Vacuum Technology
PHYS 312

Techniques for producing and characterizing properties of vacuum are widely used in a variety of physics fields. The lowest achievable pressure in a laboratory environment is about 10^{-12} torr, about 15 orders of magnitude lower than atmospheric pressure (760 torr). Because of this wide range of pressures, a number of different techniques are used in different pressure ranges.

On the fundamental properties of vacuum is that the mean free path of gas atoms becomes large compared with typical laboratory scales. The mean free path is given by

$$\lambda = \frac{1}{n\pi d^2}$$

where n is the number density of atoms and d is their approximate diameter. At atmospheric pressure the average distance traveled by an atom before colliding with another atom is about 0.1 μm. As the pressure and density of the gas is reduced the mean free path increases and reaches about 10 cm at 10^{-3} torr. For lower pressures the atoms travel in straight lines and collide only with the walls of the apparatus. As a result, collective motion effects, such as viscosity, sound waves, diffusion, and convection disappear. The transport of atoms through the system is governed by simple ballistic motion. However, when atoms collide with a wall, they typically stick for a short time and emerge in a random direction.

1. Pumping Speed

One of the critical parameters in vacuum system operation is the pumping speed, that is the rate at which the atoms flow from the regions of high pressure (concentration) to regions of low pressure (concentration). The pumping speed can be calculated by averaging over different paths of molecular motion. For example, the flux of atoms out of a hole with an area A is given by

$$\Phi = \frac{n\bar{v}A}{4}$$

where $\bar{v}$ is the average thermal velocity. If a box with a volume V is being evacuated through the hole, the number of atoms in the box will decrease exponentially

$$N = N_0 e^{-\frac{\bar{v}A}{4V}t} = N_0 e^{-\frac{S}{V}t}$$

Here $S = \bar{v}A/4$ is the pumping speed of the hole, usually measured in liters/second. In practice, one has to use a tube to connect the system to a vacuum pump. This slows down the pumping process because when atoms hit the walls of the tube, they are equally likely to bounce in any direction. A calculation (see Kittel, for example) gives the following equation for the pumping speed of a tube

$$S = \sqrt{\frac{\pi RT}{18M}}\frac{d^3}{L}$$

where d is the diameter, L is the length of the tube, and M is the molar mass of the gas and T is the temperature. Numerically, for a 1 m long tube with a diameter of 1 cm the pumping speed is about 0.1 liters/sec. With this pumping speed it would take about 30 minutes to pump out a 10 liter volume by 6 orders of magnitude in pressure. At low pressures, the atoms are not pushed by pressure from other atoms into the regions of lower pressure but have to find their way by random walk. Since the pumping speed increases as the third power of the tube diameter, vacuum systems typically use large diameter tubes.

2. Surface Adsorption

Another important aspect of vacuum system operation is the large effect played by atoms and molecules adsorbed on surfaces. Most surfaces exposed to atmosphere for a long time have several mono-layers of water adsorbed on the surface. In addition, gases like He and H_2 can often diffuse deep into the material and have to slowly diffuse out under vacuum. For example, if one mono-layer of molecules with typical intermolecular spacing of 3 Å is desorbed into a volume of 10 liters, the pressure would increase by about 10^{-2} torr. Thus, to achieve vacuum levels of 10^{-3} torr and below it is necessary to pump out all molecules adsorbed onto and diffused into the surfaces. The rate of atoms desorbing from the surface can be described by a simple thermal excitation process

$$R_s = R_0 e^{-E_a / kT}$$

where R_0 is the vibration frequency of the atom bound to the surface, about 10^{12} $\sec^{-1}$ The energy of adsorption on the surface E_a is usually much larger than the thermal energy, so it can take a long time for the atom to come off the surface. The rate of desorbtion is exponentially sensitive to temperature, for this reason vacuum systems are often baked out at high temperature to help pump out atoms that would otherwise come off the surface during the experiment.

To reduce the effects of adsorption and permeation of atoms into walls, vacuum chambers are built from metal and/or glass. To achieve low pressures it is important to maintain the surfaces clean. Plastics, glue, tape, etc cannot be used in vacuum systems. Even finger grease can significantly increase pump-out times. Vacuum chambers are usually sealed using special rubber o-rings. But for ultra-high vacuum operation only metal seals can be used.

3. Vacuum Pump Technology

There are several different vacuum pumping techniques used in different pressure ranges. Most systems use more than one pump.

a) Roughing pumps (atmosphere to 10^{-3} torr)

These pumps are used to initially pump out the system from atmospheric pressure

Mechanical (Oil) pump

This is the oldest type of vacuum pump. The basic idea is to mechanically compress the gas (as in a cylinder with a piston) and eject it into the atmosphere. The pump actually uses rotating pistons and oil is used to provide a vacuum seal. The lowest achievable pressure is about 10^{-3} torr. The main limitation of this pumping technology is that oil vapors tend to slowly contaminate the surfaces of the vacuum system.

Diaphragm Pump

At the name suggests the pump uses a rubber diaphragm to compress the gas. Several stages are often necessary to achieve sufficient compression. These pumps are oil free but relatively slow and can only achieve pressures of about 0.1 torr.

Scroll pump

These pumps use a rubber hose squeezed by rotating rollers that push the gas out. This is fairly new technology that is oil free, and fast, but relatively unreliable. The lowest pressure is about 10^{-2} torr.

Cryo-Sorption pumps

These pumps do not compress and eject the gas, but absorb it inside the pump. They typically use charcoal or similar porous material with a very high surface area. When the charcoal is cooled with LN_2 most gases stick to its surface. This pump is fast, clean, and can achieve low pressures, but has a limited pumping capacity before it has to be regenerated by warming up the charcoal.

b) High Vacuum pumps (10^{-3} torr to 10^{-8} torr)

Diffusion pumps

These pumps use a jet of oil to push the gas and compress it. Hot and heavy oil molecules hit gas atoms and push them out. The effect is similar to the downward air drift created in the shower that results in the shower curtain being sucked in. Diffusion pumps compress the gas to about 10^{-3} torr and have to be backed up with a roughing pump. Diffusion pumps are fast and cheap, but they cause oil contamination especially if accidentally exposed to atmospheric pressure. The minimum pressure is about 10^{-8} torr.

Turbo-pumps

These pumps are basically super fans that push the gas with fast-moving blades. To achieve efficient operation the fan blades have to move close to the thermal speed of atoms, at several hundred meters/sec. Turbo-pumps have several hundred blades and rotate at about 70000 revolutions per minute. Modern turbo-pumps can withstand accidental exposure to atmospheric pressure. The minimum pressure is about 10^{-9} torr.

Cryo-pumps

High-vacuum cryo-pumps use a He refrigerator to cool charcoal or similar material to about 15 K, at which point most gases are frozen on the surface and He is trapped by surface adsorption. The minimum pressure is about 10^{-8} torr. Cryo-pumps do not eject the gas and thus have a limited capacity.

c) Ultra-high vacuum pumps (10^{-8} to 10^{-12} torr)

Ion pumps

Ion pumps create a plasma discharge within their volume. Gas atoms entering the plasma are ionized and accelerated by a high voltage toward a Ti surface. Upon collision they eject Ti atoms which then coat all surfaces. Gas is removed by chemical reaction with Ti and by being buried under a fresh layer of Ti. Ion pumps are robust and have no moving parts. The lowest pressure is about 10^{-11} torr. Ion pumps have a low gas holding capacity and cannot be easily regenerated. They are only used at low pressures or for infrequent pump-downs.

Ti-sublimation pumps

Ti-sublimation pumps work by coating the surfaces of the vacuum system with Ti which is chemically reactive and absorbs most gases. Pressures down to 10^{-12} torr can be achieved by a combination of ion pump and Ti-sublimation pump.

4. Pressure Measurement Technology

Measurement of low pressure also requires several techniques depending on the pressure range.

a) Mechanical Pressure measurements

Dial pressure gauges

These gauges use a thin copper tube bent into a coil. The tube bends when filled with high-pressure gas. These gauges are cheap and are used mostly for pressures above atmospheric.

Capacitance Monometers

These gauges use a thin metal membrane that bends in response to pressure. The degree of bending is determined from the capacitance between the membrane and a flat surface. Capacitance monometers are fairly accurate and can be used down to about 1 Torr.

b) Gas thermal conduction

Thermocouple gauge

This gauge works by measuring the heat conductivity of the gas, which decreases with pressure. It uses a hot filament and a thermocouple to measure the temperature of the filament. These gauges are not very accurate, but often used for rough diagnostic purposes. Their pressure range is from 10 torr to 10^{-3} torr

Pirani Gauge

The Pirani gauge works on the same principle of gas thermal conductivity. It measures changes in the resistance of a heated platinum filament using a Wheatstone bridge arrangement. Pirani gauges are more accurate and work down to 10^{-5} torr.

c) Ionization Gauges

Hot Filament gauge

This gauge uses a hot filament, similar to the filament in a light bulb, to ionize gas atoms. The atoms are neutralized on another electrode. The current flowing between the electrodes is proportional to the pressure. Hot filament gauges work in the range 10^{-3} to 10^{-11} torr. However, the filament can be easily burned out if exposed to atmospheric pressure.

Cold-cathode gauges

These gauges use a low intensity plasma discharge to ionize the atoms. Ionized atoms are neutralized on the anode and the resulting current is proportional to the pressure. Cold-cathode gauges are similar to ion-pumps and have a certain self-pumping action that can lead to falsely low pressure reading. They work in the range of 10^{-3} to 10^{-10} torr and are not damaged by exposure to air.