PHYS 210
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Vacuum Technology

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. Recall that atoms are moving with thermal velocities of hundreds of meters per second. At atmospheric pressure the average distance traveled by an atom before colliding with another atom is about 10 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, diffusion, and convection disappear. The transport of atoms through the system is governed by simple ballistic motion.

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 for a long tube one obtains

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

where d is the diameter, L is the length of the tube, and M is the molar mass of the gas. The pumping speed is measured in liters/sec. If a box of volume V is pumped out through the tube, the pressure in the box will decrease as

$$p = p_0 \exp(-S\, t/V).$$

Numerically, for a 1 m long tube 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. For example, if one mono-layer of molecules with typical intermolecular spacing of 3 Å is disorbed 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. High vacuum systems are often baked at high temperature to increase the rate at which the atoms are disorbed from surfaces.

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 roting 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, similar to the Cryo-cooler that we used before. They 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 the changes in the resistance of a heated platinum filament using the 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.

5. Vacuum Deposition

One of the common uses of high vacuum is to deposit thin films of materials with desired properties. There are several techniques of thin film deposition

a) Evaporative deposition

   The desired material is heated in high vacuum until it begins to evaporate at a significant rate. Evaporated atoms travel in straight lines until they hit the substrate. This technique works the best for simple metals with relatively low melting temperatures. The material is heated using either a resistively heated element or a high intensity electron beam.

b) Sputtering

   In this technique the material is not heated but bombarded with high energy ions. The ions eject the molecules of the material which are then deposited on the substrate. Argon ions created by an RF discharge are typically used. This technique works for materials with a high melting temperature or complicated molecular composition.

c) Molecular beam epitaxy

   This technique uses molecular beams to form complicated molecular materials. Individual elements are heated in high vacuum and evaporating atoms are collimated into a narrow beam. Several beams with different materials are directed simultaneously at the substrate, where they form a film with desired chemical composition. This technology is widely used in semiconductor manufacturing.

6. Thickness measurements

Among several methods for measuring the thickness of thin films the most widely used is based on frequency changes of a mechanical oscillator. A quartz crystal oscillator (similar to the crystals used in watches) is mounted in the vacuum system near the substrate. The thin film deposited on the surface of the crystal changes the mass of the crystal and that affects its resonance frequency ($\omega = \sqrt{k/m}$). Crystal thickness monitors have sensitivity of a few Å, which is just a single atomic monolayer.