Understanding Turbomolecular Pumps

In attaining ultra-high vacuum (UHV), we use three different pumps: a rotary pump, a *turbomechanical* pump, and an ion pump. To understand our setup better, we must understand how each pump works and what limits the pressures under which they can work. In this section, I describe the second pump, often called *turbopump* for simplicity, which reduces the pressure from about 10^{-3} Torr to about 10^{-7} Torr. The basic working principle of the turbopump is similar to that of the turbine in an airplane. It consists of a stack of rotors with blades, or slots, depending on the specific pump. In between rotor disks are *stators*, fixed discs that contain the same blades, or slots, as the rotors, but oriented in the opposite direction. Figure 1 shows a lateral view of the inside of a turbopump, and figure 2 shows a rotor-stator pair.

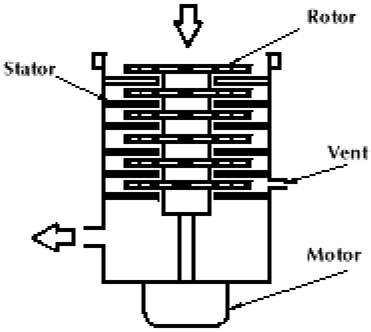


Figure 1. Lateral view of the inside of a turbopump. The *motor* makes the *rotor* spin about the axis. The *stators* are fixed disks in between rotors, and the *vent* is a hole through which we can let a gas through if we wish to bring the pump back to a higher pressure. The big arrows show the flow of pumped molecules. (Ref. 1)

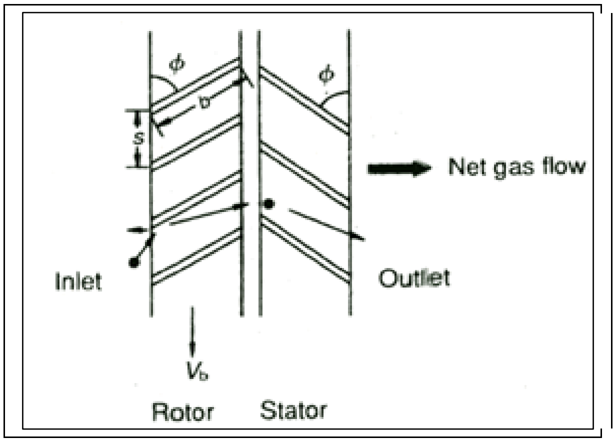


Figure 2. Rotor-stator pair. If we define Figure 1 with cylindrical coordinates, v_B (the speed of the rotor) points in the $-\mathbf{\Phi_{hat}}$ direction. (Ref. 2)

When the blades, spinning at 20000 rpm (about 2100 rad/s), hit the molecules, they impart momentum on these. Because of the angle of orientation of the blades of the rotor and the stator, the molecules are likely to move to the right in Figure 2, thus getting to the next rotor. This succession of rotor-stator pairs drives the molecules towards the exhaust, where they are collected by a backing pump. In principle, a molecule to the right of the stator in Figure 2 *could* move towards the left, but the probability of it doing so is low, because of the orientation of the blades.

At atmospheric pressure, the flow of gases is described as "viscous flow", where the molecules move in bulk and interact with each other much more significantly than they do with the walls of the container. Most turbopumps - including ours - cannot work in this regime. The reason is the force exerted by a blade on a molecule is not significant compared with the collisions between the molecules, and so the general flow remains unaffected. For this reason, a rotary pump has to remove gases before the turbopump is turned on, down to about 10^{-3} Torr At this pressure, the flow is called "molecular flow", meaning that molecules are relatively free and, to a good approximation, do not interact with each other. In this regime, the turbopump imparts momentum on each molecule independently, so they can properly go towards the other end of the pump. The text "Working with turbopump" published by Pfeiffer Vacuum gives some formulas for the estimation of time it would take the rotary pump to get down to 10^{-3} Torr These formulas are there for reference, but they should, in principle, not be necessary, since we have a pressure gauge that will tell us when to turn on the turbopump.

Once turned on, the turbopump will work for quite a long time reducing the pressure, until at some point the pressure will not go down significantly any longer. This happens between 10^{-6} and 10^{-8} Torr (which I shall nominally call 10^{-7} Torr), and it is due (mainly) to three effects:

a) Desorption of materials from the seals and bearings becomes greater at lower pressures. Desorption raises the pressure, counteracting the effect of the turbopump.

b) Leaks through the seals become more significant at lower pressures, due to the increased difference between the external and internal pressures.

c) The turbopump has reached its maximum compression ratio, defined to be the ratio of the outlet pressure to the inlet pressure.

The effect of leaks is probably quite small compared to the other factors since, in our setup, the seals are made of copper gaskets, and these are quite strong for our purposes. However, there could still be leaks, and they will only be detected if we find problems during the experiment that can be explained by the presence of leaks. The effect of desorption of material from the seals and bearings can or cannot be significant, depending on the conditions under which the pump and the chamber setup were put together. The third effect is quite important, though, and it is probably the one that limits the lower pressure the most. As I said, the compression ratio for a certain gas is defined to be:

$$\mathbf{K=P_{outlet}/P_{intake}} \quad \mathbf{[1]}$$

In the book “Vacuum Physics and Techniques” by T.A. Delchar is a formula for the maximum compression ratio:

$$\mathbf{K_{max}=\{\exp[(v_B M^{1/2})/(2k_B N_A T)^{1/2}]f_{(\phi)}\}^n} \qquad \mathbf{[2]}$$

where M is the molar mass of the gas in question, v_B is the average tangential velocity of the blades, k_B is Boltzman’s constant, N_A is Avogadro’s number, T is the operating temperature, $f_{(\phi)}$ is some function of the blade angle, and n is the total number of blades. From these equations, we can see that at a fixed speed of rotation of the blades and molecular mass, if the rotary pump always pumps down to the same pressure (so P_{outlet}

is approximately constant), then when P_{intake} is low enough that $K=K_{max}$, the pump cannot bring the pressure down anymore. This limit on the compression ratio comes from the fact that when there are not many molecules left in the chamber, the probability of a molecule coming back from the outlet to the intake is comparable to the probability of a molecule being driven towards the outlet by the pump. At higher rotational speeds, the probability of a molecule being pumped would increase and the compression ratio would be higher, but this could only be attained by changing our turbopump for a faster one. If we want to make an estimate of K_{max} for our, we need to remember that formula [2] is an estimate to begin with, since it is a local formula, at a given radius, while we are taking v_B to be simply the velocity at the average radius. Also, we do not know the function of the blade angle (we take that to be 1, for an order of magnitude estimation), and we can only estimate the radius of the rotors (by measuring the diameter of the body of the pump at the narrowest point) and the operating temperature (by touching the surface of the pump). These would be:

$$R=7.5\ \mathrm{cm}$$
$$v_B={}^{R\omega}/_{2}={}^{7.5\ \mathrm{cm}*20000\ \mathrm{rpm}}/_{2}\ ({}^{1\ \mathrm{min}}/_{60\ \mathrm{s}})({}^{2\pi}/_{\mathrm{rev}})({}^{1\ \mathrm{m}}/_{100\ \mathrm{cm}})=79\ {}^{\mathrm{m}}/_{\mathrm{s}}$$
$$M=(0.21*32\ {}^{\mathrm{g}}/_{\mathrm{mol}}+0.79*28\ {}^{\mathrm{g}}/_{\mathrm{mol}})({}^{1\ \mathrm{kg}}/_{1000\ \mathrm{g}})=0.029\ {}^{\mathrm{kg}}/_{\mathrm{mol}}$$
$$k_B=1.38*10^{-23}\ {}^{\mathrm{J}}/_{\mathrm{K}} \qquad N_A=6.022*10^{23}\ \mathrm{mol}^{-1}$$
$$T=50°\mathrm{C}=323\ \mathrm{K}$$
$$K_{max}=(1.2)^{n}$$

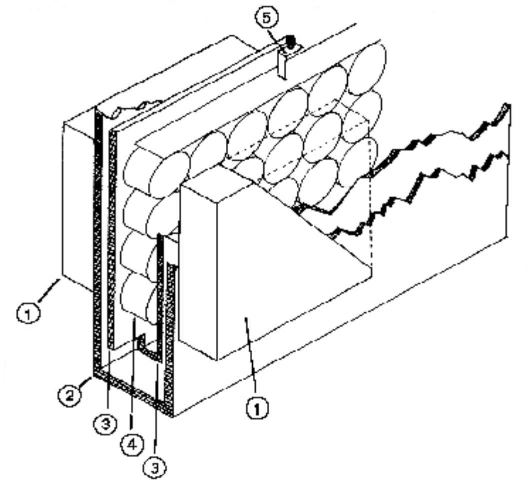
We do not know how many blades are in the pump, and the data sheets do not seem to show this, so we cannot go any further. For a reality check, we expect that the compression factor will be 10000, and for that we would need to have n=50, which is a reasonable number (it would mean 25 rotors and 25 stators).

In conclusion, we must be careful to operate the turbopump in the correct range of operation, to avoid malfunction and possible damage. Even if we wait very long for the turbopump to act, the pressure will not go below a certain value around 10^{-7} Torr. In order to bring the pressure further down to UHV, we must use the ion pump, which is explained in the next section. This more detailed study of the pumps helps us understand the risks they run, and the care we have to exercise in order to keep the equipment running properly at all times.

Theory and Operation of the Ion Pump

The ion pump works on a handful of sophisticated processes. Its function rests on residual gas molecules in the vacuum chamber becoming adsorbed or “buried” into a titanium surface within the pump. The namesake of the ion pump comes from the fact that gas molecules are ionized in order to give them a net charge. The ion pump operates at a wide range of pressures ranging from 10^{-6} Torr to 10^{-11} Torr.

The interior of the pump consists of an array of positively charged, parallel axis, cylindrical anodes. To the left and right of this array are two titanium plates (whose normal vectors point along the axes of the anodes) which are kept at a negative electric potential. Still outside of these plates lie permanent magnets which establish a magnetic field whose lines lie along the axes of the anodes. (Ref. 5)



1. Permanent magnets
2. Pump envelope
3. Titanium cathodes
4. Anode cell array
5. Positive high voltage lead (Ref. 4)

Ionization of gas molecules in the chamber occurs when free electrons, which take on helical paths about the magnetic field lines, strike the free gas particles. When a gas particle is ionized in the collision, it takes on a net positive charge and is immediately accelerated toward one of the negatively charged titanium plates. (Ref. 4) Adsorption takes place when the ion carries sufficient kinetic energy to pierce the surface of the titanium. The process of adsorption is specifically one of covalent bonding between the gas ion and the titanium surface. Once the ion is adsorbed, it remains bonded to the titanium indefinitely. (Ref. 6)

Operation of the ion pump is safe at a wide range of pressures. Above roughly 10^{-6} Torr, the pump will automatically shut itself off. This is not to say that operation in higher pressures is dangerous. However, at higher pressures, much more ionization of gas occurs, and hence there is more adsorption into the titanium. Consistent usage of the pump at pressures near 10^{-3} Torr will cause so much gas to be adsorbed that the titanium surface can become saturated, reducing the pump's effectiveness. (Ref. 5) The pump continues to reduce the pressure in the chamber until it reaches 10^{-9} to 10^{-10} Torr. At this point, mean free paths of the gas particles become large (~ 1 meter) and collisions become very infrequent. The pump will cease to lower the chamber's pressure when the effect of out-gassing (emission of contaminants from surfaces in the chamber) balances that of ionization and adsorption in the ion pump.

To place the kinds of conditions inside the UHV chamber into context, let us look at the particle densities in outer space. The particle density within our solar system is, on average, roughly 10^7 particles / m^3. (Ref. 7) That in intergalactic space is roughly 1 particle / m^3. Calculating the particle density in the chamber can be done with considerable accuracy. Without much doubt, the chamber is in thermal equilibrium with the ambient gas in the laboratory. In low pressures, the ideal gas law, $PV = NkT$ is a very reliable equation of state. Solving for N / V and using T = 300 K and P = 10^{-10}, we find that the particle density in the chamber is 3.2 * 10^{12} particles / m^3. This is still 10,000 times the density in interplanetary space, but is significantly lower than any condition found naturally on Earth, where the particle density is in the neighborhood of 10^{25} particles / m^3.

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