Cryogenic Engineering

Chapter 8.

Vacuum Technology

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8.1 Importance of Vacuum Technology

- Vacuum technology is used for

1. Insulation
2. Liquefaction system (LN_2 precooling)
3. He^3-He^4 dilution system
4. In high vacuum system – cold trap before the vacuum pump

8.2 Flow Regimes in Vacuum Systems

- **Flow in low pressure**

At low pressure, the gas molecules are so far apart that the gas cannot be treated as a continuous medium, and we obtain another flow regime – ***free molecular flow***

The dimensionless parameter used to determine the dividing line between continuum and free-molecular flow is the ***Knudsen number***, $\mathrm{K_{Kn}} = \lambda/\mathrm{D}$

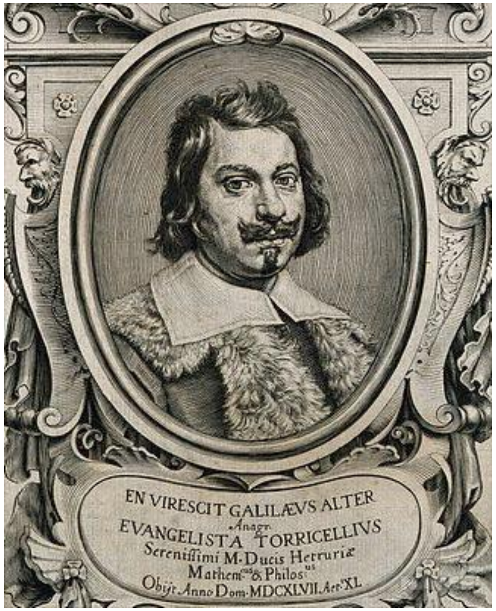
1. Continuum flow, $\mathrm{K_{Kn}} < 0.01$
2. Mixed flow, $0.01 < \mathrm{K_{Kn}} < 0.30$
3. Free-molecular flow, $0.30 < \mathrm{K_{Kn}}$

λ : mean free path of the gas molecules
D: characteristic dimension of the flow channel

▪ Degree of vacuum

1. Rough vacuum, $25 \text{ torr} < \text{P}$
2. Medium vacuum, $10^{-3} \text{ torr} < \text{P} < 25 \text{ torr}$
3. High vacuum, $10^{-6} \text{ torr} < \text{P} < 10^{-3} \text{ torr}$
4. Medium vacuum, $10^{-9} \text{ torr} < \text{P} < 10^{-6} \text{ torr}$
5. Medium vacuum, $\text{P} < 10^{-9} \text{ torr}$

$$1 \text{ torr} = 133.322 \text{ Pa} = \frac{1}{760} \text{ atm}$$



Evangelista **Torr**ichelli

8.3 Conductance In Vacuum Systems

For laminar continuum flow in a circular tube, Poisseuille's equation

$$\Delta p = 128\mu L\dot{m}/\pi D^4 \rho g_c$$

$$\begin{aligned} \text{where } L &= \text{tube length} \\ D &= \text{tube diameter} \\ \bar{\rho} &= \text{mean fluid density} \\ \mu &= \text{fluid viscosity} \end{aligned}$$

Substituting $\bar{\rho} = \frac{\bar{p}M}{R_u T}$, where $\bar{p} = (p_1 + p_2)/2$

$$\Delta p = 128\mu L R_u T\dot{m}/\pi D^4 g_c \bar{p} M$$

8.3 Conductance In Vacuum Systems

According to kinetic theory of gases (Kennard 1938), the mass flow rate for mixed flow in a circular tube

$$\dot{m} = \frac{\pi D^4 g_c \bar{p} \Delta p}{128 \mu L R_u T}\left[1 + \frac{8\mu}{\bar{p}D}\left(\frac{\pi R_u T}{2 g_c M}\right)^{1/2}\right]$$

For free-molecular flow in long tubes

$$\dot{m} = \left(\frac{\pi g_c M}{18 R_u T}\right)^{1/2}\left(\frac{D^3 \Delta p}{L}\right)$$

8.3 Conductance In Vacuum Systems

The throughput is commonly used in vacuum work

$$Q = p\dot{V} = \dot{m}R_uT/M$$

A conductance C for a vacuum element

$$C = \frac{Q}{\Delta p} = \frac{\dot{m}}{\Delta p}$$

8.3 Conductance In Vacuum Systems

The conductance for a long tube may be written as follows.

1. Laminar continuum flow

$$C = \pi D^4 g_c \bar{p} / \; 128 \mu L$$

2. Mixed flow

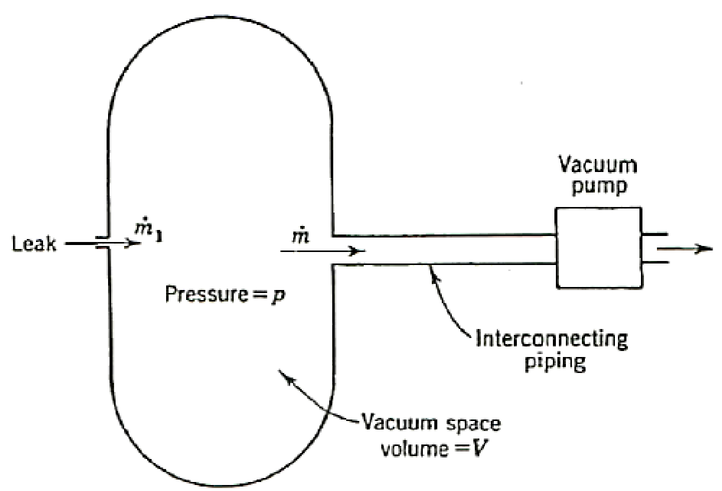
$$C = (\pi D^4 g_c \bar{p} / \; 128 \mu L)[1 + (8\mu / \bar{p} D) \left(\frac{\pi R_u T}{2 g_c M}\right)^{1/2}]$$

3. Free molecular flow

$$C = (\pi g_c R_u T / \; 18M)^{\frac{1}{2}} (D^3 / L)$$

8.4 Calculation of Pump-Down Time for a Vacuum System

One of the important factors in the design of a vacuum system is the determination of the pump-down time, or the time required to reduce the pressure of the system from ambient pressure to the desired operating pressure.



Vacuum system for pump-down equation development

8.4 Calculation of Pump-Down Time for a Vacuum System

The capacity of a vacuum pump is given in terms of the pump speed S_p defined as

$$S_p = \frac{Q}{p_i}$$

Where Q is the throughout of the pump and p_i is the pressure at the inlet of the pump. Similarly, the system pumping speed S_s is defined by

$$S_s = \frac{Q}{p}$$

Overall conductance of the piping system between the vacuum space and the vacuum pump can be calculated as

$$C_0 = \frac{Q}{(p - p_i)}$$

$$\frac{1}{S_s} = \frac{1}{S_p} + \frac{1}{C_0}$$

8.4 Calculation of Pump-Down Time for a Vacuum System

The mass flowrate of gas from the system is given by

$$\dot{m}_{out} = \rho S_s = pS_s/RT$$

Applying the Conservation-of-Mass Principle to the vacuum system and assuming that the gas obeys the ideal-gas equation of state,

$$\dot{m}_1 - \dot{m}_{out} = \frac{dm}{dt} = v\frac{d\rho}{dt} = \frac{V}{RT}\frac{dp}{dt}$$

$$\frac{dp}{dt} = \frac{Q_i}{V} - \frac{S_s p}{V}$$

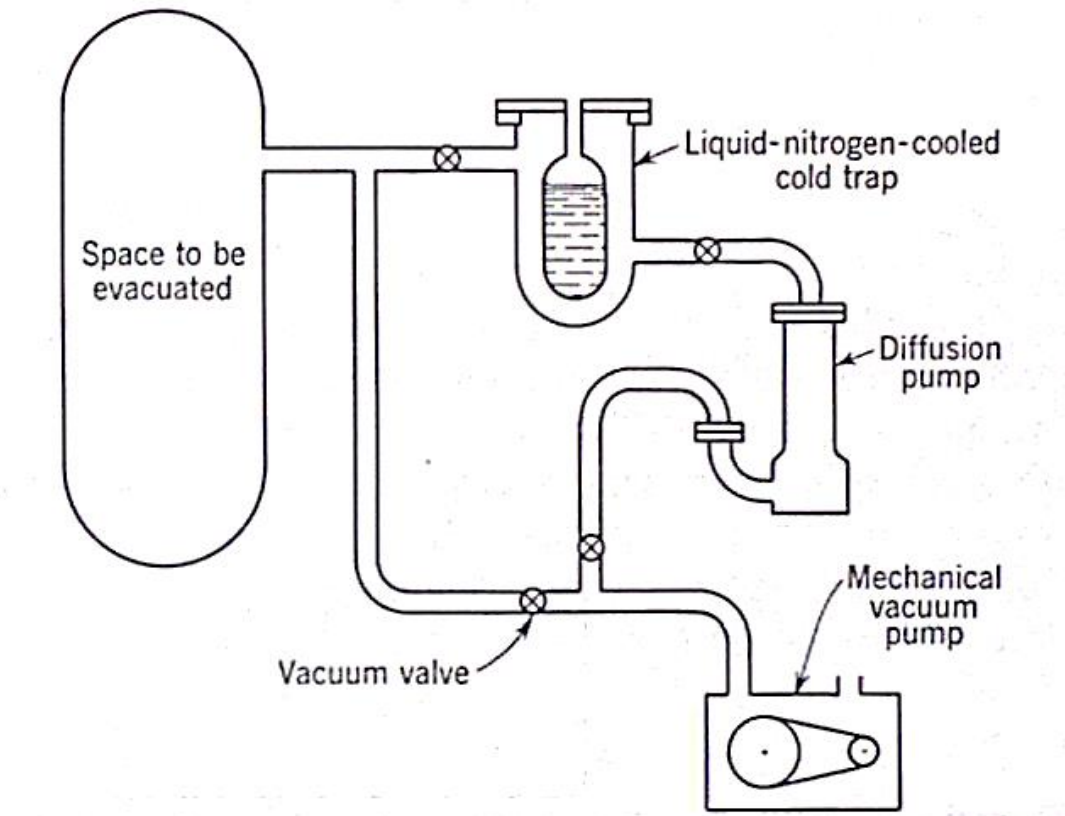
$$p_u = \frac{Q_i}{S_s}$$

$$t_p = \left(\frac{V}{S_s}\right)\ln\left(\frac{p_1 - p_u}{p_2 - p_u}\right)$$

$$S_S = \left(\frac{F_S V}{t_p}\right)\ln\left(\frac{p_1}{p_2}\right)$$

Where F_s is allowance factor, t_p is pump down time

8.5 Components of Vacuum Systems



Basic elements of a typical vacuum system

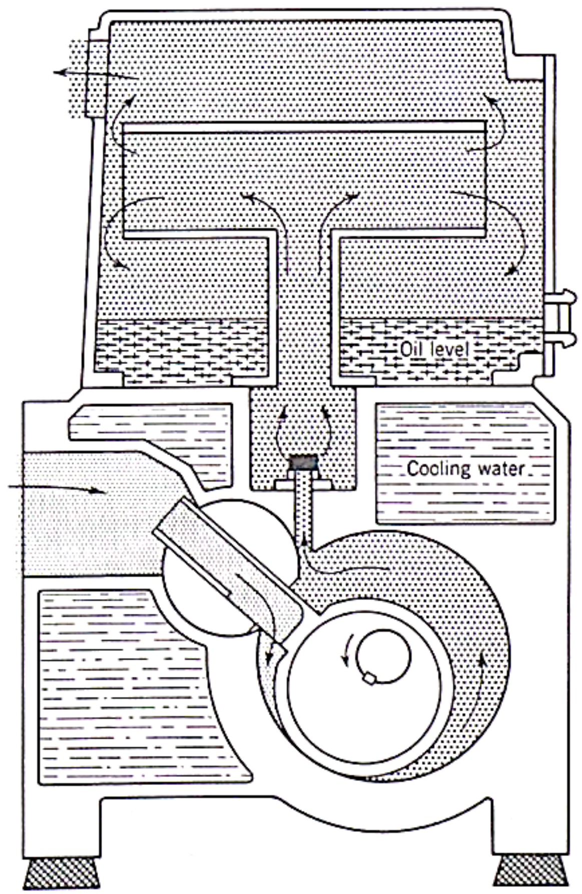
8.5 Components of Vacuum Systems

- Mechanical vacuum pump is used as a fore-pump or roughing pump to reduce the system pressure to approx. 1.0 Pa

- Diffusion pump operates if the pressure reduces about 1.0 Pa – valve in the by-pass line is closed

- Cold trap or baffle are provided near the inlet of the diffusion pump – preventing back streaming of oil vapor, to freeze out condensable gases

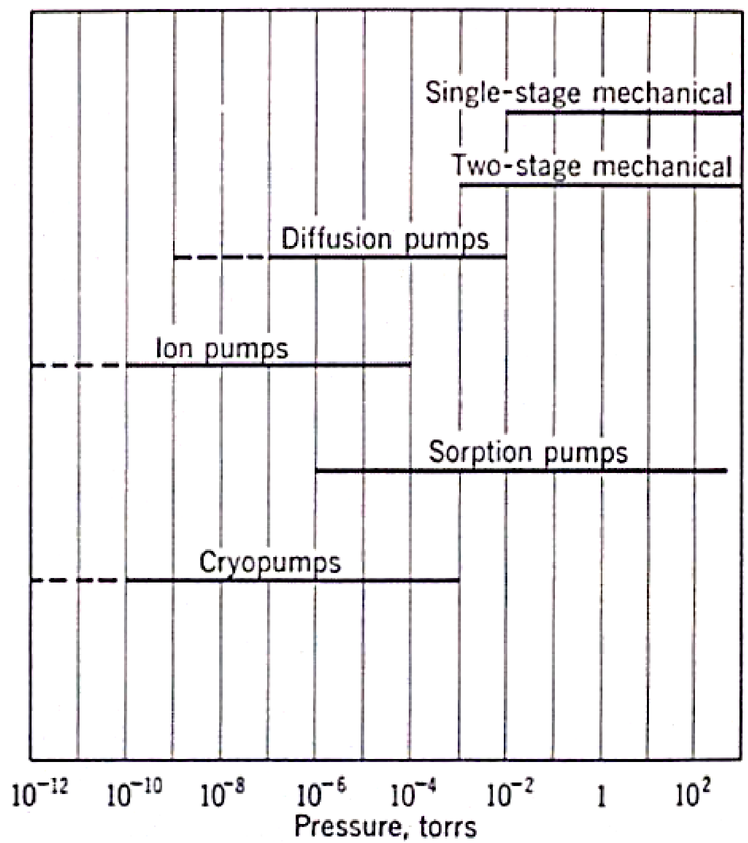
8.6 Mechanical Vacuum Pumps



<Section view of a typical rotary-piston mechanical vacuum pump>

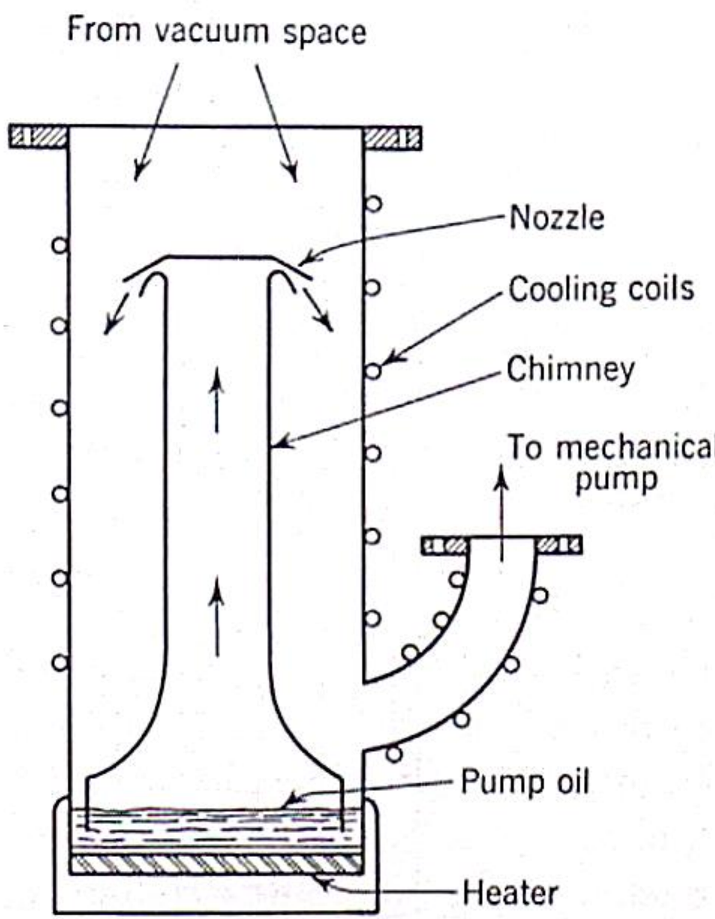
8.6 Mechanical Vacuum Pumps

- Basic principle – the same as the rotary pump for higher pressures!
- Eccentric rotor(piston) rotates within the cylindrical jacket.
- Gas enters the space between the two cylinders is compressed to a higher pressure as the piston rotates.
- Gas is discharged through a check valve that prevents backflow of the air into the pump space.
- Oil separator is provided to remove the oil from the gas and return the oil to the pump.
- Gas Ballast – To prevent moisture condensation within the pump volume.
  – Admit sufficient atmospheric air into the pump space.



Operating range for various vacuum pumps

8.7 Diffusion Pumps

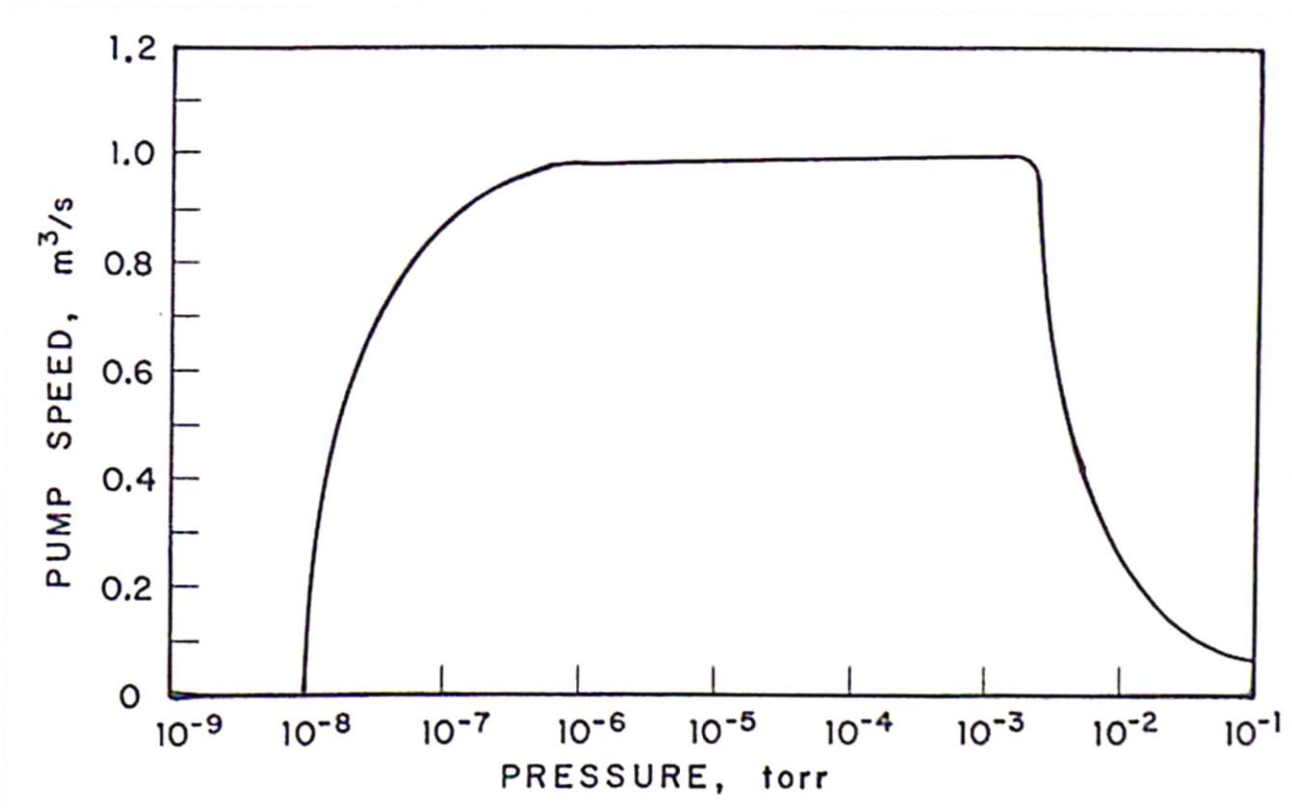


Schematic of a single-stage diffusion pump

8.7 Diffusion Pumps

- Diffusion pumps – similar to the action of a steam ejector pump.
- Ordinarily operates in the free-molecular flow regime rather than the continuum regime.
- Working fluid is evaporated in the boiler at the bottom, flows up the chimney, vapor is ejected at high velocities in a downward direction from vapor jets.
- Vapor molecules strikes gas molecules – force the gas molecules downward and out the pump exhaust.
- Vapor molecules are condensed and returned to the boiler.
- Gas molecules – removed by a mechanical backing pump.

8.7 Diffusion Pumps



Pumping-speed curve for a diffusion pump having a nominal diameter of 100mm(4in)

8.7 Diffusion Pumps

Ideal case, a diffusion pump should remove gas molecules as fast as they diffuse into the pump inlet

→ maximum pumping speed is the same as the conductance of an aperture!

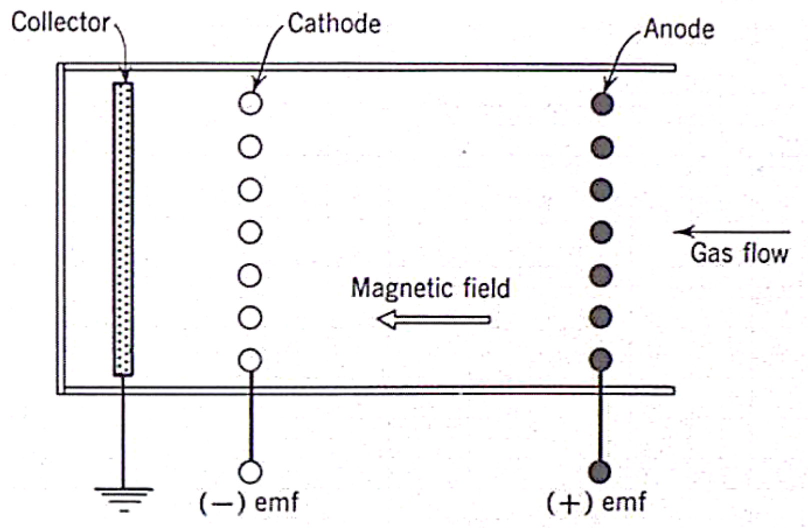
$$S_p^0 = \left(\frac{\pi g_c R_u T}{32M}\right)^{1/2} D^2$$

The ratio of the actual pump speed to the theoretical pump speed is called the H_o coefficient

$$S_p = H_0 S_p^0$$

Typical H_o coefficients for commercial vacuum pumps range between 0.40~0.55.

8.8 Ion Pumps



Schematic of an ion pump

Ion pump structure :

- Combination of ionization and chemisorption
- A large positive electric potential – Anode, a large negative electric potential – Cathode
- Magnetic field is applied to the entire unit

8.8 Ion Pumps

- Electrons from cathode – attracted to the anode
- Due to the magnetic field, electrons moves cycloidal path
- Collision supplies more free electrons
- Positive ion – attracted to the Cathode
- Remainder of the ions bombard the cathode and tear out
- Sputtered material buries the gas ions
- The gas ions are driven to the collector
- The Ion pump has relatively high pumping efficiency!