

Optional Reading: “Creating a Vacuum”, “Pump down curves”, and “Pumping speed in drydown zone”.

1) Introduction

- a) What is a vacuum?
 - i) A little tricky to define. “No air” is not technically correct. “Lower than ambient pressure” works on Earth, but not in space. “Much less than 1 atm pressure” is also somewhat reasonable.
- b) Units of vacuum (all are PRESSURE)
 - i) SI unit is Pascals (Pa), defined as 1 N/m^2 . $1 \text{ atm} = 101,325 \text{ Pa}$. Very inconvenient for typical calculations, but still should be used in publications. I tend to give pressures in Pa, with other units in parentheses, e.g. 10.132 kPa (0.101 bar)
 - ii) Atmosphere (atm). Very convenient, not commonly used.
 - iii) Torr – most common in US; $1 \text{ atm} = 760 \text{ Torr}$; this is basically equivalent to using feet and inches in a publication
 - (1) Is approximately equal to 1 mm Hg ; note also mTorr tends to be called “microns”, as in thousandths of an inch of Hg, in the US
 - (2) Named after [Evangelista Torricelli](#), an Italian physicist and mathematician who discovered the principle of the barometer in 1644
 - iv) Bar (mbar) – most common in Europe. Defined as $100,000 \text{ Pa}$, so $1 \text{ atm} = 1.0135 \text{ bar}$.
 - v) See conversion scale to go between them. To rough approximation, $1 \text{ mbar} = 1 \text{ Torr}$, $1 \text{ mTorr} = 1 \text{ micron} = 10^{-3} \text{ mbar}$.
 - vi) Also beware absolute versus gauge pressures (latter is mainly in industrial useage)

2) Vacuum and flow regimes

- a) See table of representative regimes
- b) Filtering/drying applications are typically low to medium vacuum. Instruments are typically high to UHV vacuum.
- c) Can describe vacuum either in terms of pressure (more typical), or in terms of number density (atoms/L), or mean free path
- d) Flow Regimes
 - i) Mean free path. One of the key, defining characteristics of different regimes; think of this as average distance between collisions.
 - (1) At relatively high pressure, molecular collisions are very frequent, any pressure differences get quickly balanced out (collision-driven flow). If you remove molecules from one end, all the rest shift that direction. Like water in a pipe.
 - (2) At low pressure, collisions are rare, and molecules move essentially at random. If you remove some from one end, have to wait for diffusion to balance out pressure differences. This means that strategies for removing molecules vary considerably depending on pressure.
 - (3) Mean free path is a function of density, molecular size, and average velocity (Fn of temp):
 - (a) $l = \frac{k_B T}{\sqrt{2} \pi d^2 p}$
 - (b) k_B is Boltzmann constant (J/K), T is temp (K); these define distribution of velocities in terms of temperature
 - (c) p is pressure (Pa)
 - (d) d is particle diameter (meters)
 - (e) thus smaller atoms (He) have a longer mean free path than larger ones (N_2 , Ar); hotter systems have longer mean free path than cold ones

- ii) Gas flow can be categorized in two regimes by comparing mean-free path to characteristic distances of system (ie, tube diameter); known as the Knudsen number
 - iii) The **Knudsen number (Kn)** is a dimensionless number defined as the ratio of the molecular mean free path length to a representative physical length scale.
 - (1) Viscous flow – dominated by interactions between molecules (Knudsen number $\ll 1$). Pressure-driven flow. Behaves like water in pipes. Does not fractionate isotopes.
 - (2) Molecular flow – dominated by collisions with walls (Knudsen number $\gg 1$). Diffusion-like flow, rate dependent on mean-free path and probability that a gas molecule flies into pump orifice. Does fractionate isotopes, because velocity varies with mass.
 - iv) Related concept of Knudsen Diffusion occurs for $\text{Kn} \gg 1$, typically because diffusing through a very small orifice or pinhole.
 - v) Transition between viscous and molecular flow depends on geometry of physical system. Smaller diameters will experience viscous flow at higher pressures. (see graphic). Becomes very important in talking about dual-inlet systems.
- 3) Water and Hydrogen
- a) If atmosphere was entirely noble gases, creating vacuum would be fairly easy. However, once you reach molecular flow conditions, different gases begin to behave differently, and the composition of remaining gas changes.
 - b) Water. Unfortunately, water is ubiquitous in our atmosphere. It is very polar (sticky), and can hydrogen bond to O on surfaces, and so there is typically a lot more water coating all surfaces (adsorbed phase) than there is in the gas phase. Precise amount is related to surface area and surface properties. Once you pump out air, this adsorbed gas will begin to vaporize, providing a steady stream of gas until the reservoir is depleted. This influences a variety of factors in vacuum system design, including materials, baking, etc. Will talk about this more next time.
 - c) Hydrogen. Main problem with H_2 is that its very small size means it is not pumped efficiently by turbomolecular pumps, and so need other kinds of pumps to remove it.
- 4) How to create a vacuum.
- a) Starting at 1 atm, in viscous flow regime the simplest way to move air is by displacement. Fill a volume, seal it off, compress it and push its contents out. Syringe with two 1-way valves would be a simple example. More practical examples include rotary-vane (oil) pump, scroll pump, diaphragm pump, etc.
 - i) As the number density of molecules drops, this type of pump quickly loses effectiveness, because flow into evacuated volume is too slow. As a result, they are typically limited to about 1mTorr (10^{-3} mbar) pressure.
 - ii) Often characterized by “Compression ratio”, = exhaust P / inlet P
 - (1) Typically 10^6 ; if exhaust fixed at 1atm, then that limits P to 10^{-3} mbar
 - b) Under conditions of molecular flow, need a different strategy. Probability of a molecule exiting system depends on it hitting the exit, thus proportional to cross-sectional size. Want to provide a large opening, while keeping molecules from coming backwards into vacuum. Class of pumps known as “momentum transfer”, in which momentum from moving blades/disks/molecules is transferred to gas molecules to help push them out, and stay out. Can reach 10^{-10} mbar.
 - c) At highest vacuums, water and hydrogen are significant problems. H_2 is not pumped efficiently by turbos, and water is continually desorbing. Class of pumps that simply trap molecules rather than moving them. Include cryo pumps (cold trap, liquid He or N_2), getter pump (charged plates), ion pumps (ionizing electrons, acceleration). All reach excellent vacuum (pressures of 10^{-11} mbar to 10^{-12}) but have limited capacity and must be periodically regenerated.
- 5) Positive Displacement Pumps
- a) Rotary Vane pumps
 - i) Basic idea is a rotating shaft set asymmetrically inside a round chamber. Moveable vanes make seal against walls. Must be bathed in oil to make good seal, and to keep cool.

- Configuration allows space to fill at low pressure, be compressed and then exhausted at higher pressure.
- ii) Can have 2 stages in series to increase total compression ratio.
 - iii) Can use belt drive (bigger, cheaper motors; slower speed) or direct drive (smaller, faster, more expensive); former usually used for large industrial applications, latter for instrumentation
 - iv) Pros: best compression ratio of all displacement pumps; relatively cheap; very compact; easily serviced (motors, seals, etc)
 - v) Cons: messy (oil), frequent oil changes, hot, loud
 - vi) Pumping speed. Usually quoted as the rate of gas removal at 1atm inlet pressure. Needs to be sized to match volume of system and gas load. Generally this is done for you, just remember to find a replacement with similar or higher speed.
 - (1) Note that most manufacturers overdo pumping speed to get rapid pumpdown, which results in wasted power. Current trend toward using smaller pumps, accepting longer pumpdown time to maximize energy efficiency.
 - vii) Ultimate vacuum. The best vacuum that will be obtained under zero gas load. Based on compression ratio.
- b) Scroll pumps
- i) Works by oscillating 1 spiral shape inside another. Points of contact move continuously outward, pushing gas as they go.
 - ii) Big advantage is that they are oil-free.
 - iii) Big disadvantages are cost (roughly 2x) and noise
- c) Diaphragm pumps
- i) Works by moving a diaphragm in and out between two one-way valves, sucking material in and pushing it out.
 - ii) While sold as ‘vacuum pumps’, their ultimate vacuum is on the order of 1 Torr, so not generally suitable for instrumentation
 - iii) Excel at filtering/drying applications where high vacuum is not needed, lots of water getting pulled into pump
- d) Jet interface pump
- i) New development from Thermo. Very expensive. Much higher pump speed. Not sure how it works.
- 6) Momentum pumps.
- a) Turbomolecular pumps.
- i) This is basically a fan operating at high speed, although principle of operation is different because of molecular flow (not viscous flow). Consists of many pairs of rotor/stator.
 - (1) Rotating rotor has angled blades, when they strike a gas molecule they give it momentum downward; gas molecule then passes through the stator which serves to separate stages
 - (2) Series of stages with increasing compression (decreasing spacing) at each one. Limit is ultimately based on machining tolerances.
 - ii) Compression ratio of the fan is a function of velocity, thus spinning speed is at a premium. Commonly operate at 80-90,000 rpm. Very special manufacturing goes into bearings, and in fact these are export-controlled technologies.
 - iii) Note that fan is ineffective if molecule collisions are more common than fan/molecule collisions; thus need a mean-free path that is longer than the spacing between rotor/stator, ie pressure below 1mbar at least. Turbo pumps thus need to be “backed” by a displacement pump that can lower pressure to point where turbo can begin pumping
 - iv) One drawback is that pumping of small molecules (H_2 , He) is very inefficient
 - v) Pros: clean, quiet, very high vacuum, little maintenance
 - vi) Cons: quite expensive (~\$5k), somewhat fragile
- b) Drag/hybrid pumps.

- i) Similar in principle, using a rotating disk instead of fan blade. Operate at somewhat higher pressure, and with greater pumping speed, so really optimized for systems with high gas loads (vacuum lines, etc). No real advantage in instrumentation.
- c) Diffusion pumps.
 - i) Work by boiling a low-vapor pressure liquid, and shooting the gas out through small jets at very high velocity (supersonic). Oil vapor jets transfer momentum to gas molecules, to help them move out of pump.
 - ii) Called ‘diffusion pump’ because of original observation that gas cannot diffuse backwards against jet. More aptly called a “gas-jet pump”.
 - iii) Originally built using Hg as liquid, now commonly use hydrocarbon oil or silicone oil.
 - iv) Pros: cheap, no moving parts, very durable, high speed for all molecules
 - v) Cons: tendency to backstream oil into vacuum chamber; for mass spectrometers measuring hydrocarbons, this is virtually fatal
- 7) Entrapment pumps
 - a) Cryopumps: basic idea is to simply provide surface area for gas molecules to adsorb onto; Typically implemented as series of disks.
 - i) Tradeoff is that larger surface area provides more space for adsorption, but greater radiative heating.
 - ii) Typically cooled by liquid N₂ or He
 - b) Ion pumps
 - i) Cloud of electrons is contained inside a tube; when gas diffuses in it becomes ionized, and then accelerated out the end into a titanium plate where it becomes embedded and trapped.
 - ii) Can reach extremely low ultimate vacuum (<10⁻¹¹ mbar), but pumping speed quite slow.