Basics of Vacuum Technology

Unit: Pa = N/m^2 = J/m^3

Unit		Pa or N/m^2
bar		10^5
mbar		100
atm	= 760 torr	1.01325×10^5

Three states of residual gas

- d = typical distance between walls
- $<\lambda>$ = average collision distance

Viscous state: $<\lambda> < d/100$

- Collisions, energy transfer through collisions, viscous flow, diffusion

Intermediate state: $d/100 < <\lambda> < d$

Molecular state: $d < <\lambda>$

- Molecules collide with the walls, heat transfer from wall to wall with molecules, no viscosity

Vacuum regions

Vacuum region	**Pa**
Rough	$10^5 – 10^2$
Intermediate	$10^2 – 10^{-1}$
High	$10^{-1} – 10^{-4}$
Good high	$10^{-4} – 10^{-7}$
Ultra	$10^{-7} – 10^{-10}$
Good ultra	10^{-10} –

Vacuum region	
Rough	Viscous
Intermediate	Changing to molecular
High	Mainly molecular
Good high	Molecular Materials, tightness, baking (150 – 400 ^{o}C)
Ultra	Surfaces stay clean Materials critical, metal seals, baking
Good ultra	

Residual gas

- Initially air
- Rough vacuum: mainly air
- Intermediate vacuum: gas starts to get out from surfaces (outgassing)
- High vacuum: Mainly gases from surfaces, typically 70 – 90 % water

  Gradually water decreases and CO + CO_2 increase
- Ultra vacuum: mainly Hydrogen
- Depends on Pump/pre-pump: most pumps pump easier heavy gases
- Nobel gases difficult to pump
- *Principally residual gas is NOT thin air*

Note!

The composition of residual gas depends on

- how long time the vessel has been open
- how it was vented
- what molecules can have attached on the surface (e.g. humidity -> water)
- possible leaks
- Etc.

Vacuum forces

$$F = P \cdot A$$

Practically "zero" pressure on the vacuum side and 1 atm on the pressure side.

- e.g. 10 cm x 10 cm square flange:

$$F = 1.013 \times 10^5 N / m^2 \times (0.1m)^2 = 1000 N$$

This is important when designing vacuum vessels/chambers!

Some constants and equations

$N_A = 6.02205 \cdot 10^{23}\,\mathrm{mol}^{-1}$ Avogadro constant

1 mol ideal gas in NTP = 22.4 l

$R = 8.3144\,\mathrm{J/mol} \cdot K$ molar gas constant

$$P \cdot V = n \cdot R \cdot T$$

Equation of state for residual gas in terms of moles

$k = R / N_A = 1.3806 \cdot 10^{-23}\, J/K$ Boltzmann constant

$$P \cdot V = N \cdot k \cdot T$$

Equation of state for residual gas in terms of number of molecules

Number of gas molecules

One cubic-cm in NTP

$$N = \frac{P \cdot V}{k \cdot T} = \frac{10^5 \, {}^{N}\!/_{m^2} \cdot 10^{-6} m^3}{1.38 \cdot 10^{-23} \, {}^{J}\!/_{K} \cdot 293K} = 2.5 \cdot 10^{19}$$

10^{-7} mbar = 10^{-5} Pa: N = 2.5 x 10^9 (molecules in cm^3)

Energy in residual gas

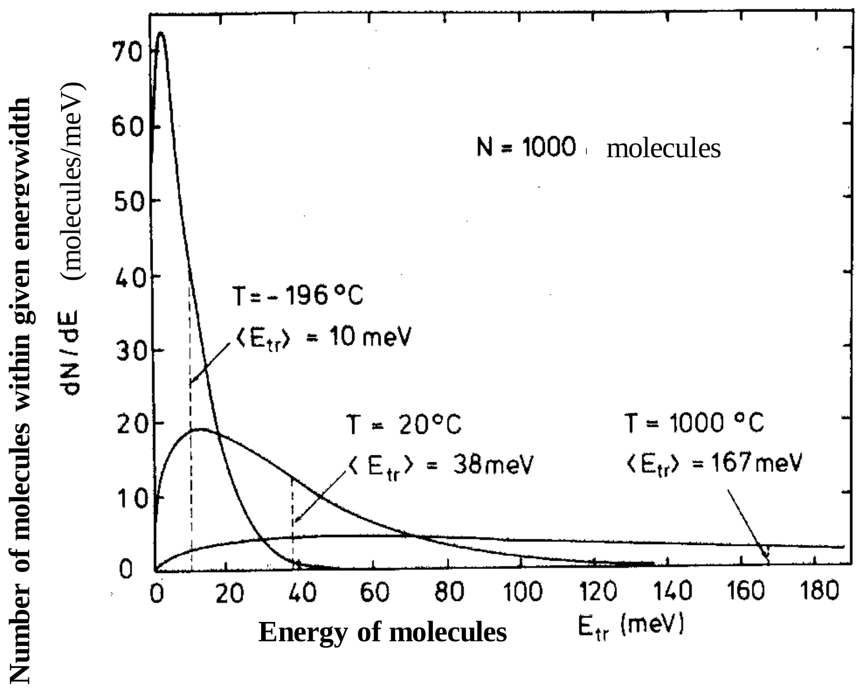
Maxwell-Boltzmann theory:

$$\frac{dN}{dE} = \frac{2 \cdot \pi \cdot N \cdot E^{1/2}}{(\pi \cdot k \cdot T)^{3/2}} \cdot E^{-E/kT}$$

Energy distribution of translation energy

$$\langle E_{tr} \rangle = \tfrac{3}{2} \cdot k \cdot T$$

Average translation energy of a gas molecule



Translation energy distribution at some temperatures.

Energy

$$U_{tr} = \frac{3}{2}NkT = \frac{3}{2}nRT$$

Translation energy

$$U_{rot} = NkT = nRT$$

Rotation energy (for a 2-atom molecule)

Velocity

$$\frac{dN}{dv} = 4\pi N\left(\frac{m}{2\pi kT}\right)^{3/2} v^2 e^{-\frac{mv^2}{2kT}}$$

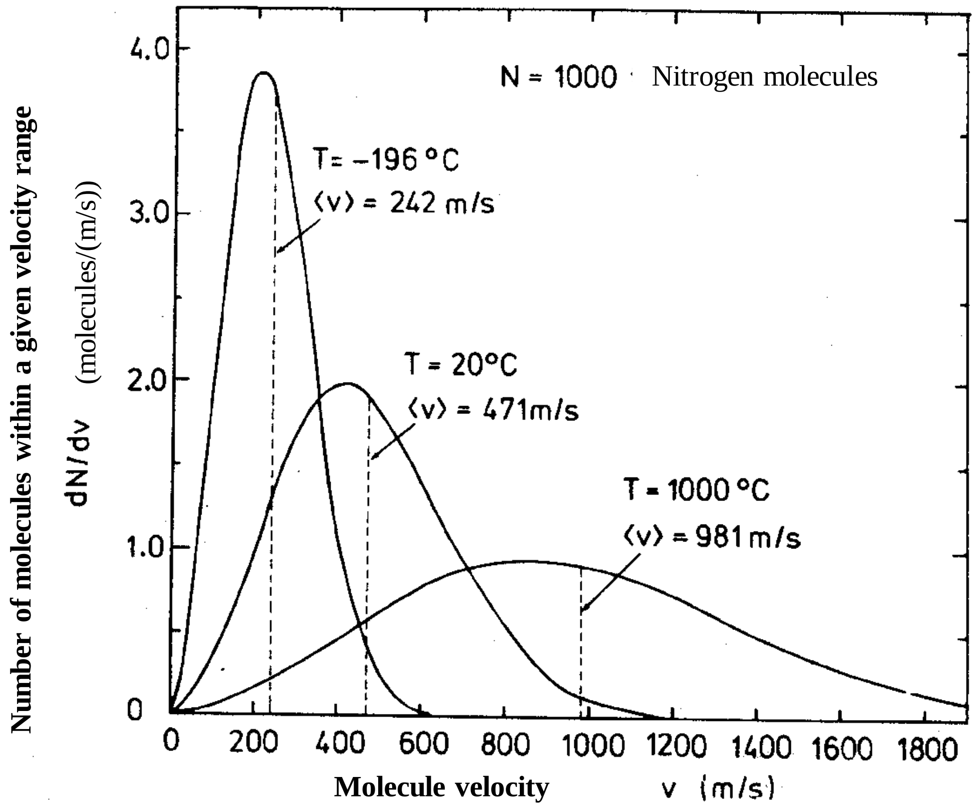
Velocity distribution for gas molecules

$$\langle v \rangle = \left(\frac{8kT}{\pi m}\right)^{1/2}$$

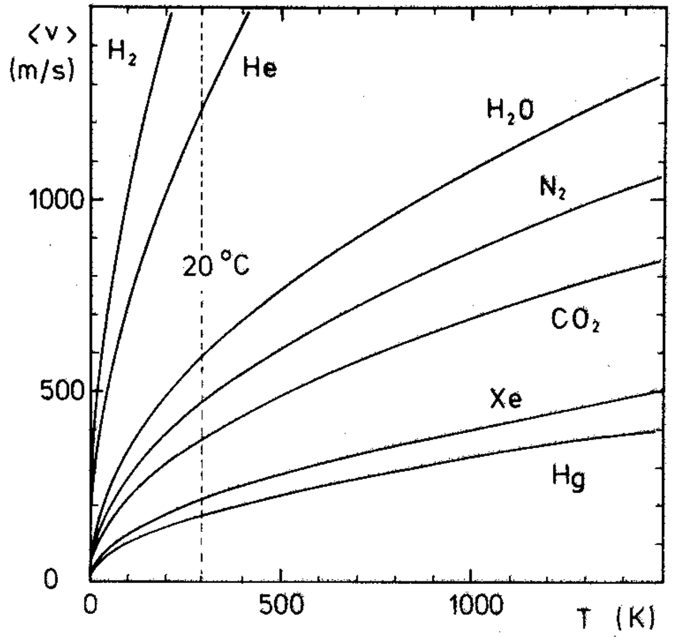
Average velocity

$$v_{prob} = \left(\frac{2kT}{m}\right)^{1/2}$$

Most probable velocity



Velocity distribution of Nitrogen molecules at some temperatures



Application in energy saving windows and thermal insulators: which gas?

Average velocity of some molecules at different temperatures

Molecules on the surface

Molecules of the residual gas stick on the surface

$$\Phi = \frac{P}{(2\pi mkT)^{1/2}}$$

Collision rate on unit area

$$\tau_m = \frac{1}{\xi^2 \Phi}$$

Time for one molecular layer formation

ξ = residual gas molecule diameter

In ultra vacuum, Hydrogen is the dominating gas. At a pressure of 10^{-5} Pa and at 20 ^{o}C the molecule layer formation time is

$$\tau_m = \frac{\left(2\pi\langle\mu\rangle ukT\right)^{1/2}}{\xi^2 P} =$$

$$\frac{\left(2\pi 2.016\cdot 1.66\cdot 10^{-27}\,kg\cdot 1.38\cdot 10^{-23}\,J/K\cdot 293K\right)^{1/2}}{\left(2.68\cdot 10^{-10}\,m\right)^2\cdot 10^{-5}\,N/m} = 12.8\ s$$

Collision distance

We get also from the M-B distribution for the average collision distance or mean free path:

$$\langle \lambda \rangle = \frac{kT}{\pi \sqrt{2} P \xi^2}$$

For a Nitrogen molecule at 20 ^{o}C and 100 kPa

$$\langle \lambda \rangle = 64 \text{ nm}$$

Pressure [Pa]	Collision distance
10^{-10}	64000 km
10^{-7}	64 km
10^{-4}	64 m
10^{-1}	64 mm
10^{2}	64 μm
10^{5}	64 nm

Residual gas (N) collision distances at 20 ^{o}C

If a fast electron, ion or molecule moves in a residual gas the residual gas molecules can be considered to be at rest. This leads to

$$\langle \lambda \rangle = \frac{kT}{\pi P \xi^2} = \sqrt{2}\langle \lambda \rangle$$

Fast particle

$$\langle \lambda_e \rangle = 4\sqrt{2}\langle \lambda \rangle$$

Electron

So, the mean free path for an accelerated ion at 10^{-5} Pa = 10^{-7} mbar is 905 m

This was the criterion for JYFL vacuum level!

Vacuum criteria

- For beam transport and accelerators:
    - Mean free path = trajectory length
    - Decay time due to collisions
- For “clean” manufacturing (crystal growth, surface manipulation, electronics:
    - Time for building a molecular layer
- What else?

Vacuum pumps

Capacity of a vacuum pump

$$S = \frac{dV}{dt}$$ Pumping speed

$$Q = P \cdot S$$ Transmission of the pump

Evacuation of a vacuum chamber (without additional sources of gas or vapor)

Rough vacuum

- Estimate the required effective pumping speed $\mathbf{S_{eff}}$ to pump the volume **V** from pressure **p** to $\mathbf{p_{end}}$ in a given pump-down time **t**.
- Assume constant $\mathbf{S_{eff}}$
- Assume $\mathbf{p_{end}} \ll \mathbf{p}$

Then

$$-\frac{dp}{dt} = \frac{S_{eff}}{V} \cdot p$$

- Start from 1013 mbar at t = 0
- **p** at **t** is calculated from

$$\int_{1013}^{p} \frac{dp}{p} = -\frac{S_{eff}}{V} \cdot t$$

$$\ell n \frac{p}{1013} = -\frac{S_{eff}}{V} \cdot t$$

$$S_{eff} = \frac{V}{t} \cdot \ell n \frac{1013}{p} = \frac{V}{t} \cdot 2.3 \cdot \log \frac{1013}{p}$$

- Introduce a dimensionless factor

$$\sigma = \ell n \frac{1013}{p} = 2.3 \cdot \log \frac{1013}{p}$$

Then

$$S_{eff} = \frac{V}{t} \cdot \sigma$$

$$t = \tau \cdot \sigma$$

with $$\tau = \frac{V}{S_{eff}}$$

and $$\sigma = \ell n \frac{1013}{p}$$

Example

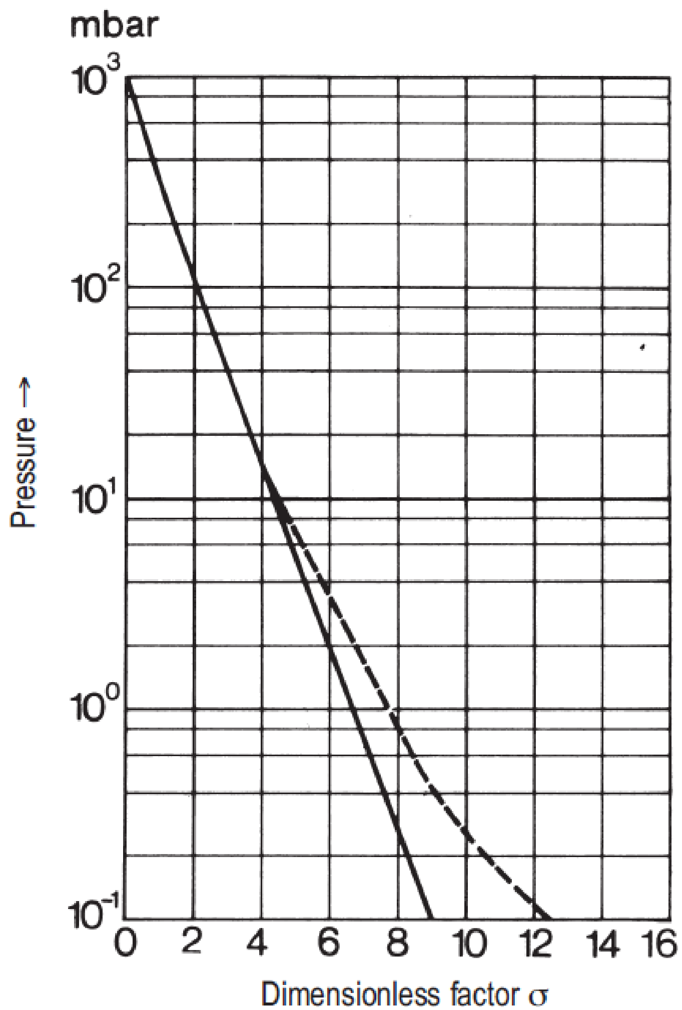
- Volume V = 500 l = 0.5 m^3
- Pumping time to 1 mbar in 10 minutes = 1/6 h

$$S_{eff} = \frac{0.5}{1/6} \cdot 2.3 \cdot \log \frac{1013}{1}$$
$$= 3 \cdot 2.3 \cdot 3.01 = 20.8\ m^3/h$$

- Solid line: constant pumping speed
- Dashed line: pumping speed reduces below 10 mbar

$$S_{eff} = \frac{0.5}{\frac{1}{6}} \cdot 7 = 21\,m^3/h \quad \text{or}$$

$$S_{eff} = \frac{0.5}{\frac{1}{6}} \cdot 8 = 24\,m^3/h$$



Evacuation of a vacuum chamber with additional sources of gas or vapor

High vacuum region

- Leaks
- Vaporization (e.g. water droplets)
- Outgassing ($mbar \times l \times s^{-1} \times cm^{-2}$)
    - Porous material (epoxy, some plastics, etc.)
    - Molecules on surfaces (eg. water)
- Permeation P ($m^2 \times s^{-1}$)
    - $Q = P \times A \times \Delta p \times d^{-1}$
    - Diffusion through walls
        - Metals $<10^{-14}$
        - Neoprene $10^{-13} – 10^{-11}$
        - Plastics $10^{-12} – 10^{-11}$
        - Viton 10^{-12}
- When the gas evolution Q is known, the effective pumping speed must be at least

$$\mathbf{S_{eff} = Q/p_{end}}$$

Conductance of the flow channel

$$Q = C \cdot \left(P_1 - P_2 \right)$$

Q = transmission of the flow channel

P_1 = Pressure at inlet

P_2 = Pressure at outlet

C is called the conductance of the flow channel

$$[C] = m^3/s$$

$$\frac{1}{C} = \text{resistance}$$

$$C = \frac{\pi}{8} d^2 \langle w \rangle \frac{P_1 + P_2}{P_1 - P_2}$$

Conductance for a long round tube in incompressible flow

$$C = \frac{\pi d^4}{256 \eta L} \left(P_1 + P_2 \right)$$

Conductance for a long round tube in laminar flow

$$C = \frac{1}{6} \left(\frac{2\pi k T}{m} \right)^{1/2} \frac{d^3}{L}$$

Conductance for a long round tube in molecular flow

Note! This does NOT depend on pressure