Solar Photovoltaics: Fundamental Technology and Applications
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Lecture - 37
Introduction to Vacuum Technology

Welcome everyone to our 8th week, second module. In the last lecture, we have started with the vacuum technology and we have seen that for a making a solar cell, while we fabricate a counter electrode, we need to make a vacuum inside the chamber. Now we learn that what is the importance of creating vacuum in the system and we have also seen to solve that parameters like mean free path and then conductance, molecular flow, etc.

In context of the vacuum technology, as we have said that this will be very, very important while talking about the vacuum gadgets subsequently. In today's lecture, we learn about the different kind of vacuum pumps, which is necessary to create this kind of vacuum.

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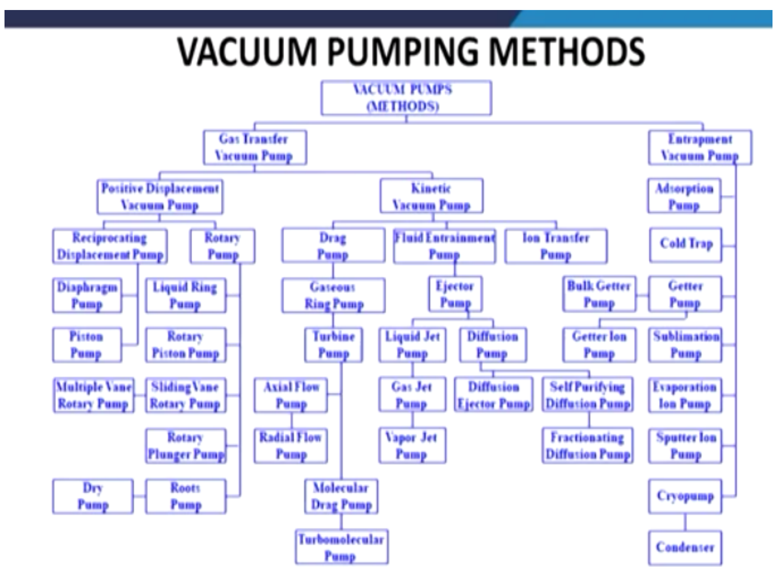

Okay, so now let us see that this chart which is showing the different kind of the vacuum pumps and probably do not be confused or do not be fearful about looking at these pumps. So there are so many different types of the pumps can exist depending upon their mechanisms, depending upon how many phases they create, etc., etc., and just look at it. Like all the vacuum pumps can be broadly classified as a gas transfer vacuum pump and the entrapment vacuum pump.

Now this gas transfer vacuum pump, they can be positive displacement that come pump or kinetic vacuum pump. Now this positive displacement vacuum pump, they can be also the reciprocating displacement pump and rotary pump. Now the reciprocating displacement pump, they are further classified as diaphragm pump and piston pump and the rotary pump, there are liquid ring pump, rotary piston pump, then sliding vane rotary pump, rotary plunger pump and roots pump.

And also there dry pump is there and also they are like multiple vane rotary pump is there. Now this kinetic vacuum pump, they can be drag pump, fluid entrainment pump, ion transfer pump. Drag pump it will be a gaseous ring pump or turbine pump, axial flow pump, radial flow pump, molecular drag pump, or turbo molecular pump. Similarly, fluid entrainment pump, they can be ejector pump which can be classified as a liquid jet pump or diffuse hand pump.

Now liquid jet pump can be gas jet pump or vapor jet pump and diffusion pump that can be diffusion ejector pump or self purifying diffusion pump and then there are fractionating diffusion pump okay. So the entrainment vacuum pump that can be in an adsorbent based pump with a cold trap pump and then getter pump, sublimation pump, evaporation ion pump, sputter ion pump, cryo pump and condenser pump.

So these are all like you know different varieties of the pump, but mostly important what I will discuss there are three different varieties, which is used extensively in material science and in different industry. One is this positive-displacement pump. Now as a positive displacement pump we will learn about the rotary pump and then for a kinetic vacuum pump, we will learn about this turbo molecular pump and we will learn about some entrapment vacuum pump.

So this rotary pump which we sometimes also call as a rough pump like that creates 10 to the power -2 to 10 to the power -3 millibar pressure whereas the turbo pump that can go through to high vacuum like 10 to the power -7 millibar, whereas this entrapment pump that can go even 2 more high vacuum like 10 to the power -9 or 10 to the power -10, or 10 to the power -11, something like that. So these 3 different kinds of pump, we will discuss in our lecture.

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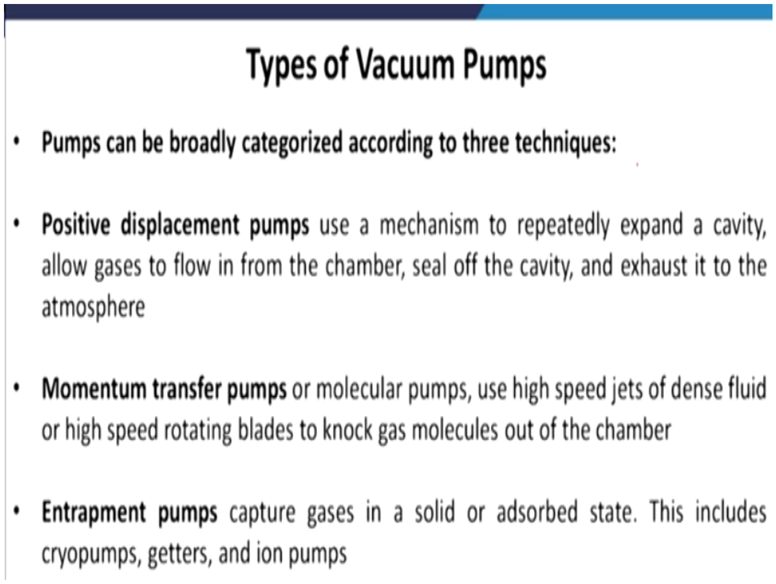

Now they can be broadly, the pumps can be broadly classified according to 3 techniques, one is the positive displacement pumps. They use a mechanism to repeatedly expand the cavity, allows gas to flow in from the chamber, seal up the cavity and exhaust this to the atmosphere. So first this positive displacement pump, they first expand the cavity, allow the gas molecule to enter inside the cavity, then they seal up the cavity and then exhaust it to the atmosphere.

Momentum transfer pump or molecular pumps, they use high-speed jets of dense fluid or high speed rotating blades to knock gas molecule out of the chamber and then entrapment pump, they capture gases in a solid or absorbed state. This includes cryo pumps, getters and ion pumps.

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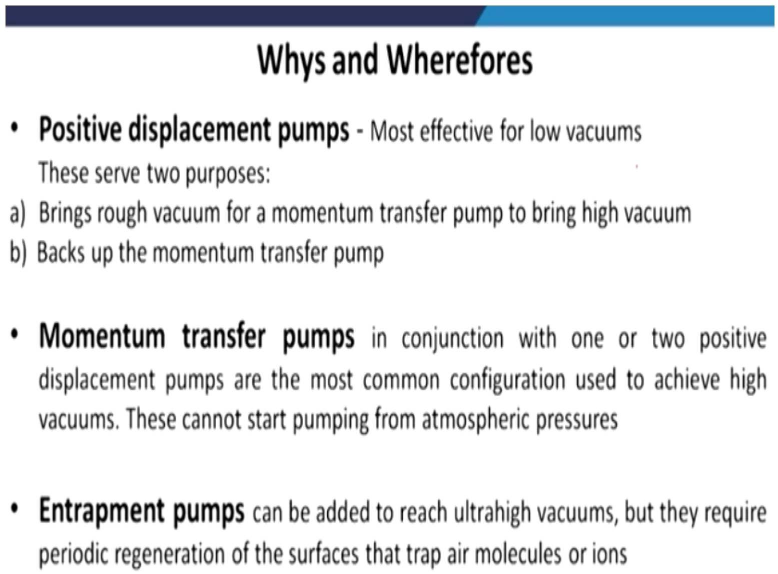

Now the positive displacement pump, the most effective for low vacuums. This have 2 purpose, first they bring rough vacuum for a momentum transfer pump to bring high vacuum, backs up the momentum transfer pump okay. So basically let us say, I wanted to create 10 to the power -6 millibar. So I cannot create from the atmosphere directly 10 to the power -6 millibar. So what I have to do, I have to first make the atmospheric pressure to 10 to the power -2 millibar.

That is the rough vacuum and from there we have to go to the high vacuum 10 to the power -6 millibar by using a turbo molecular pump or using a momentum transfer pump. So to work with the momentum transfer pump, we need a rough pump and that is done by this positive displacement pump. Momentum transfer pumps in conjunction with one or two positive displacement pumps are the most common configuration used to achieve high vacuums.

This cannot start pumping from atmosphere and entrapment pumps can be added to reach ultra-high vacuum, but they require periodic regeneration of the surface that trap the air molecules or ions and that consequently increase the cost of this kind of pump okay.

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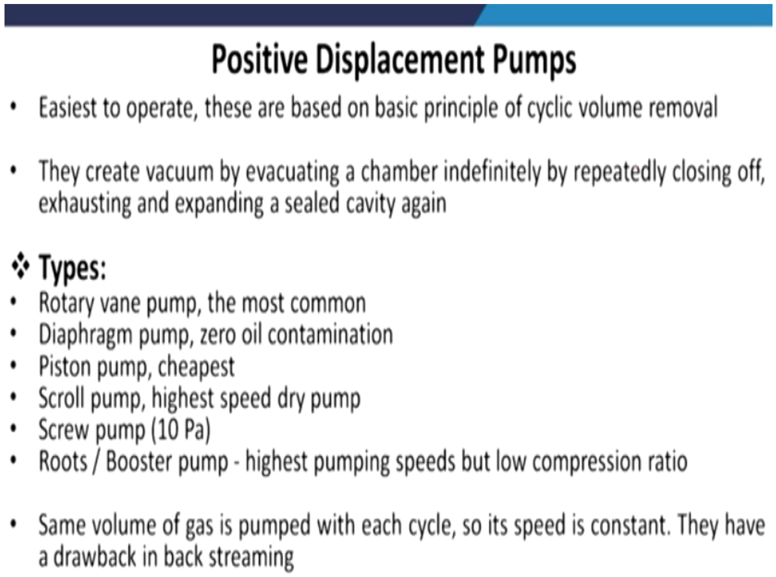

So the positive displacement pump, they are the easiest to operate. These are based on basic principle of cyclic volume removal. They create vacuum by evacuating a chamber indefinitely by repeatedly closing up exhausting and expanding a sealed cavity region. So basically it is like a balloon. So it first expands, allows the gas molecule enters inside, seals up the cavity and then exhaust to the atmosphere and then this whole process repeats again and again.

Now the types of the positive displacement pump, they can be the rotary vane pump which is most common, a diaphragm pump that is also called the zero oil contamination pump, piston pump which is the best, scroll pump, high speed type dry pump, screw pump which creates 10 Pascal, route pump or booster pump, highest pumping speed but low compression ratio. So these are the different types of the positive displacement pump, which we use in the industry and in our daily life one.

But the most commonly we use the rotary vane pump and then sometimes diaphragm pumps, sometimes the scroll pump. Same volume of the gas is pumped with each cycle. So its speed is constant. They have a drawback in black streaming. So what happens like you know while pumping, there is a possibility that is half the gas molecule can go to the backward direction. So back streaming is one of the problems in the positive displacement pump.

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Momentum Transfer Pump

Here gas molecules are accelerated from the vacuum side to the exhaust side (which is usually maintained at a reduced pressure by a positive displacement pump)

Momentum transfer pumping is only possible below pressures of about 0.1 kPa

Molecular pumps sweep out a larger area than mechanical pumps

Two main types of molecular pumps are the **diffusion pump** and the **turbo molecular pump**

Both types of pumps blow out gas molecules that diffuse into the pump by imparting momentum to the gas molecules. Diffusion pumps blow out gas molecules with jets of oil or mercury, while turbomolecular pumps use high speed fans to push the gas

Momentum transfer pump, here gas molecules are accelerated from the vacuum site to the exhaust site, which is usually maintained at a reduced pressure by a positive displacement pump. Momentum transfer pumping is only possible below pressure of 0.1 kilopascal. Molecular pumps sweeps out a larger area than mechanical pumps. So basically the molecular pumps will work only with a mechanical pumps or rough pump.

So the one end should be a high pressure, another end should be a low pressure okay. Two main types of molecular pumps are the diffusion pump that we will discuss and the turbo molecular pump. Both types of the pump below, they blow out the gas molecules that diffuse into the pump by imparting momentum to the gas molecules. Diffusion pump blows out gas molecules with jets of oil or mercury while turbo molecular pumps use high speed fans to push out the gas.

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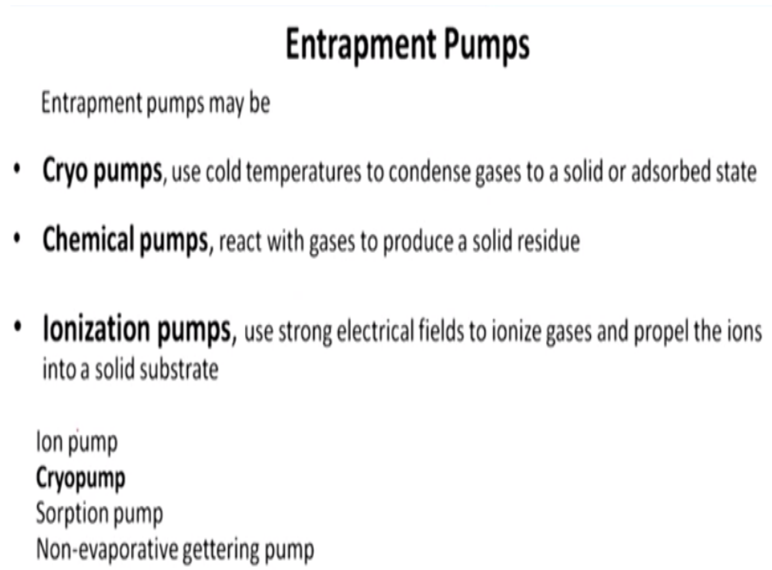

Finally, the entrapment pumps, they adsorb the gas molecules or the ions. They can be cryo pumps which used cold temperatures to condense gasses to a solid or adsorbed state. Chemical pumps they react with gasses to produce a solid residue. Ionization pump use strong electrical field to ionize gases and propel the ions into a solid substrate. So both these ion pumps, cryo pumps and adsorption pump or even the non-evaporative gettering pump, the fourth one.

They all required the regeneration of the surface because here the ions or the molecules get absorbed on the surface. So after some time, we need to regenerate the surface and that is why this process is very, very complicated. An entrapment pump is used to create a very ultra-high vacuum in conjunction with a molecular pump along with a turbo pump okay. So the first example is a rotary vane pump which is a positive displacement pump.

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Rotary Vane Pump

- A rotary vane vacuum pump is an oil-sealed rotary displacement pump. The pumping system consists of a housing (1), an eccentrically installed rotor (2), vanes that move radially under spring force (3) and the inlet and outlet (4).
- The outlet valve is oil-sealed. The inlet valve is designed as a vacuum safety valve that is always open during operation. The working chamber (5) is located inside the housing. Rotor and vanes divide the working chamber into two separate spaces having variable volumes.
- As the rotor turns, gas flows into the enlarging suction chamber until it is sealed off by the second vane. The enclosed gas is compressed until the outlet valve opens against atmospheric pressure. In the case of gas ballast operation, a hole to the outside is opened, which empties into the sealed suction chamber on the front side.
- The Rotor moves with the help of a motor attached to it.

A rotary vane pump is an oil sealed positive displacement pump. The pumping system consists of a housing and eccentrically installed rotor, vanes that move radially under spring force and the inlet and outlet.

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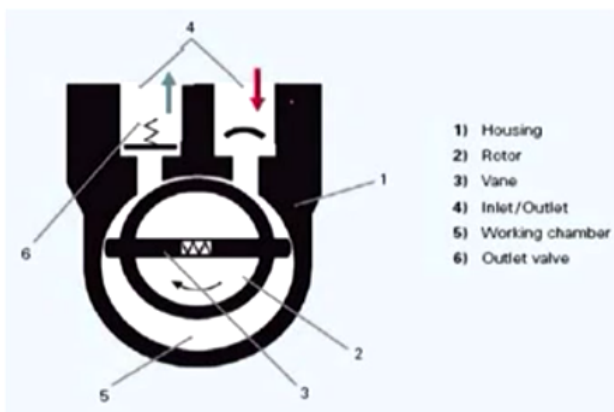
Rotary Vane Pump



Animation video of the working of a Rotary (vane) pump
http://www.youtube.com/watch?v=AFHogF-9eGA&hd=1

So basically if we go to the next picture, you can see that. So there is this black color housing. This one the housing all right and then number 2 is the rotor, so this is the rotor so which rotates and then there is a vane which separates the rotor into two different chamber and then there are this inlet and the outlet and then working chamber. This is the working chamber where the gas molecules enter. Now the sixth is the outer valve. So this is the outer valve.

So basically there are six different parts. One is this body the housing, another is this rotor another is this vane, which is eccentrically placed and then this chamber inlet and outlet and this exhaust systems okay. So we have this housing, eccentrically installed rotor, vanes that moves radially under the spring force and the inlet and outlet. So the outlet valve is oil sealed. The inlet valve is designed as a vacuum safety valve, that is always open during operation.

The working chamber is located inside the housing. Rotor and vane divides the working chamber into two separate space having variable volumes. As the rotor turns, gas flows into the enlarging suction chamber until it is sealed up by the second vane. The enclosed gas is compressed until the outer valve opens against atmospheric pressure. In the case of the gas ballast operation a hole to the outside is opened, which empties into the sealed suction chamber on the front side.

The rotor moves with the help of a motor attached to it. So as you can look in this figure, this working chamber, the white shaded region that is divided into two parts by this rotor and this vane and this rotor is eccentrically placed. So that means the separation is not symmetrical. So what will happen when this rotates, so some of the gas molecule enters here. So it gets compressed and then expanded and then again it gets leaks out.

So this process goes again and again. So basically this is expanding the cavity by successive compression and expansion and that is the process and it take out the gas molecule from the chamber and then it reduce the gas molecule. So there is an animation video of the rotary pump which we will show you in the next slide. The second pump is a diaphragm pump.

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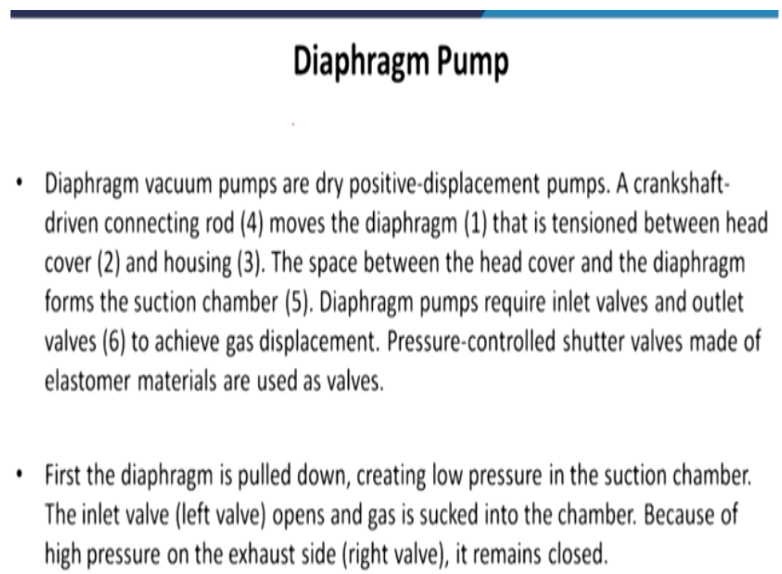

Diaphragm vacuum pumps are dry positive-displacement pumps. A crankshaft driven connecting rod most the diaphragm that is tensioned between head cover and housing. The space between the head cover and the diaphragm forms the suction chamber. Diaphragm pumps require inlet valves and outlet valves to achieve gas displacement. Pressure control shutter valves made up elastomeric material, they are used as valves.

So in this case both the inlet valves and the outlet valves, they are used to achieve the gas displacement. First the diaphragm is pulled down creating low pressure in the suction chamber, the inlet the left valve opens and the gas is sucked inside the chamber, because of the high pressure on the exhaust site right valve, it remains closed.

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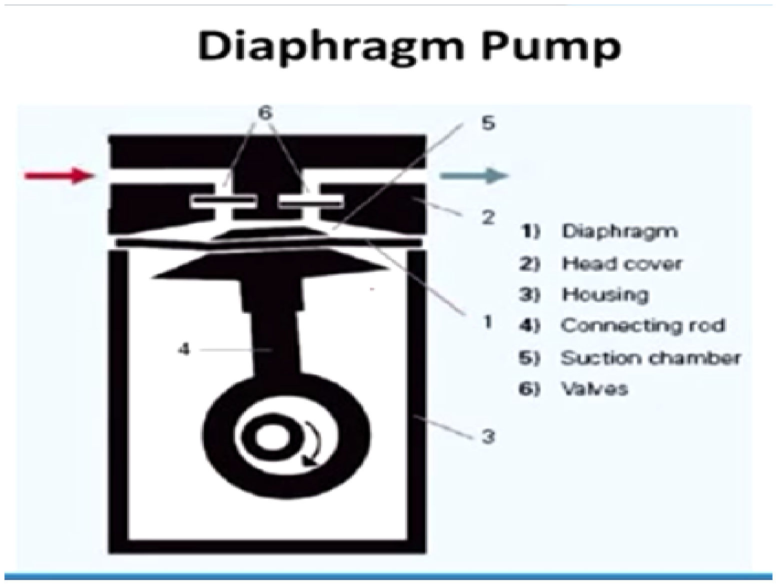

So this is a picture of a diaphragm pump. So here this is the diaphragm which can compress. If it compresses so what will happen, you can see there is a head cover at this place and 3 is the housing and this is the housing and this is a connecting rod which is a crankshaft rod and 5 is the suction chamber and the 6 is the valves. As the diaphragm get compressed, so basically what happens the connecting rod, they get a force.

So that rotates this crankshaft and what will happen, so the volume of the gas molecule inside the chamber that get compressed and one of the valves remain closed, the outer valve, because the pressure is high here and the another valve is open always, so that the gas molecule can pass through them.

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Scroll Pump

- A scroll pump (dry pump) is a device for compressing air or refrigerant
- It uses two interleaved scrolls to pump where vane geometry may be involute, archimedean spiral, or hybrid curves
- Often, one of the scrolls is fixed, while the other orbits eccentrically without rotating, thereby trapping and pumping air between the scrolls
- Another configuration consists of co-rotating the scrolls, in synchronous motion, but with offset centers of rotation. The relative motion is the same as if one were orbiting

And then the scroll pump, a scroll pump or a dry pump is a device for compressing air or refrigerant. It used two interleaved scrolls to pump where vane geometry may be involute, archimedean spiral or hybrid curves. So basically it used two interleaved scrolls which can be an archimedean spirals or can be a hybrid curves. Often one of the scroll is fixed while other orbits eccentrically without rotating, thereby trapping and pumping air between the scrolls.

Another configuration consists of correlating the scrolls in synchronous motion, but with offset centers of rotation. The relative motion is the same as if one were orbiting.

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Scroll Pump

Video of the working of Edwards Scroll Vacuum Pump
http://www.youtube.com/watch?v=s3xulCRrjos

So you can see here, so there are two scrolls are there. So there are two springs and this is kind of like an archimedean spring. So one is fixed and another rotates. So this is the overall picture of this scroll pump. If I open it, we can see this kind of spiral structure inside it. So one of the spiral structure is fixed whether another rotates. Now when the gas molecule enters, so they get trapped inside this white chambers and since there is a variable volume here.

And that variable volume because of the relative motion of the one of the scroll, it correspond to the another scroll, so the pressure difference is created. To understand it better, we are showing you next a working video of a scroll pump.

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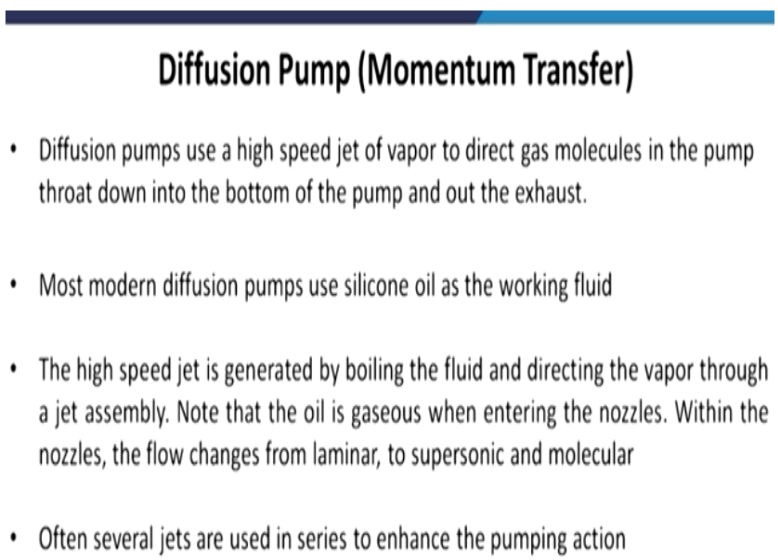

The second class of the pump was the diffusion pump which is a momentum transfer pump, which is used to create the high vacuum diffusion pump use a high-speed jet of vapour to direct gas molecules in the pump, throw it down into the bottom of the pump and out the exhaust. Most modern diffusion pump use silicon oil as the working fluid. The high speed jet is generated by boiling the fluid and directing the vapor through a jet assembly.

Note that the oil is gaseous when entering the nozzles. Within the nozzles the flow changes from the laminar to supersonic and molecular and several jets are used in series to enhance the pumping action.

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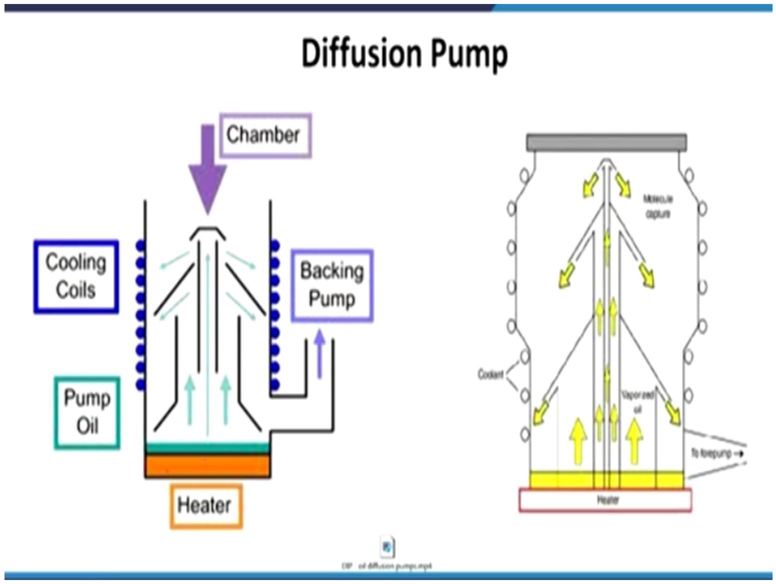

So in a diffusion pump as you can see that there are pumping oil we use and there is a heater is there. So this oil is usually a saturated hydrocarbon oil. For example, nowadays we use silicon oil. Now if we heat this oil, so there will be a vapor of this oil. So now there are this nozzles, which have been connected here and now whenever the vapor of the gas molecule enters through here this can comes out using these nozzles okay and then there are these cooling coils which is surrounding the chamber.

And then there are the backing pumps, which takes it out now whatever the gas molecule which comes out from these nozzles. So basically there is a heater here so the vaporized oil passes through this cylindrical structure and then they comes out through these nozzles right and then once it comes out through there, whenever it is goes up the top portion, as it comes down then it becomes cools down and whatever it cools down, it collected as a liquid.

Whatever it is gaseous form, that is get out by using this turbo pump or this vacuum pump. Now a overall video of the whole process of the mechanism, we are showing you in the next slide.

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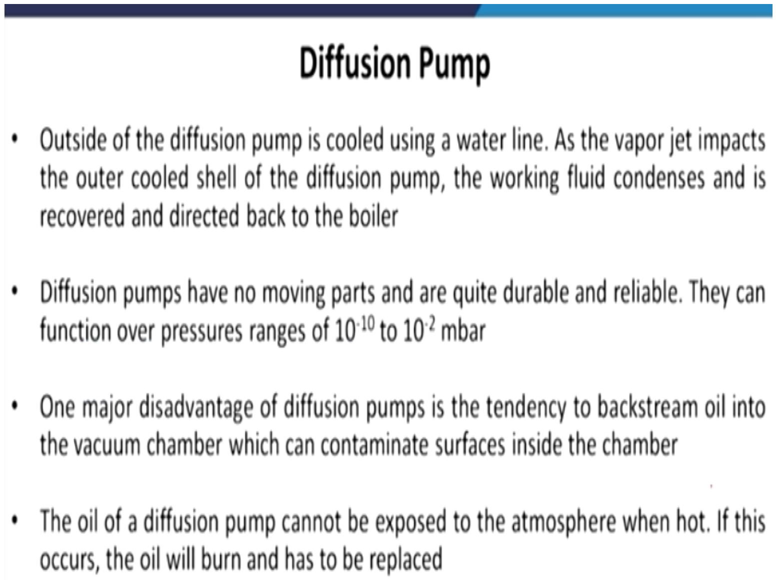

A diffusion pump outside of that is cooled using a water line. As the vapour jet impacts, the outer cooled shell of the diffusion pump, the working fluid condense and it is recovered and directed back to the boiler. Diffusion pumps have no moving parts and are quite durable and reliable. They can function over pressure range of 10 to the power -10 to 10 to the power -2 millibar. So once the roughing pump or once the rotary pump brings the pressure from the atmospheric pressure to 10 to the power -2 millibar.

Then the diffusion pump plays into action and it brings the pressure from 10 to the power -2 millibar even to 10 to the power -10 millibar. Now for this metal depositions in our as an electrode, we usually require 10 to power -7 million. So this diffusion pump is sufficient for our like you know depositions of the electrode. One major disadvantage of diffusion pump is the tendency to back stream oil into the vacuum chamber, which can contaminate surface inside the chamber.

The oil of a diffusion pump cannot be exposed to the atmosphere when hot. If this occurs, the oil will burn and has to be replaced.

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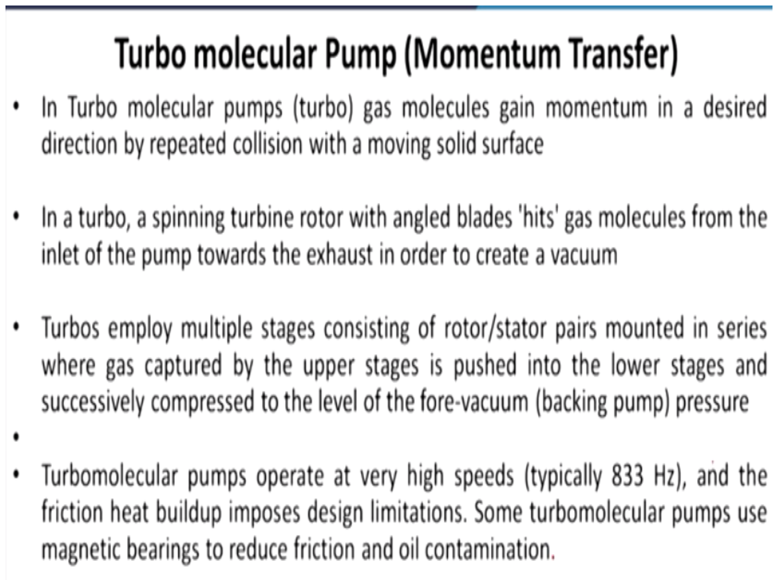

Another kind of this molecular pump or this momentum pump is the turbo molecular pump. In turbo molecular pump which is a momentum transfer pump. So in turbo molecular pump which is also called a turbo, gas molecules gain momentum in a desired direction by repeated collisions with a moving solid surface. In a turbo, a spinning turbine rotates with angled blades hits gas molecules from the inlet of the pump towards the exhaust in order to create a vacuum.

Turbos employ multiple stages consisting of rotor or stator spares mounted in series whereas gas captured by the upper stages is pushed into the lowest stage and successively compressed to the lower level of the four vacuum or the vacuum pump pressure. Turbo molecular pump operate a very high speed, typically 833 Hertz and the friction heat buildup imposed design limitations. Some turbo molecular pumps use magnetic bearings to reduce the friction and oil contaminations.

Since the blades rotate at very high speed, so that is why it can be the friction can happen and because of the friction the heat can generate and that is one of the disadvantage with this turbo molecular pump.

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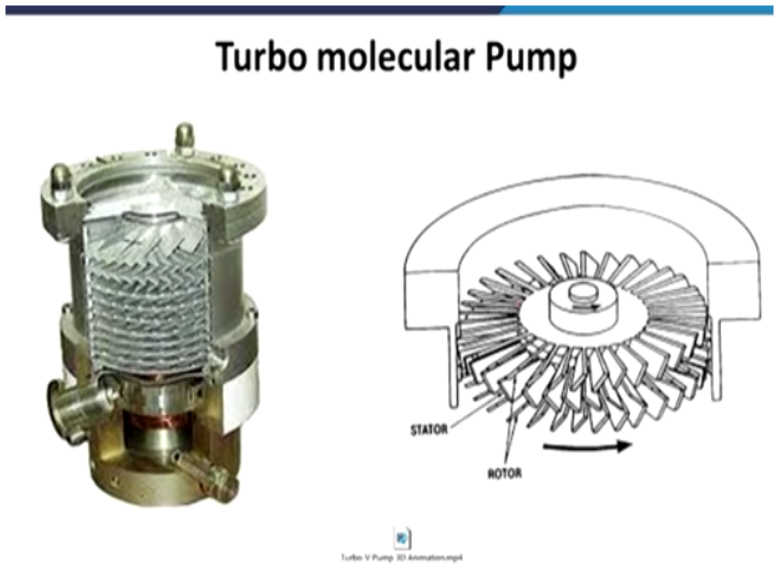

This is the typical picture of a turbo molecular pump and you can see here, there are the stator and the rotor blade which is there and which rotates and ejects the gas molecule. Now the mechanism or the animation of a working principle of a turbo molecular pump is shown in the next video.

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Ion Pump (Entrapment)

- An ion pump or sputter ion pump) is a type of vacuum pump capable of reaching up to 10^{-11} mbar (UHV)
- An ion pump ionizes gases and employs a strong electrical potential, typically 3kV to 7kV, to accelerate them into a solid electrode
- A swirling cloud of electrons produced in hollow Penning cells ionizes incoming gas atoms and molecules while they are trapped in a strong magnetic field. The swirling ions strike the chemically active cathode inducing sputter and are then pumped by chemisorption which effectively removes them from the vacuum chamber, resulting a net pumping action
- Ion pumps have no moving parts and use no oil, and are therefore clean and low-maintenance, and produce no vibration, which is an important factor when working with scanning probe microscopy

The third class of pump is the ion pump or an entrapment pump. An ion pump or a sputter ion pump is a type of vacuum pump capable of reaching up to 10 to the power -11 millibar ultra-high vacuum. You remember we said that 10 to the power -11 millibar is the atmospheric pressure in moon. So that is a very, very ultra-high vacuum and ion pump ionizes gases and employs a strong electrical potential typically 3 kilovolt to 7 kilovolt to accelerate them into a solid electrode.

A swirling cloud of electrons produced in hollow Penning cells ionize incoming gas atoms and molecules while they are trapped in a strong magnetic field. The swirling ions strike the chemically active cathode inducing sputter and are then pumped by the chemi-absortion which effectively removes them from the vacuum chamber resulting in a net pumping action.

Ion pumps have no moving parts and use no oils and are thereafter clean and low maintenance and produce no vibration which is an important factor when working with the scanning probe microscopy. So that is why in scanning probe microscopy like SEM or FM or like in an STM, we use ion pumps, because here we can go to very, very high vacuum and that kind of high vacuum is required for taking a very nice image of the nanomaterials or any kind of material structures.

So in today's lecture, we have discussed about different kind of pumps like you know, I mean positive displacement pump, rotary pump and what is the working principle of a rotary pump, then we have talked about the molecular pump, molecular diffusion pump like turbo molecular pump and the working principle of a turbo molecular pump and finally we talked about the ion pump like an entrapment pump, which actually acts on the principle of adsorption.

And since it is an adsorption, we need to regenerate surface again and again and these 3 different kinds of pump is used to create 3 different types of vacuum. Now the next question is that okay now we know how to make the vacuum, but how can I measure the vacuum. So next thing we need to learn is some measuring principle of the vacuum. So that is done by gauge. So there are two different types of gauge gain is there.

One is called the Penning gauge and another is called the Pirani gauge. So these two gauges are used to measure the reading of the vacuum. In the next lecture, we will discuss about these two different gauges and also some accessories or some of the parts, which is related to the vacuum technology. Thank you so much.