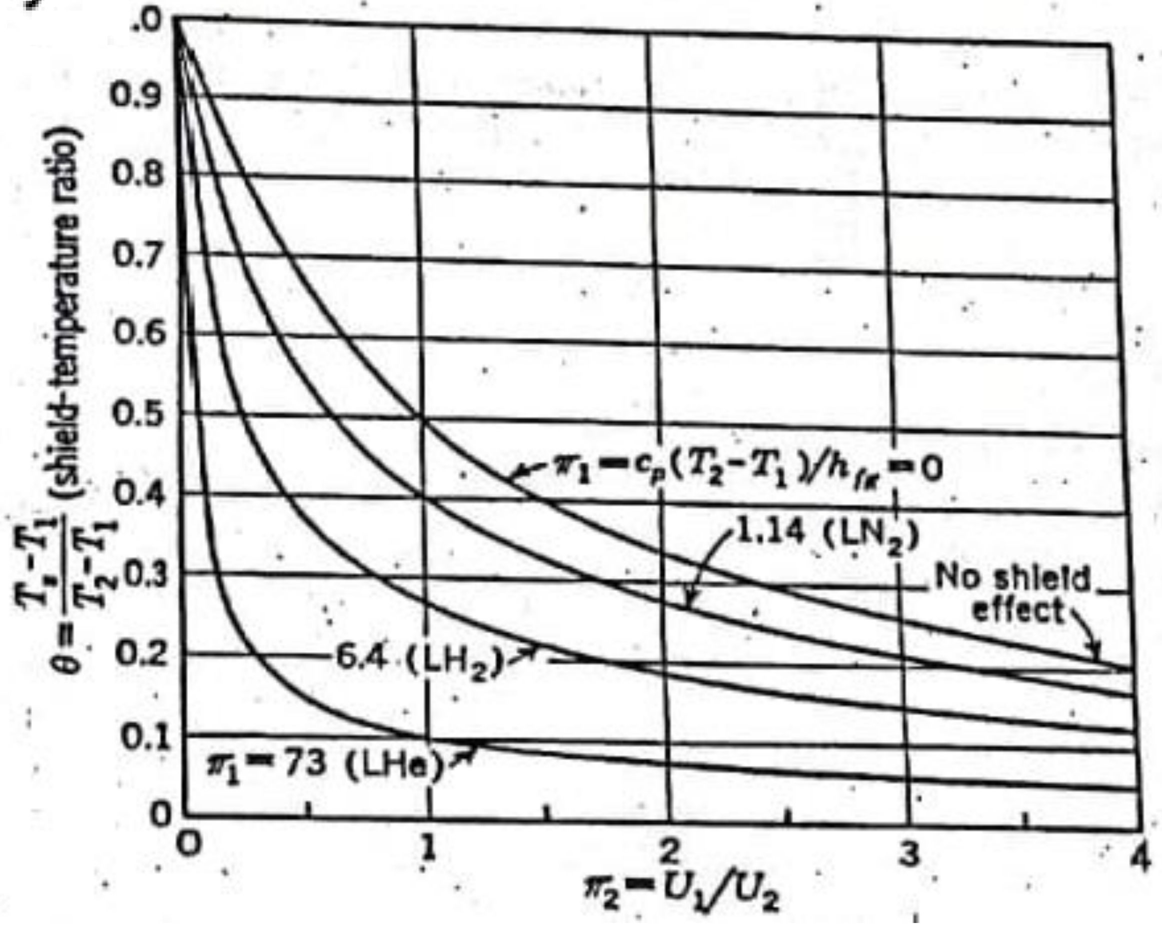
Vapor Shielded vessels



$$\theta = \frac{\pi_2 + 1}{2\pi_1\pi_2}\left\{\left[1 + \frac{4\pi_1\pi_2}{(\pi_2 + 1)^2}\right]^{1/2} - 1\right\}$$

$$\pi_1 = c_p(T_2 - T_1)/h_{fg}$$
$$\pi_2 = U_1/U_2$$
$$\theta = (T_s - T_1)/(T_2 - T_1)$$

Fluid	$\pi_1 = c_p(T_2 - T_1)/h_{fg}$
Helium	72.9
Hydrogen	6.37
Neon	6.40
Nitrogen	1.14
Oxygen	0.87



Cryogenic Fluid transfer Systems

Longer the line and larger the flow rate, the more the problem with insulation.

- 2- phase flow
- Thermal contraction
- Bowing of line under partially filled conditions
- Heat leaks at the joints etc.

Types:

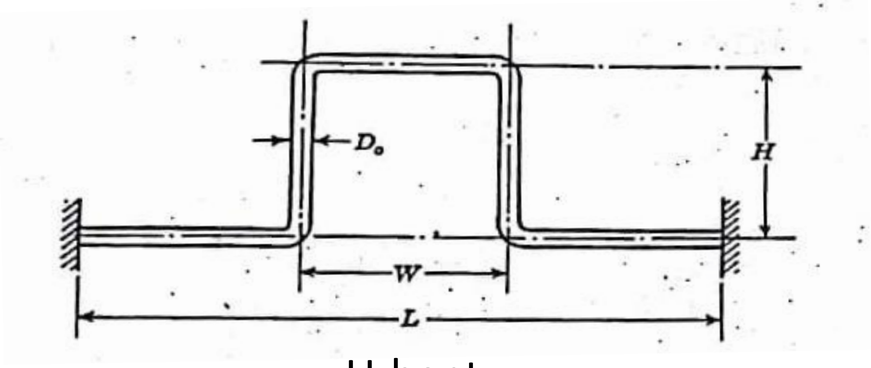
1. Uninsulated and Porous Insulated lines
2. Vacuum insulated lines

Uninsulated and Porous Insulated lines

- Uninsulated lines.
  - Most economical
  - Short length, short-time flows
  - Suitable for L Air, LO_2, LN_2 → Formation of frost layer over the pipe, aiding insulation. [*LO_2 line: 1.8 kW/m^2(uninsulated), 1 kW/m^2 (2.5mm frost), 2.8 kW/m^2 (3.6 m/s wind)*]
  - Not suitable for LH_2, LHe etc → condensation of air over the pipe leading to high convective losses. [*LH_2 line: 11 kW/m^2(uninsulated), 19 kW/m^2 (6.7 m/s wind)*]
- Porous insulations.
  - Improves insulation.
  - Fiber glass, polystyrene foam, polyurethane foam etc.
  - Vapor barrier required to avoid diffusion of moisture into the foam.
  - Air condensation (rich in O_2) outside LH_2 lines pose safety hazard.

Vacuum insulated lines

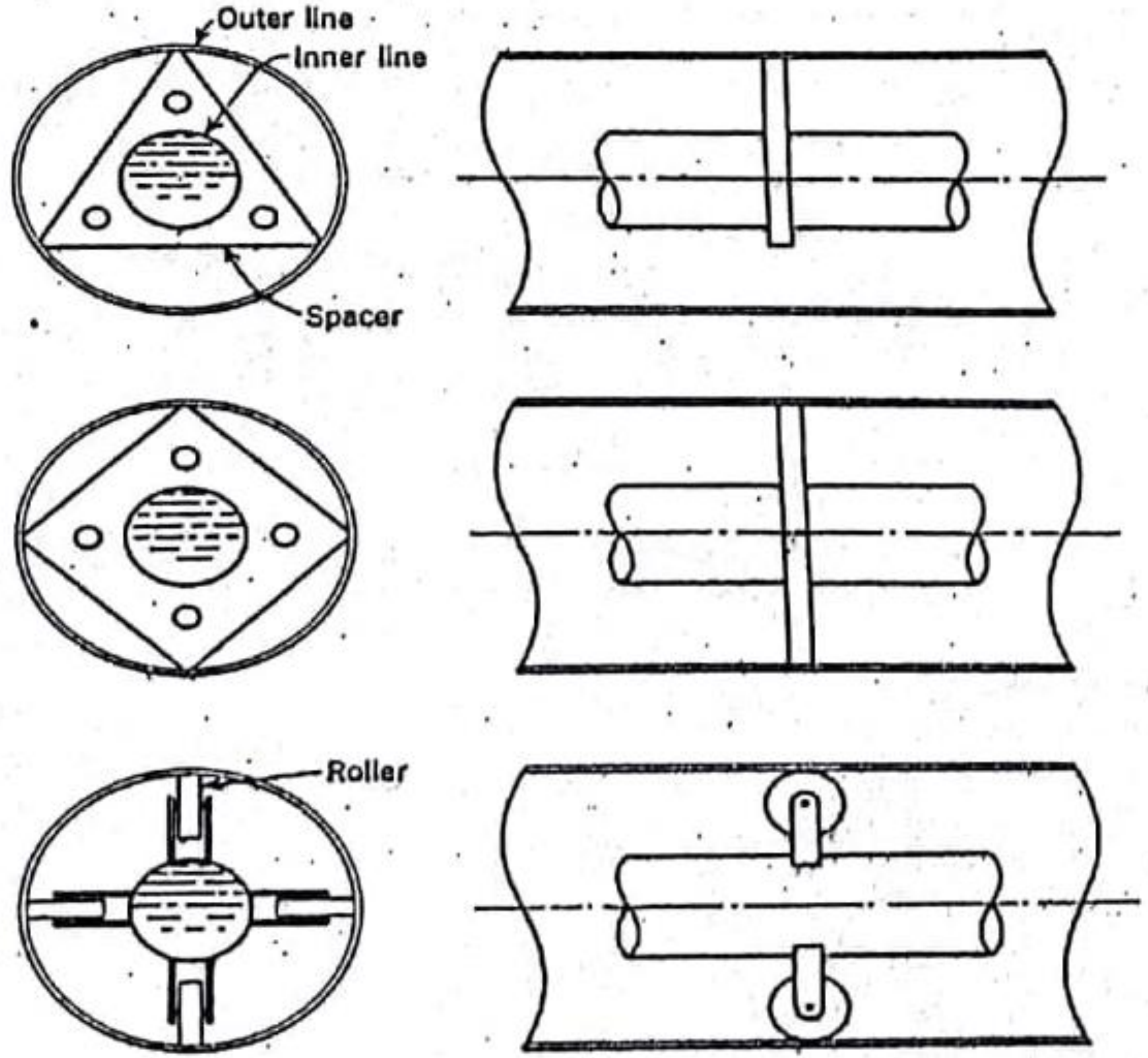
- Inner line and concentric outer vacuum jacket.
- Long distance, long time transfer.
- Multi layer insulation or vacuum alone.
- Thermal contraction avoided by,
  - Bellows for outer pipes.
  - U-bent for inner pipes.
- Spacers (between inner and outer pipes)
  - Low thermal conductivity.
  - High strength.
  - Low outgassing rate.
  - Low specific heat.



U-bent

Spacers:

- Materials,
  - Flexi glass
  - Fluorocarbon plastic
  - SS
- Small area of contact.
- Should not block annular space.
- Roller spacers to avoid contact stresses.



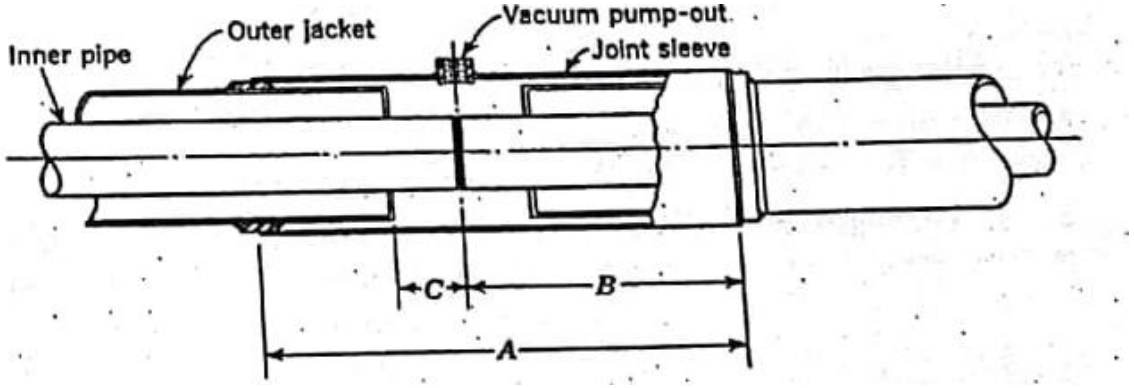
Vacuum-insulated line joints

Bayonet Joint (high performance cryogenic pipe joints)

- Used where low heat inleaks, frequent dismantling are required.
- Male portion telescopes within the female portion with a clearance such that no liquid can flow between and gaseous convection is suppressed.
- *Neoprene O-ring* sealing is located at the warm flange-end rather than the cold end to avoid low temperature sealing problems.
- A *V-band clamp* is used to hold both parts together and for easy assembly.
- For applications were the line is seldom taken apart, **field welded joint** is used.

Bayonet Joints

Cut Away View of VJ Pipe



Field welded Joints

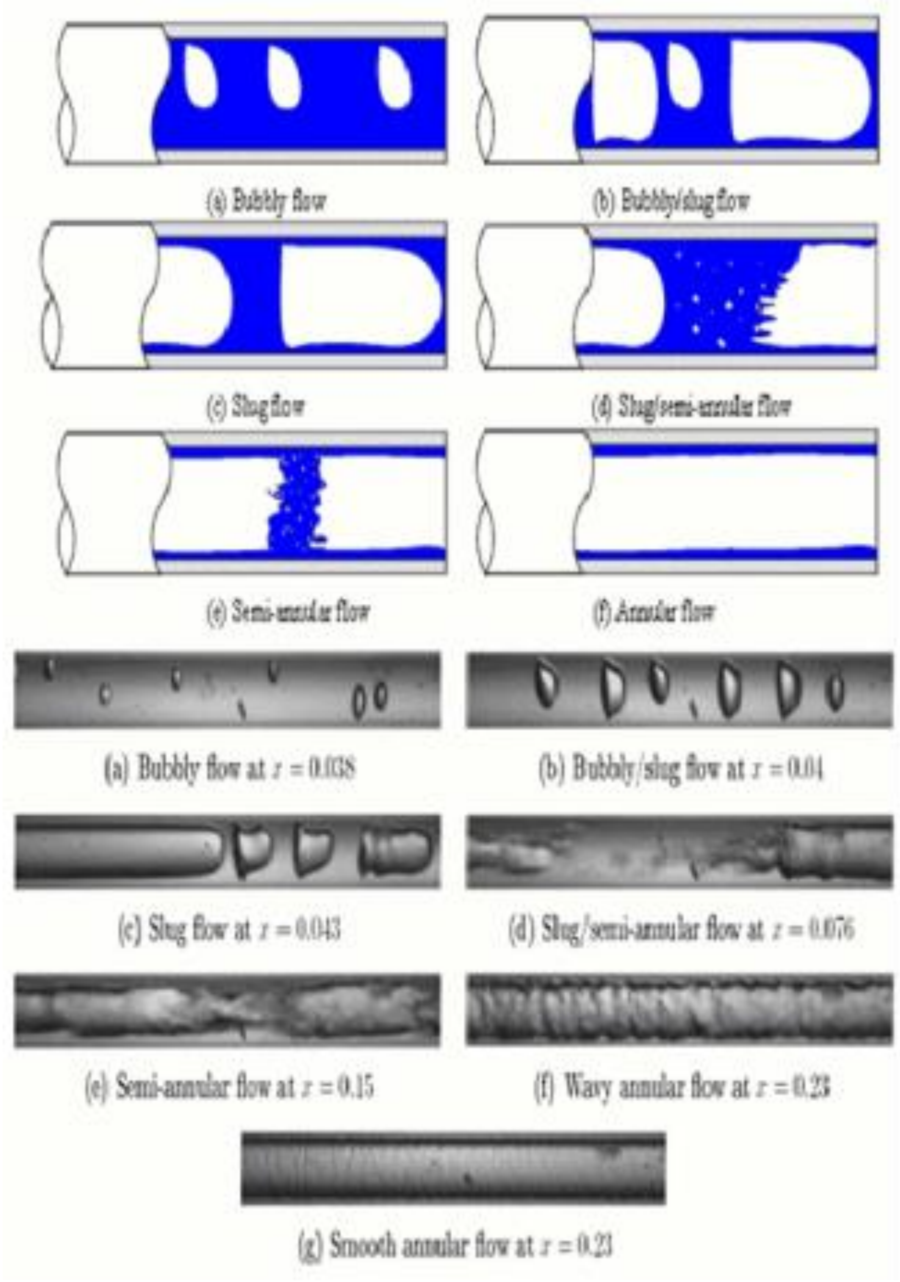
Cryogenic Valves

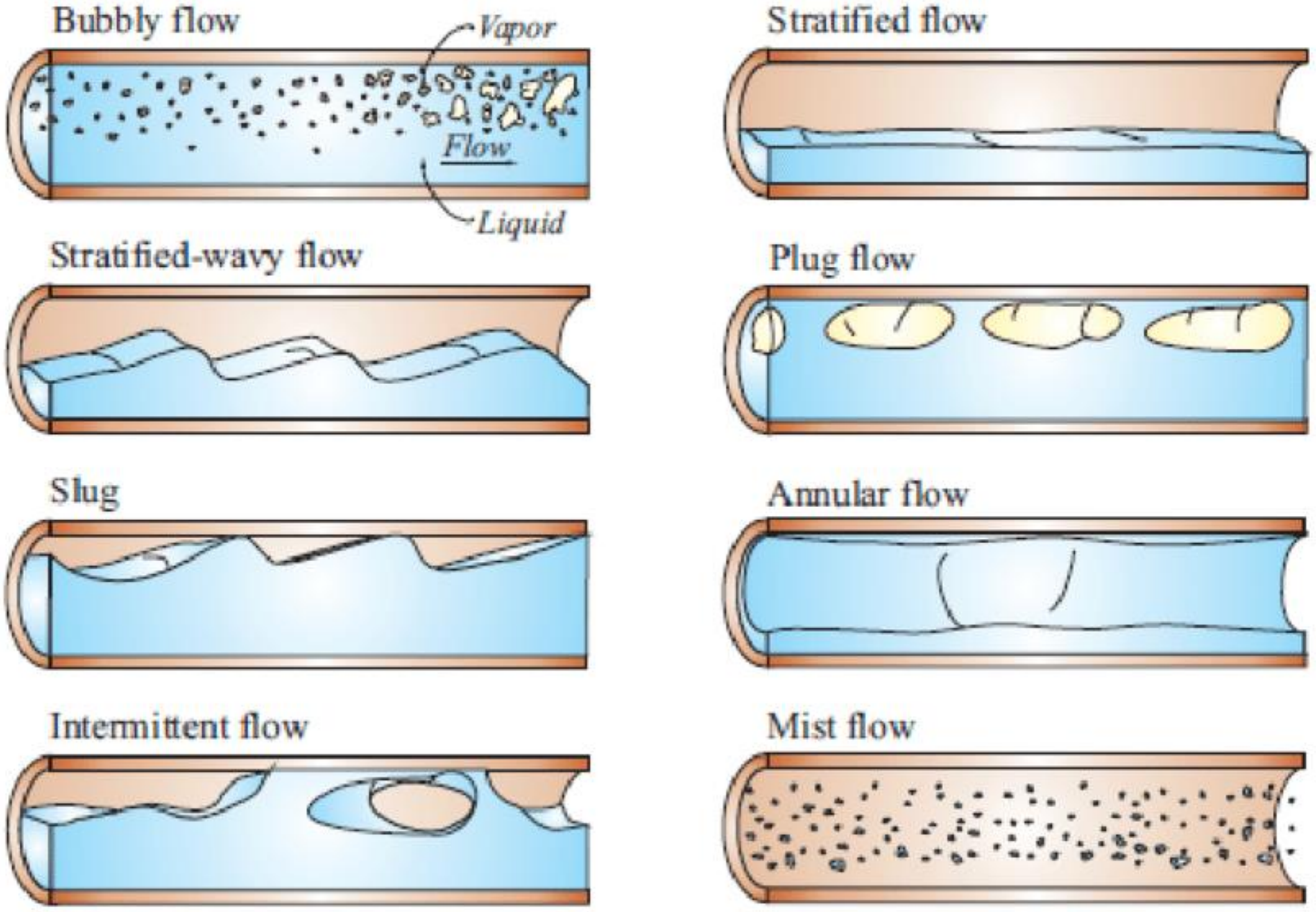
1. Extended stem valve
   - Resembles an ordinary valve
   - But with an extended stem through thin walled tubing:
     1. Maintains valve handle at room temperature to protect the operator.
     2. Valve stem may be **sealed** at ambient temperature than cryogenic temperature thereby increasing reliability.
2. Vacuum jacketed valve
   - Has a vacuum jacket around the extended stem and valve body to avoid heat inleaks.
   - Thin walled sections to reduce cool down losses.
   - Multi layer insulation is used where more insulation performance is needed.

Extended stem valves & vacuum jacketed valves

Two-phase flow

- Due to heat inleaks two phase flows are not uncommon.
- Becomes difficult to predict the pressure drop in the pipe.
- Different flow pattern for horizontal, vertical and inclined tubes.
- Several flow patterns may exist depending on the nature of flow. (refer fig.)
- May be laminar in the liquid phase and turbulent in the gaseous phase.
- Flow pattern may change along the length due to changing quality (due to heat leaks and pressure drop).





2-phase flow patterns