Cryogenic Engineering
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Lecture No. # 38
Vacuum Technology

Welcome to the lecture number 38 on Cryogenic Engineering under the NPTEL program.

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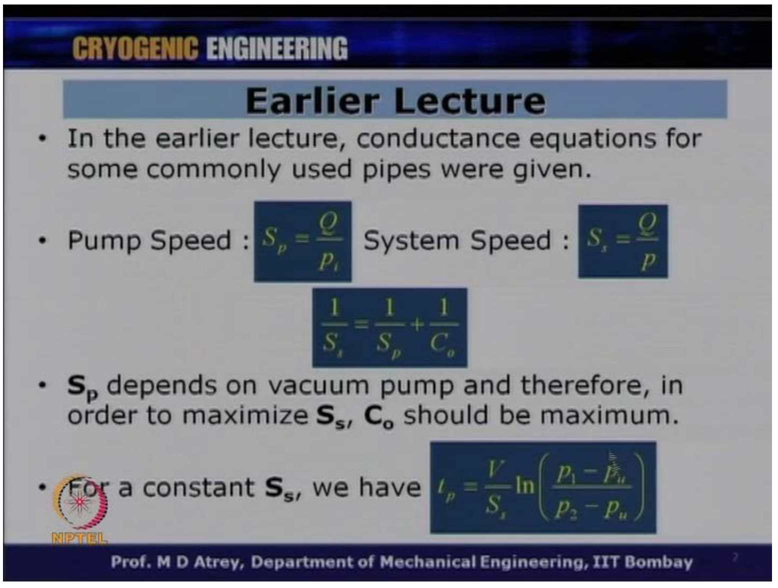

So, taking from where we left earlier, in the earlier lecture, we talked about conductance; we talk about the conductance equation that has to be considered in order to calculate the pumping speed. And, we have talked about various conductance equations for some commonly used pipes. We also know the concepts of pumping speed S p and we know the meaning of the word system speed or S s. So, the pumping speed will depend upon throughput and the pressure – the vacuum you get at the inlet of the pump; while the system speed is basically due to this conductance plus the pumping speed. And therefore, the system speed is going to be less than the pumping speed and it is equal to Q upon p, that is, what actual vacuum you get, which is going to be less than the p i value.

Now, this (Refer Slide Time: 01:18) S s and S p – the system speed and the pump speed gets related to each other and we have seen this equation 1 upon S s is equal to 1 upon S p plus 1 upon C o; where, C o is the conductance of the connecter of the vacuum pump and the system to be pumped. So, one can see from here, this is a kind of a reciprocal rule. We know that S s is going to be less than S p and less than C o. So, in order to maximize S s, we have to use such a pump, which has got a maximum C p. And, we have to use such an arrangement to get a maximum conductance, so that the value of S s is going to be as high as possible. So, one can see from here from this equation and also we know that S p depends on vacuum pump. So, what kind of pump do we use? The vacuum pump actually will decide what maximum S p it can deliver. Therefore, one of the most important variables in order to calculate system speed is S p while C o is going to be depending on arrangement or how easily one can access the system.

Can I use big diameters? Can I use minimum of curvatures? All these will decide in order to maximize conductance and that has to be done. In a good vacuum system design, the C o has to be kept as much high as possible. Normally, it will get governed by the geometrical placement or the configurations something like that. However, the most important component is S p and this S p will be governed by what kind of vacuum pump we choose. Now, this vacuum pump will be chosen based on various parameters, which are cost, time, space. All these parameters will decide what kind of vacuum pump you want to use and this is what you are going to see in this lecture.

Also, we had seen, once we got an S s value, it will also decide the time that you require to create vacuum. So, depending on the volume availability, how much volume you have to vacuum and what is the S s? So, higher the S s, less is the value of t p, that is, time to reach a particular value of p 2 from the pressure p 1 while p u is the ultimate pressure. All these things we had seen in the earlier lecture. So, this particular lecture is going to actually decide what kind of S p we can get; and therefore, what kind of vacuum pumps that one should use. So, we will understand what are different available vacuum pumps and depending on the requirement, how you choose different vacuum pumps.

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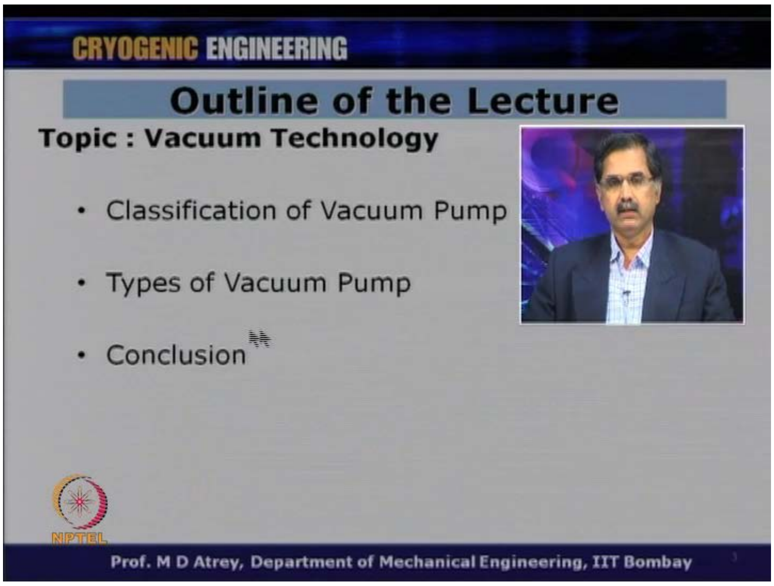

So, outline of this lecture is classification of vacuum pumps. So, vacuum pumps can be classified based on… There are various vacuum pumps available depending on their functioning; and therefore, we have to understand how do they get classified. Then, we have got various types of vacuum pump under each classification mode. And therefore, we will try to take an example of each of the working of different systems that could be normally used in these applications. And finally, we (( )) lecture of this vacuum technology topic.

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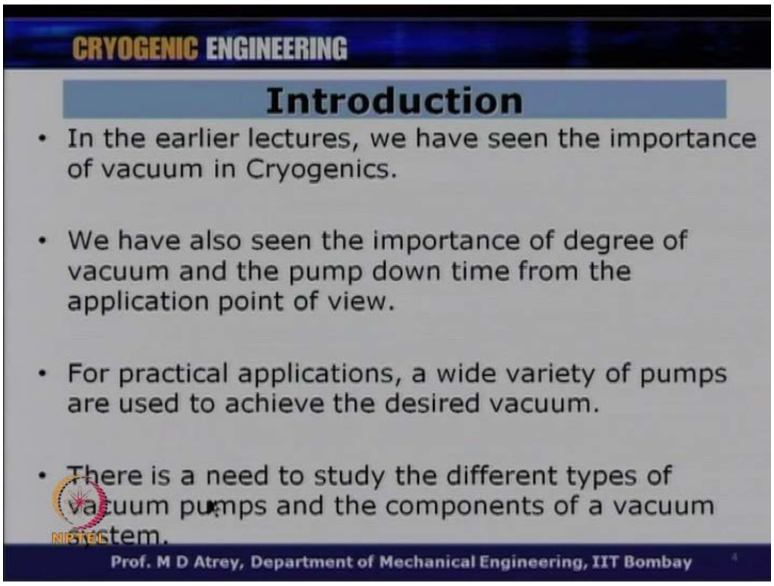

Now, introduction to this topic; in the earlier lecture, we have seen the importance of vacuum in Cryogenics. We have also seen the importance of degree of vacuum and the pump down time from the application point of view. For practical applications, a wide variety of pumps are used to achieve the desired vacuum, because there are several kinds of vacuum pumps available. And therefore, based on applications, based on availability, we have to choose right kind of pump; that this choice of pump is very important in Cryogenics. There is a need to study the different types of vacuum pumps and the components of a vacuum system. This is very important to understand what kind of vacuum pumps you select for your operation. And therefore, how do we classify vacuum (( )) How do these vacuum pumps – in what way they work? What kind of vacuum levels they can create? And, things like that. These are very important. How much time do they take to reach a particular vacuum? These are very important parameters. And, based on these parameters, the selection of vacuum pump is done.

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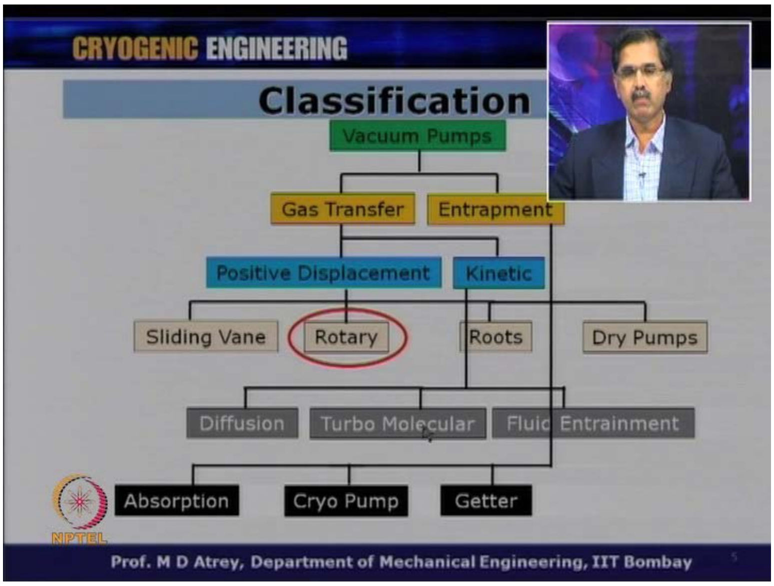

So, the classification of vacuum pump is a most important thing to understand. And, the vacuum pump is basically classified in two parts. And, that is depending on how do they transfer gas; how do they create vacuum. So, any space – you got a space over here in which you want to remove this gas and create a vacuum. So, there are various ways of how this gas will be taken out from here. And, these two ways are: one – the gas would be taken out from here and left to the atmosphere; that is one possibility; that you just take out the gas and put it back to the atmosphere basically. While, in the other case, which is an entrapment – the classification based on gas transfer is one thing in which gas is physically taken out from that place and dumped it to atmosphere. The second possibility is you do not take the gas out of it; you just trap the gas then and there only; that means, the gas will not be allowed to move now; it will be just trapped; and therefore, there will not be any motion of gas; the gas will be kind of absorbed or adsorbed over there; and therefore, gas will not be present in the working space. So, in this case, we are not transferring the gas out of that system; the gas is kept in the system itself; it is trapped over there. So, there are two major ways in which vacuum pumps can be classified.

Now, if we want to understand, there are (Refer Slide Time: 06:23) various ways of gas transfers. Gas transfer – I will do by taking this gas out from the system and dumping it outside. How can I do that thing? One is positive displacement. This is a very standard way of pumps, which delivers waters to your houses basically. You just take water from the tank and delivery it top of the house. Similarly, I will just take this gas from the system using a positive displacement; that means, I have got some positive way – some directional dependence. For example, some simple compressor – you got an inlet valve; you got an outlet valve; this gas transfer therefore will happen because of some movement of some rotor element. There will be something, which is moving; it will just displace this gas from this system to be vacuumed and dump it. It will give a direction to it and dump it to the atmosphere; it will try to dump it to atmosphere or try to dump it to the next pump, which ultimately will leave it to the atmosphere. So, positive displacement pump will basically take this gas from the system; it will create a (( )) pressure difference. Because of which pressure difference, the gas will be taken out from the system; it will be given a direction – correct direction, so that it goes from system A to system B; or, directly from system A to the atmosphere. Sometimes, it can go from system A to system B and it can go to atmosphere. So, here creating a direction, taking this gas from the system and dump it to the atmosphere – this is what we call as a positive displacement type of gas transfer.

The other one is – you have got several gas molecules over there (Refer Slide Time: 07:49) and it is not possible for you to give a direction in this case, because now, we are talking about molecular levels. In this case, what we do is, give a direction to the molecules; give a velocity to the molecule in a correct direction. So, each and every molecule is actually bombarded with other molecule maybe of gas or a fluid; it will give its kinetic energy to that particular molecule; that means, the momentum will be transferred; and therefore, the molecule will travel; and, the travel will happen, so that the gas molecule goes out of that particular system creating a vacuum over there. So, these are the two different ways of gas transfer.

And, under each type now, there are several kinds of pumps. For example, under positive displacement pumps, we have got four different characteristics of pump, which is sliding vane type of pump; we have got rotary vacuum pump; we have got roots pump; and, we have got dry pumps. So, in which all these cases, there is something which is moving. And, this moving element will move this gas from the system to be vacuumed to the atmosphere. And, we will see for example, the rotary pump and roots pump how do they work. And, in the similar fashion, all these pumps normally would work.

Now, under kinetic (Refer Slide Time: 08:58) kind of vacuum pumps… Kinetic – as I just told you that the velocity is important. Therefore, momentum is transferred from molecule to molecular level. Most of the times, kinetic kind of vacuum pumps are used for molecular levels. So, in which category, we have got a diffusion type of pump; we have got a turbo molecular pump; and, we have got a fluid entrainment pump. So, there are three different types of which we will talk about diffusion and turbo molecular pumps in detail to understand how do this function; the third category or the second category of vacuum pump, which is based on entrapment. These are all the types, which come under gas transfer pump.

The second possibility is to have a trapping of (Refer Slide Time: 09:35) these gases; that means, the gases will not be physically taken out from the system; but, that trap inside the system only. Under this category now, we have got several types of pumps again. We have got absorption phenomena, where the gas is just taken over and absorbed like sponge basically. So, the gases are retained over there only; they are just absorbed. Then, the cryo pump – here the temperature of the gas is lower to such a level that they get solidified. So, they get sort of dumped over there; they cannot move. And therefore, the vacuum gets created. Then, we have got a getter, where adsorption phenomena could be utilized; or, there is going to be chemical action – because of this, a gas molecule will cease move and some chemical may happen and they will get trapped over there. So, we have got three different ways of having to trap this gas. And, we have got a four different ways of having gas transfer by positive displacement type.

Again, we saw that under (Refer Slide Time: 10:29) the kinetic category, we have got three different pumps. So, this is an overall classification structure. One has to understand, is it a gas transfer type or entrapment type. Naturally, you cannot trap lot of gases; you cannot trap a big number of gas molecules over there. So, that is the limitation. But, a gas transfer can happen continuously. And therefore, this is the most acceptable kind of mechanism that is normally used in big systems. Entrapment is to improve the vacuum further if you go to minus 5; if you go from minus 5 to minus 6, normally, trapping would be done. Now, let us see (Refer Slide Time: 11:00) an example, how does a rotary pump work. We can see few examples like rotary pump or roots pump, diffusion pump, turbo molecular pump, cryo pump. These are the pumps, which are normally used in most of the engineering applications.

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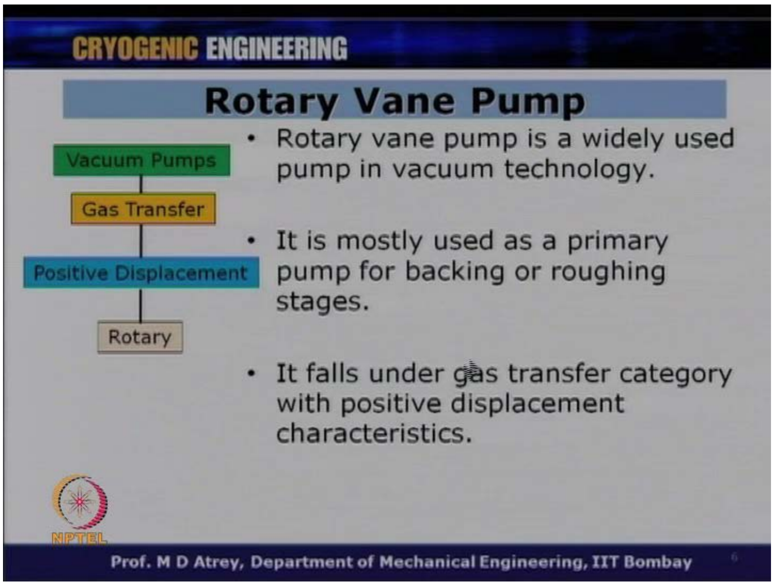

Let us see how does a rotary vane pump works. Rotary when pump is a widely used pump in vacuum technology. In most of the primary applications, rotary one, vane pumps will be used. It is mostly used as a primary pump for backing or roughing stages; that means, you can get a minus 2 or a minus 3 levels of vacuums, which are sometimes used as a backing to other pumps; or, you can get some rough vacuum of minus 2, minus 3. And then, afterwards, you can use different pumps. This is called as a backing kind of pump or you can create a rough vacuum with these pumps. And, obviously, this pump falls under the category of gas transfer and positive displacement; it is what we just talked. So, it falls under the gas transfer category with positive displacement characteristics; that means, it has got some directions from where it is taken and delivered to atmosphere.

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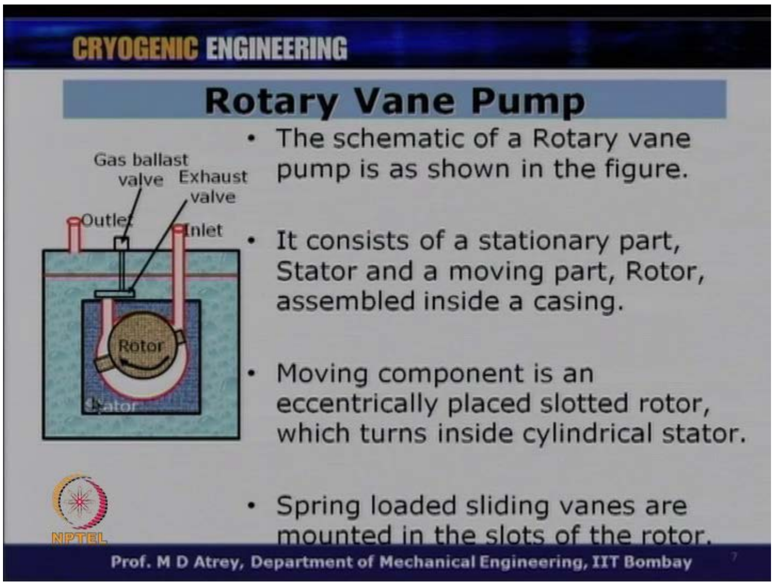

How does a rotary pump work? What is principal of working of a rotary pump? This can be shown in this schematic over here and we can understand how a rotary pump works. The schematic of a rotary vane pump is as shown in this figure. It consists of a stationary part – stator, which is what you see here. The blue colored is a stator; it does not move at all; while there is other component, which is called rotor, which moves in this stator. So, it consists of a stationary part stator and a moving part rotor assembled inside the casing. This is the casing to which we call as a stator; and, this is a rotor, which is actually attached to a motor, which will rotate this. But, you can see this rotor is little eccentrically placed with this. So, this is what constitutes a rotary pump.

Moving component (Refer Slide Time: 12:44) is an eccentrically placed slotted rotor. This rotor is not a simple rotor; it has got slot. And, through this slot, runs a vane. And, this is what we can see here. So, moving component is an eccentrically placed slotted rotor, which turns inside the cylindrical stator. So, why eccentricity? You can see that there is a sealing; there is actually some kind of seal contact between this rotor and stator. So, there is an inlet of the gas; this is exit of the gas. And, this inlet of the gas cannot go directly to the exit; it has to go through this way only. And therefore, this is kind of sealing. Therefore, for which case, you have to minimize the difference of the opening between the stator and rotor; there should not be any gap left over here. And therefore, this rotor is eccentrically placed with this stator. And, whatever gap remains there, they are actually sealed with the oil, which is present over there as lubrication also. So, there is no rubbing as such over here. It is a rolling contact between the rotor and stator.

This (Refer Slide Time: 13:44) spring loaded sliding vanes are mounted in the slots of the rotor. So, we can see the rotor over here and there are slots in this case. And, these slots, which will have a sliding vane; and, these sliding vanes are spring loaded with a spring inside, which sees to it that these vanes are always in contact with these walls. So, actually, they get rubbed on this wall. And, the springs, which are in tension sees to it that this vane is always hard pressed against this stator, because spring loaded sliding vanes are mounted in the slots of the rotors. So, this rotor will rotate; these vanes will rub against these walls; but, they will never seems to be not having contact with this stator; always they will be in the rubbing contact with this stator.

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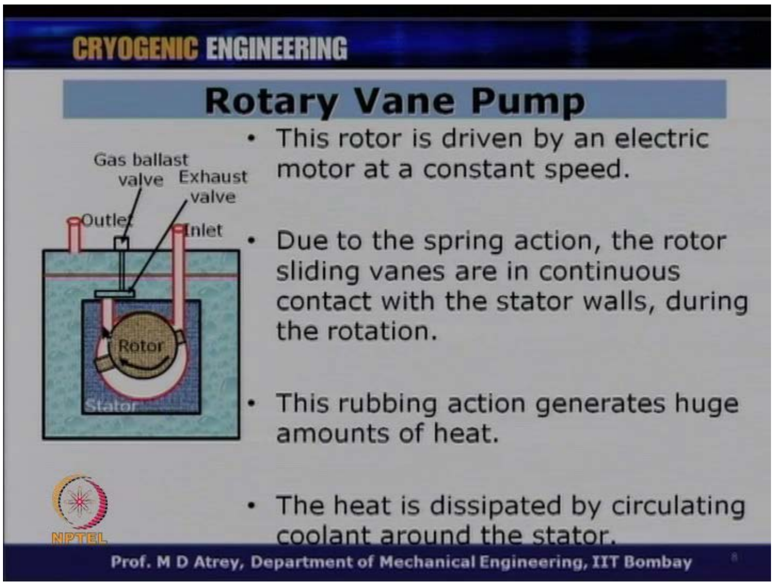

This rotor is driven by an electric motor at a constant speed. So, the rotor is driven by a motor, which rotates at a constant speed. Due to the spring action, the rotors sliding vanes are in continuous contact with the stator walls during the rotation. This is what I just told you that this spring will ensure that vane is always in contact with these walls. This rubbing action generates huge amounts of heat naturally. And therefore, we need to have some kind of cooling mechanism; the heat is dissipated by circulating coolant around the stator. You can have some oil or some kind of air or something; some cooling medium will always be there to cool the rubbing, the heat, which is generated due to rubbing.

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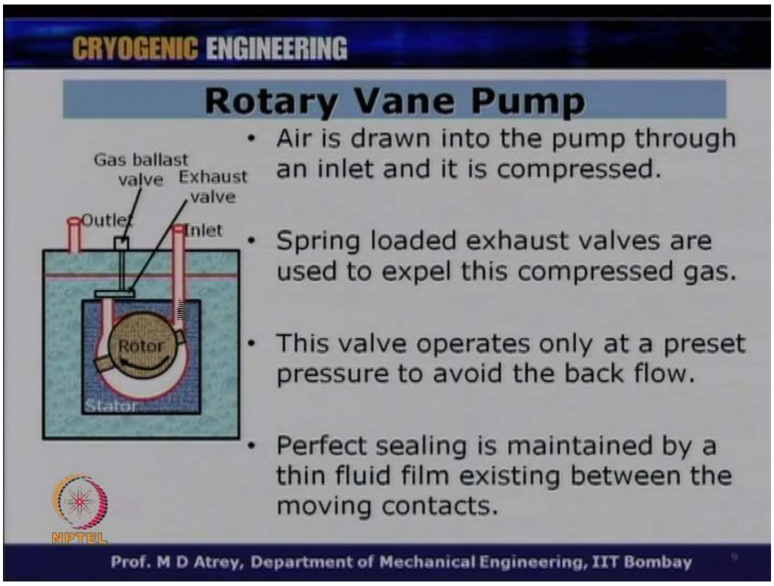

Now, how does it work? The system to be vacuumed will be connected to the inlet of this pump. And, air, which has got a working medium we can say – it is drawn over here through this inlet, because as soon as this rotor start moving, the pressure, which is going to be generated at this point is going to be less than the atmospheric pressure, which is existed over here. So, as soon as that happens, this air at atmospheric pressure will start coming inside. Why this happens? Because the rotor is moving all the time; and, this vane – see that there is no gas left inside. In fact, all the gas trapped between this space over here is basically going to be given to the outlet from here. So, as soon as the rotor starts moving, the air is drawn due to less pressure on this side; the air comes through this inlet and enters over here.

Spring loaded exhaust valves (Refer Slide Time: 16:00) are used to expel this compressed gas. So, once the gas comes, when the rotor is at this point, the air will come here; and, when they start rotating, this gas volume, which is over here now between this two vanes – it will get compressed. And, by some time, when it reaches near the exit, the pressure here will just get above the atmosphere. As soon as this pressure gets above the atmosphere, the exhaust valve, which will just open; as soon as it reaches some pressure above atmosphere, it will open and that the air will be released to the outlet. So, this sees to it that that gas comes here; it start getting compressed; just getting compress above the atmosphere, open this exhaust valve and gets delivered to the outlet to the atmosphere through this outlet opening. So, this valve operates only at a preset pressure to avoid the back flow. So, gas cannot come back. Therefore, this pressure on this side is going to be just above a predetermined value, where the exhaust valve opens and it is delivered to atmosphere.

Perfect sealing (Refer Slide Time: 16:58) is maintained by a thin fluid film existing between the moving contact. So, this is the moving contact at this point. And therefore, you have to see that there is oil over here. And, this sealing is maintained by maintaining this clearness between this rotor and stator; and, it also ensure that the gas or the air which enters over here, does not move on this said; it always comes through this; it gets compressed and then delivered to outside.

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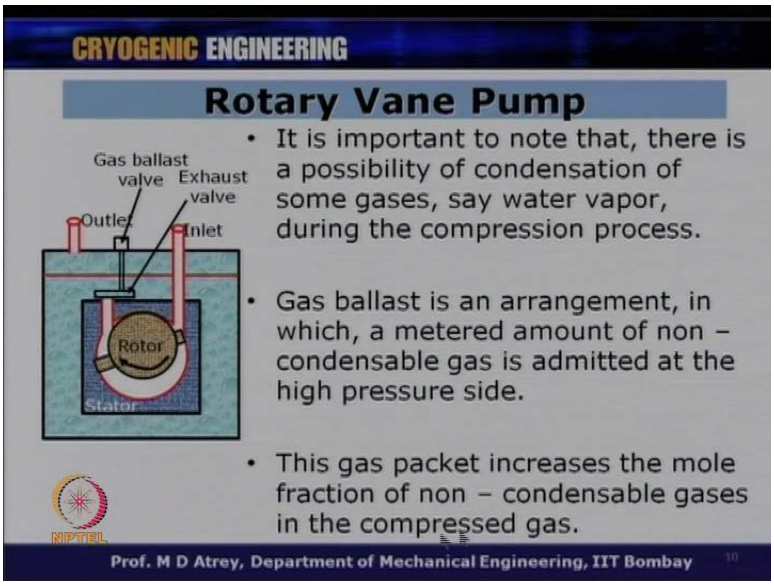

It is important to note that, there is a possibility of condensation of some gases, say water vapor, during the compression process. Now, this is very important, because air will always convey some water vapor; and, if the vapor gets, because it gets compressed, it has got a particular due point at its partially pressure. And therefore, this water can get condensed over, which is not acceptable. In the reciprocating and rotating motion, you cannot have water, which is going to get condensed at this point. And therefore, you have to ensure that such a condensation should be avoided in this case. See in order to avoid this condensation of the water vapor or any condensable matter for that case, this should be avoided over here. So, what is done for that? You have got something called as gas ballast valve.

Gas ballast (Refer Slide Time: 18:04) is an arrangement, in which a metered amount of non-condensable gas is admitted at the high pressure side. So, what we do? We admit some high pressure air from this side or non-condensable gas – you are at this point. And, because of which, this is a non-condensable gas, the partial pressure of the condensable gas, which will come down. So, please understand this. I am admitting some… Non-condensable gas is admitted at this high pressure side at this point. This gas packet increases the mole fraction of non-condensable gases in the compressed space; that means, it decreases the partial pressure of the condensable gas. Once you decrease the partial pressure of the condensable gas, the corresponding due point for that – the temperature at which it condenses will get lowered. And therefore, at this prevailing temperature, the condensation may not be possible, because the partial pressure of this condensable gas gets reduced. So, what is done to do this? We add some gas; increase the pressure of the non-condensable; and, decrease the partial pressure of condensable gases. Because of which, now, it cannot condense anymore. And then, therefore, it is delivered out in the gaseous form itself.

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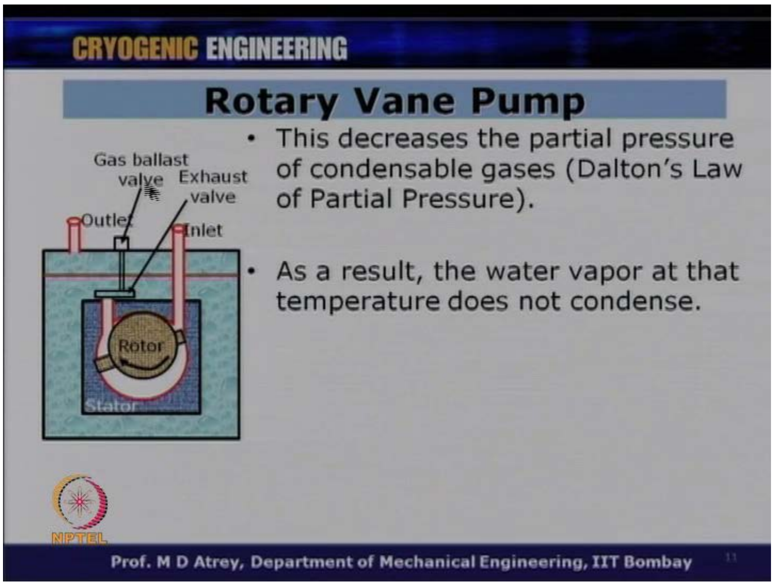

This decreases the partial pressure of the condensable gases. And therefore, as a result, the water vapor at this temperature does not condense – the very important function of the gas ballast, especially in a place, where humidity is very high. There is always a good possibility that the water vapor is there in the air. And therefore, initially for some time, when you start the rotary pump, for some time, the gas ballast valve is kept open; the air is admitted at this point. And, after some time, when the moisture in the air gets removed, the gas ballast valve can be closed; or, sometimes, it can function throughout the operation of this rotary pump.

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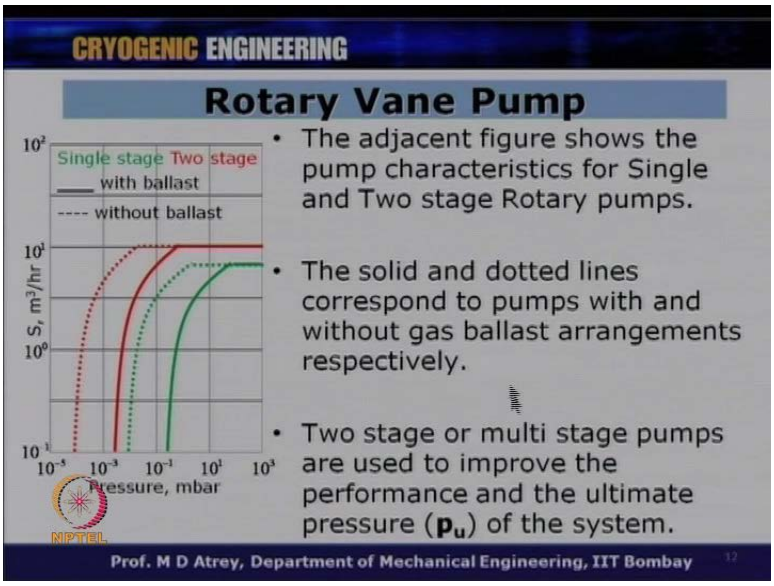

These are the characteristic of the rotary vane pump. We can see the speed versus pressure. The adjacent figure shows the pump characteristics for single and two stage rotary pumps; the solid and dotted lines corresponding to pumps. So, you can see solid line and dotted line; the solid line is with ballast. So, as soon as you got the ballast; that means, the ballast is on; you got a gas coming or the air coming from the outlet side; because the which, the capacity goes down. So, you cannot deliver low vacuum in this case, because you are adding some air deliberately from outside; while if you go without gas ballast, then you can deliver good vacuuming rate and you can come down to lower pressures also.

At the same time, such pumps can be used in two stages (Refer Slide Time: 20:35) also; that means, the outlet of the first pump will go to inlet of the second pump. In that case, the meter cube per hour; that means, vacuum speed can be increased. We have got around 10 meter cube per hour in that case possible. And also, that you can reach lower and lower pressures in this case. So, one can go for a two stage rotary vane pump; one can go for a single state rotary pump; one can have the gas ballast on continuously; in that case, one can have these characteristics; or, normally, one can start the pump keeping the gas ballast on; and, after some time, when the condensable have been taken care of, then the gas ballast can be made off; and, one can then get good vacuum. That is what is shown with without ballast.

Two stage (Refer Slide Time: 21:14) or multi stage pumps are used to improve the performance and the ultimate pressure p u of the system. So, this is the way how the rotary vane pump will work. And, this is the characteristic of the rotary vane pump with single stage and two stage arrangements or with and without gas ballast. This is what we have seen now (Refer Slide Time: 21:31). We saw the rotary pump. Let us see now the second pump, which is a roots pump. That is also a normally used, where you require high flow rates or you want to reach a lower vacuums in a very immediately; that means, less time could be taken in those cases.

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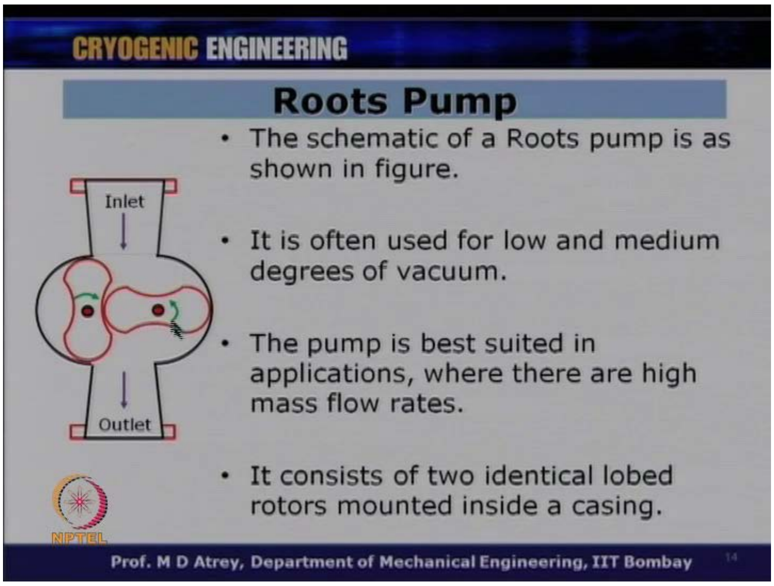

Say typical rotary roots pump would look like this. So, you have got an inlet and outlet arrangement and you have got a two lobe arrangement. This is a lobe number 1 and lobe number 2. This kind of arrangement is done in a roots pump. The schematic of roots pump in as shown in this figure. It is often used for low and medium degrees of vacuum. So, roots pumps are used at various places, but not for very high vacuum requirement. Most of the time, the roots pumps are preferred in order to reach a vacuum very fast, because the vacuuming rates here are much faster. The pump is best suited in applications, where there are high mass flow rates. So, if we want to have very high mass flow rates or you want to have a very big system to a vacuum, one can use roots pumps. Sometimes, rotary pump, rotary vane pump may not handle very high mass flow rates; or, you may have to employ two or three pumps in those cases; while, around 500 meter cube also can be handled by roots pump basically. How do they operate now? It consists of two identical lobes rotors mounted inside a casing, which you can see in this, two lobes. Actually, it has got kind of 8-shift over here. So, there are two lobes; we have got 8 kind of geometry.

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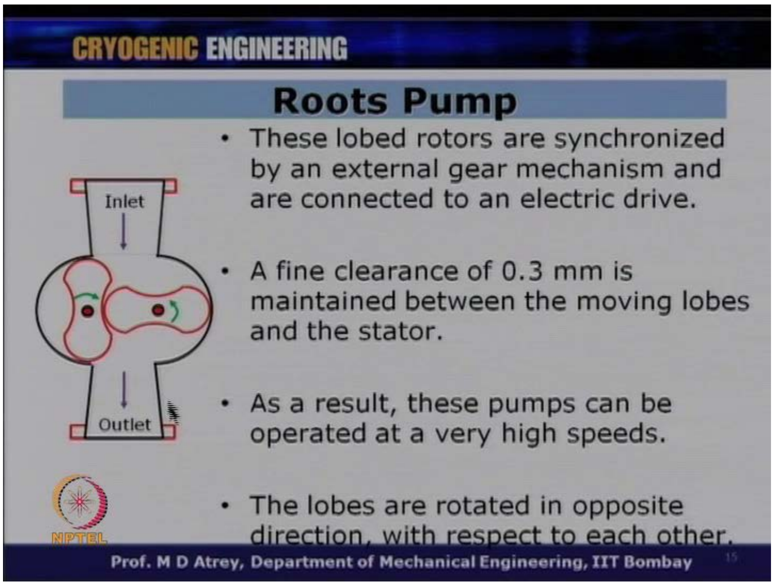

And, both these lobes are actually rotated in opposite direction. These lobed rotors are synchronized by an external gear mechanism and are connected to an electric drive. So, both of them are driven by using an electric motor. And, they are synchronized; that means, they have got a special relationship existing between their rotation. And, this synchronization is done through some external gear mechanism. A fine clearance of 0.3 millimeter is maintained between the moving lobes and the stator. You can see that there is a very fine clearance between these two. Also, you can see, there is a very fine clearance between the casing and this rotor and at this point. And therefore, the fabrication of these lobes is very important. The costs of these pumps are relatively higher, because of the fabrication cost also involved in them. The micro fabrication – that kind of thing, which is required; the high tolerance – that is need to be maintained. These are very important over here in this case. They should never touch each other basically. If this starts rubbing on each other, then it will lead to some kind of failure of the roots pump. As a result, these pumps can be operated at a very high speed.

Now, the fact that (Refer Slide Time: 23:59) there is no rubbing contact; in the earlier case, there was rubbing contact of the vane. Now, the fact that there is no rubbing contact, there will be always some clearance; they can rotate at a very high speed also. And, this high speed is responsible to have its ability to handle very high mass flow rates. So, actually, they will never basically have a rubbing contact; they can move freely. And therefore, we can operate this at very high speed. And, this is a very important characteristic of roots pump; the lobes are rotated in opposite direction with respect to each other. This is what you can see. So, basically, it will take this gas from inlet and deliver through this to the outlet; and, during which, it will get compressed. The gas here… Also, the gas can come through this also and the gas will be delivered from inlet to the outlet from the system to be vacuumed to the atmosphere.

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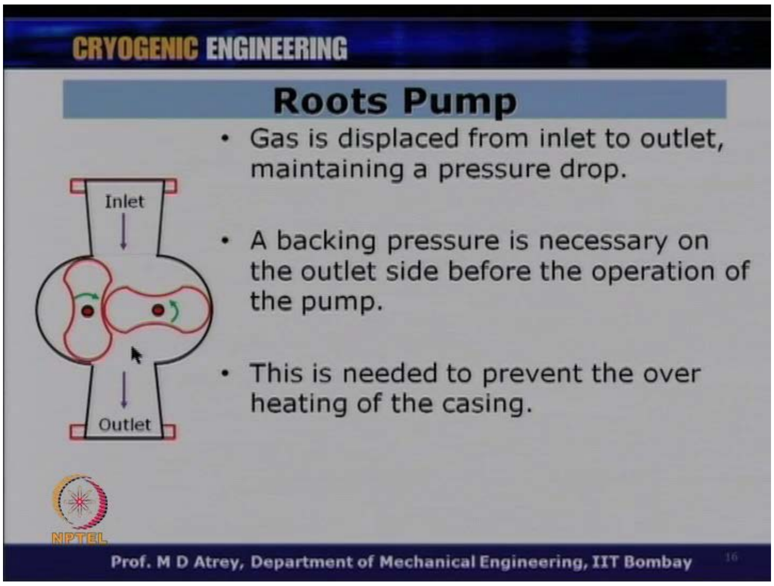

The gas is displaced from inlet to outlet, maintaining a pressure drop. So, the movement of the gas is basically going to happen, because of the pressure drop that exists across the inlet and outlet. And, gas is going to get compressed while travelling through this. And normally, the compression ratio would be of the order of 10. Sometimes, if you want to have high flow rates for example, or if you want to create low vacuum, a backing pressure is necessary on the outlet side before the operation of the pumps, so that we can create a kind of pressure difference across and these pumps can be put into operation. And then, by wished, you can really reach lower vacuums also. This is needed to prevent the overheating. Sometimes, when there is no flow occurring; when there is no delta p across, then it can create lot of heat over here; because of the motion, the gas is getting compressed, but gas is not moving. The gas will move only when the pressure difference exists across the lobes basically. So, in this case, you can have a very high heating over here. This is needed to prevent. And therefore, then the gas starts flowing; the gas also does cooling. So, it is not good to have the gas just moving over here. Gas has to transfer across here. And, during that time, it cools these lobes also. So, the viscosity of the gas also plays a very important role in creating heat in the roots pump operation.

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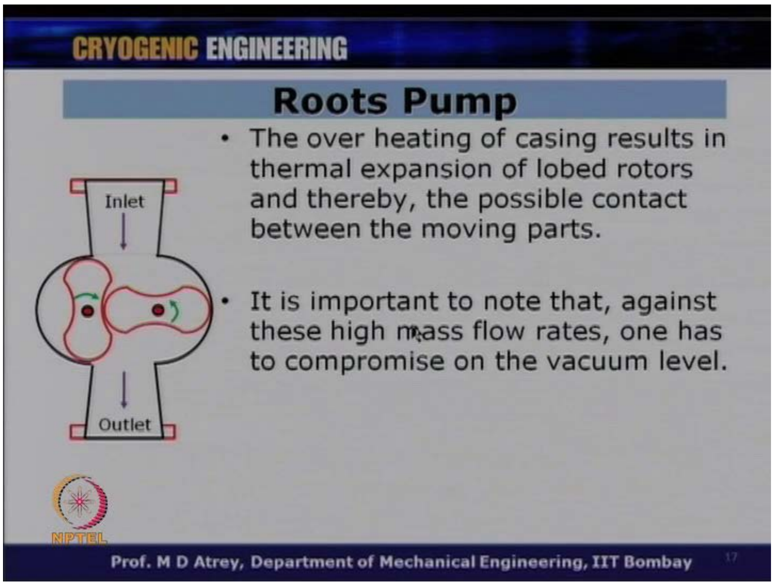

The overheating of the casing results in thermal expansion. If that happens, it will result in thermal expansion of lobed rotors and thereby, the possible contact between the moving parts – and, this should be avoided. If this starts having contact between these two, this can move and it will result in failure of roots pump. It is important to note that, against these high mass flow rates, one has to compromise on the vacuum levels. So, if you have got a very high mass flow rate, you will not get good vacuum; you cannot get very low vacuum case in that case. You can get rough vacuum and you can have very high mass flow rates in the roots pump.

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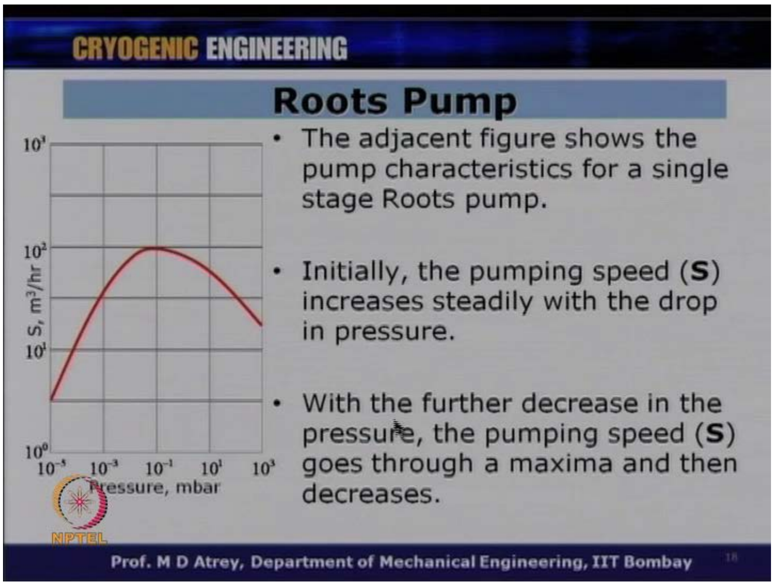

That can be seen from here also. This is the Roots pump's characteristics. You can see that the adjacent figure shows the pump characteristic for a single stage Roots pump. Initially, the pump speed s increases steadily. So, as the pressure vacuum increases, the speed will increase; it reaches to a maximum value. And, after the vacuum is created, if you further increase the vacuum level, the pumping speed decreases in that case. So, one can operate at a very high speed at this point. But, you get less vacuum in this case. So, one has to see a compromise between the pumping speed and the kind of vacuum. If you want to have very high vacuum, then the pumping speed is going to be comparatively less. With the further decreases in the pressure, the pumping speed goes through a maxima and then decreases. So, you have to decide at what pressure you want to operate.

If I want to operate only at 10 to the power minus 1 milli bar, then I am going to have a very high pumping speed. And therefore, this is where (Refer Slide Time: 27:14) almost 100 meter cube per hour; you can go to 200 meter cube or around 500 meter cube per hour also, which is very high speed as compared to that of the rotary vane pumps. And therefore, Roots pump are normally used in applications, where very high pumping speed is required at relatively low vacuum levels. So, this is what we talked about Roots pump. So, we have just not talked about Rotary pump under the positive displacement; also, we talked about Rotary pump.

Now, let us go to kinetic kind of pump and let us talk about diffusion pump in this case. It is a very important pump and we have been using diffusion pump in almost all the operations here, because kind of application we have, the diffusion pump is successfully delivering us the vacuum of minus 5, minus 6. That is what is required. At the same time, it is not very costly and it can be maintained in the lab atmosphere.

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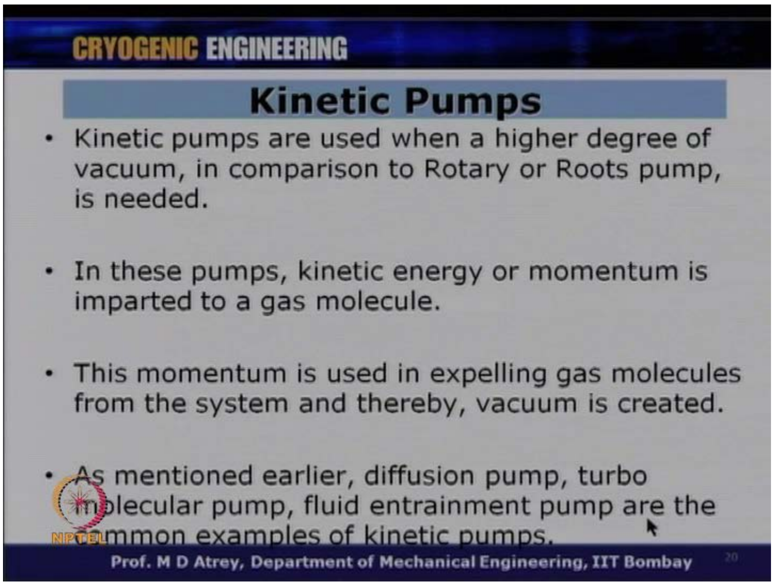

Let us see how this diffusion pump works. As we know that, the diffusion pump falls under the category of kinetic pumps now. So, kinetic pump, as I just told you that, it works in a molecular level and it basically involves transfer of momentum from fluid a fluid b. So, kinetic pumps are used when a higher degree of vacuum, in comparison to Rotary or Roots pump is needed. So, I am talking the Rotary pumps, Roots pump delivered normally the vacuum of minus 2 to minus 3. While if you want to go to minus 5 and minus 6 Torr – 10 to the power minus 6 and minus 6 Torr, we will have to look at now kinetic pumps. And therefore, these pumps work at molecular level. They work not in the continuum region; they do not start from the atmosphere; they start at minus 2 or minus 3; their working starts once the molecular levels have been achieved.

In these (Refer Slide Time: 28:51) pumps, kinetic energy or momentum is imparted to a gas molecule what we talked. This momentum is used in expelling gas molecules from the system and thereby, vacuum is created. So, the system to be vacuumed, all the gas molecule will be imparted momentum, so that these gas molecules are driven outside. As mentioned earlier, diffusion pump, turbo molecular pump, fluid entrainment pumps are the common example of kinetic pumps.

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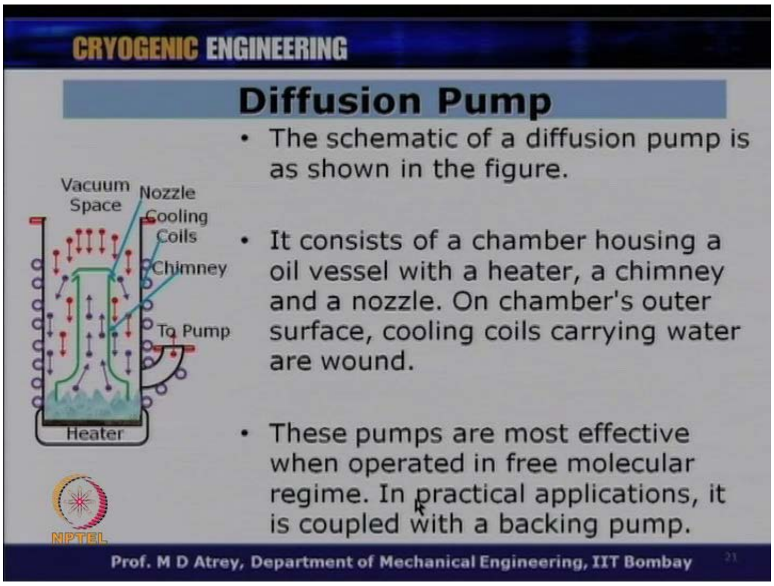

Now, this is a schematic of a typical diffusion pump. Let us see now, how does a diffusion pump works. The schematic of a diffusion pump is as shown in the figure. It consists of a chamber housing an oil vessel. We can see over here; this is the chamber talking about; and, there is oil at the bottom over here; and, there is heater at the bottom to heat this oil. So, it consists of a chamber housing an oil vessel with a heater; a chimney, which is over here; you can see a chimney over here – a chimney and a nozzle, which is at the top. So, we can see a nozzle. So, you have got a chimney over here and the nozzle at the top. On chamber outer surface, cooling coils carrying water are wound. So, you can see on this side, you have got a cooling coil. So, this is basically coil coiling is done, through which the water is following; water at room temperature – a chiller water, whatever water – it is going to be flowing all the time. So, whenever you want to operate diffusion pump, you require this water connection all the time.

These pumps (Refer Slide Time: 30:19) are most effective when operated in free molecular regime. As I was telling you that, these pumps normally look after molecules; they will impart momentum to molecules. And therefore, they cannot be started in the continuum region or they cannot be started working at atmospheric pressure. They cannot start having creating vacuum from atmospheric pressure. So, in practical application, it is coupled with a backing pump. So, some kind of pump is used over here, which will first create kind of a molecular region and then these molecules are dumped to a backing pump; and, this backing pump will leave it to atmosphere. So, this is the way the diffusion pump would work.

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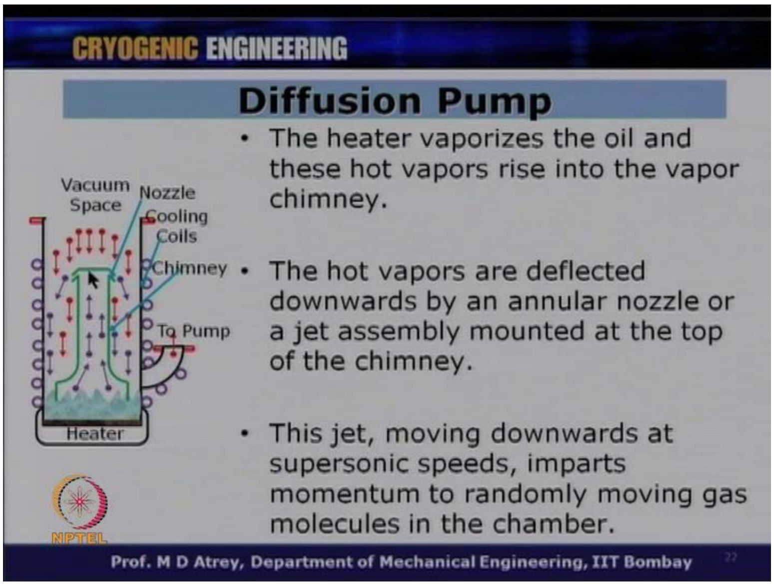

How does the diffusion pump work? Suppose I want to create vacuum in a system, which is kept at this point. And, a diffusion pump will be attached to that system to be vacuumed. I will start the heater; the heater vaporizes the oil. So, this oil will be vaporized. Depending on the vapor pressure, it will get vaporized and this oil will travel up to top; the molecules will go up; the hot vapors will go up and they will start coming out through these nozzles. The heater vaporizes the oil and these hot vapors rise into the vapor chimney. The hot vapors are deflected downwards by an annular nozzle or a jet assembly mounted at the top of the chimney. So, you can see the nozzle at this point; and, the hot vapor will go up and they will come at a high velocity when they travel through these nozzles. And, that is the work these nozzles would do; or, a jet assembly would do.

This (Refer Slide Time: 31:48) jet, moving downwards at supersonic speed, imparts momentum. These vapors, which come out this actually, will impart momentum to all these gas molecules present over here, the system to be vacuumed over here, and this gas all around here. And, when this gas comes out, this gas will impart momentum to all these molecules here. And therefore, this molecule will be given direction and this molecule will be traveling and they will hit these walls. These vapors moving downward at supersonic speeds, imparts momentum; this jet of the oil vapor, which is coming out – it will impart momentum to randomly moving gas molecules in the chamber. So, you have got a gas molecule, which is moving here; and, this jet of the water vapor, will impart momentum to these molecules and they will give direction to these randomly moving gas molecules.

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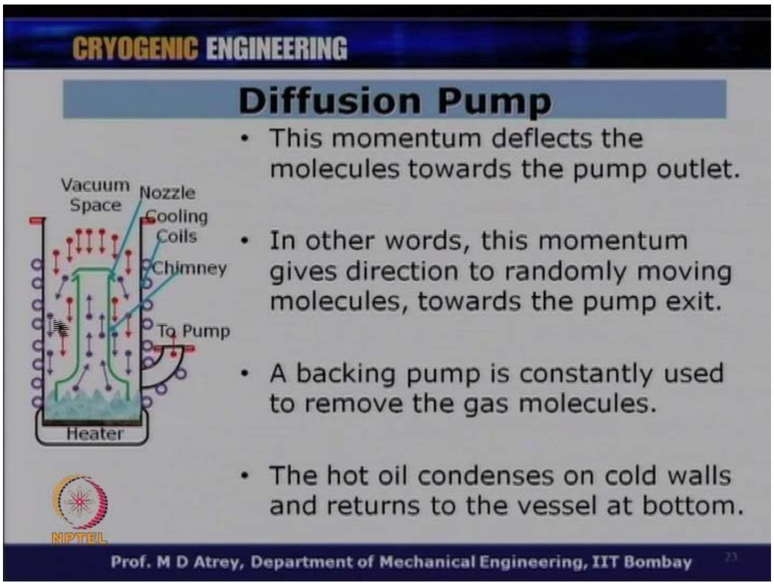

This momentum deflects the molecules towards the pump outlet. This is the pump outlet. So, all these gases will try to come towards the pump, because the momentum has been given by this high velocity jet. In other words, this momentum gives direction to the randomly moving molecules towards the pump exit. Now, having delivered them to this, there is a vacuum pump, which will take these molecules at this pressure and deliver it to atmosphere. It will compress these molecules to dump it to the atmosphere. So, the backing pump is very important, because the diffusion pump works in a molecular region. So, it will take this molecule from here and dump it to some pressure, from where it is further compressed to atmosphere by backing pump. So, a backing pump is constantly used to remove the gas molecules.

What would happen if I do not use backing pump? You can have all the molecules and atmospheric pressure here, which is a very high pressure at this point. And, such a big number of molecules will be there that this water vapor will not be able to strike to those molecules at all. So, that is why, you have to have a molecular region over here, and not a continuum region, because there is a plenty of molecules in other case. So, you have to create a molecular region, so that each and every molecule gets addressed by this jet, which is coming out of these nozzles. The hot oil condenses.

Now, what happens to the oil? The oil vapor, which is coming at (Refer Slide Time: 33:54) a very high speed, it brings these gas molecules to the outlet; the oil when it touches this wall, it will get condensed, because of this running water from outside. Hot oil will come over here; it will get condensed, because of the running water at this point. And therefore, it will again condense back and it will come back to this oil at the bottom of this chamber again. So, hot oil condenses on cold wall and returns to the vessel at the bottom. And again, it will get heated; the vapor will start up; it will get… Velocity when it comes out of this thing, it will impart momentum to this gas molecule and come back and this cycle continues.

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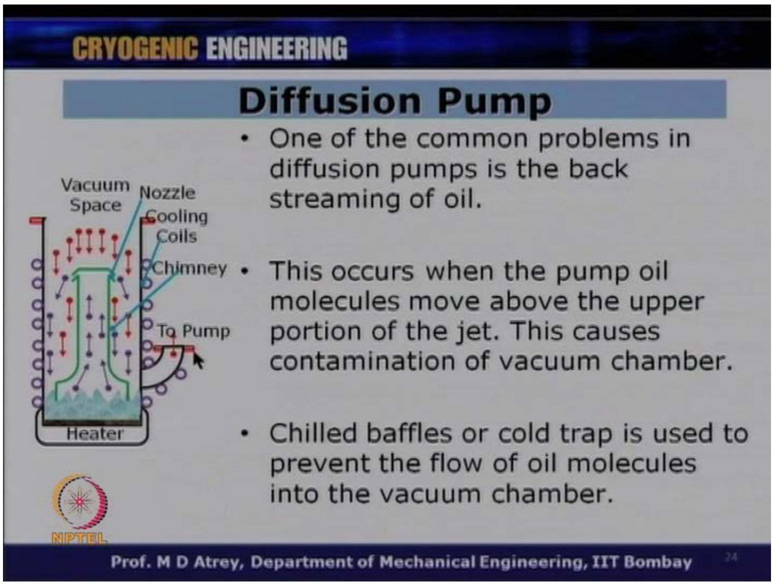

One of the common problems in the diffusion pumps is the back streaming of oil. So, sometimes, when this oil gets heated, this oil can go in the space to be vacuumed also. These are very important disadvantage, which has to be considered while using a diffusion pump. So, if a system can be handle sometime the back streaming of this oil, which has got a good possibility to come in the system itself, then in this system, the diffusion pump cannot be used, because pump handles oil and sometimes the equipment, for example, in the semi-conductor physics or microelectronics, they cannot afford to have any oil coming in the system. So, in this case, diffusion pump cannot be used. So, this is the disadvantage of diffusion pump; that sometimes, the back streaming of oil is possible. This occurs when the pump oil molecules move above the upper portion of the jet. This causes contamination of vacuum chamber. This is not permissible for certain application. And therefore, in those cases, diffusion pump cannot be used.

Now, this also (Refer Slide Time: 35:26) can avoided to an extent. So, one can have some chilled baffles over here. And, these baffles are chilled with running water or using liquid nitrogen sometimes. So, these chilled baffles or cold trap is used to prevent the flow of oil molecules into the vacuum chamber. Suppose at all, oil is travelling, it will get trapped by this cold trap, which is cooled by a liquid nitrogen or chilled baffle, which is cooled by chilled water. And, this oil will get condensed over here. This oil vapor, which otherwise, would have gone to system, can get condensed and it will come back over here. So, one can always use a diffusion pump with a cold trap in order to minimize the back streaming of oil in the system to be vacuumed. So, this is the disadvantage associated with it. At the same time, this disadvantage can be taken care of partially to a greater extent by using chilled baffles or cold trap. However, in a system where it requires very clean vacuum, where some traces of oil also cannot be allowed, in that case, one cannot used a diffusion pump. So, choice of a pump will be dictated by the kind of applications you are using it for.

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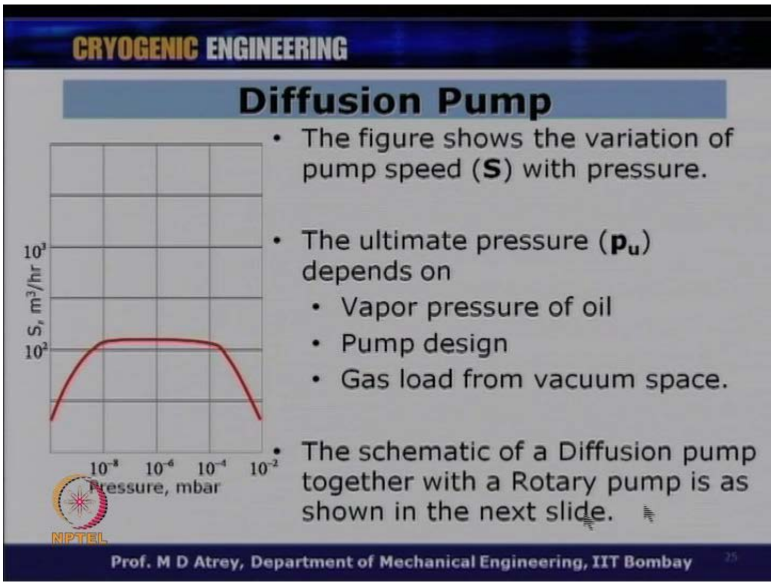

Now, this is characteristic of diffusion pump that, as soon as… See it has to work between minus 2 to almost minus 6, minus 8 milli bar region and the speed remains constant. The figure shows the variation of pump speed with pressure. So, you can see 100 meter cube per hour or 150 meter cube per hour; that kind of speed diffusion pump will have. And, you can go up to minus 8, minus 7 kind of pressures, which we have been talking about. The ultimate pressure p u – what limit this pressure is basically the vapor pressure of oil. At what particular pressure the oil gets evaporated? What is the vapor pressure of oil? That also will decided what is the limitation on the pump – pressure basically. Then, pump design of course. What is a characteristic? For what particular pressure it has been designed for? And again, the gas load from vacuum space – if you have got a very high gas to be removed – gas load, it will take lot of time first thing and you cannot reach very low vacuum in those cases. The schematic of a Diffusion pump together with a Rotary pump is as shown in the next slide.

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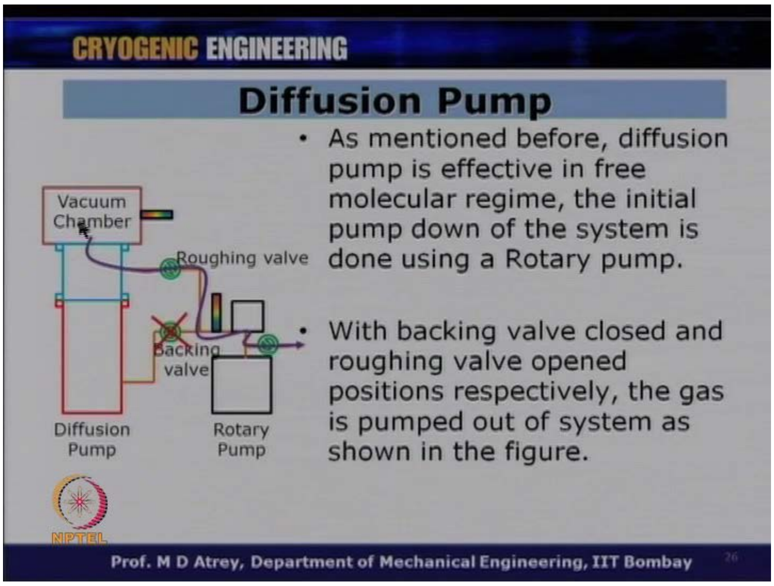

How does it work? Because it has to work with the backing pump; and, one can see a schematic. We can see that this is the vacuum chamber to be vacuumed; and, you can see that this is the Diffusion pump and this is a Rotary pump. And, this Rotary pump is connected directly to the system to be vacuumed through this roughing valve; and also, it is connected to the diffusion pump through a backing valve. As mentioned before, Diffusion pump is effective in free molecular regime; the initial pump down of the system is done using a Rotary pump. So, you cannot start Diffusion pump immediately if this vacuum chamber is at atmospheric pressure. So, in which case, I will not start Diffusion pump, but I will start only the Rotary pump. And, this Rotary pump when it is attached to the vacuum chamber through a roughing valve, it will create the minus 2 or minus 3 levels of vacuum before the diffusion pumps comes into action.

With a backing pump valve closed (Refer Slide Time: 38:29) – in that case, what will I do? I will close this backing valve; that means, Rotary pump connection with Diffusion pump is stopped; Rotary pump directly gets aligned with the vacuum chamber and roughing valve is made on. Backing valve closed and roughing valve opened – in this position respectively, the gas is pumped out of the system as shown in this figure. So, directly, the Rotary pump is attached to the vacuum chamber; it will create minus 2 vacuum; this is delivered to atmosphere; you get around minus 2 to minus 3 vacuum.

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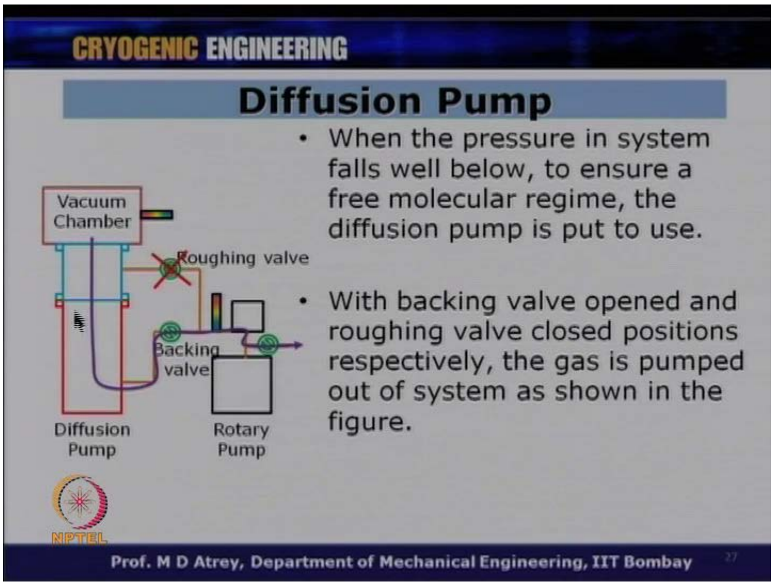

And then, when the pressure in system falls well below to ensure a free molecular regime, the Diffusion pump is put to use. And, once Diffusion pump comes into picture now, I will start this direct connection of Rotary pump to the vacuum chamber. But, I will have connection through the backing valve now. So, the diffusion pump will be made on; the diffusion pump molecules come into the molecular region; it will leave this; using this backing valve, it is dumped. Now, the Rotary pump is acting as a backing pump to the Diffusion pump as the action of which we have explained earlier. So, with backing valve opened and the roughing valve closed positions respectively, the gas is pumped out of system as shown in the figure. And, this is how the diffusion pump will work continuously now in this operation. Initially, only for sometime say one hour, you will have roughing valve opened; the rotary pump will be directly connected to the vacuum chamber to be vacuumed. But, after one to one and half hour, the roughing valve is closed, the backing valve is opened, and diffusion pump is made on. And, this will start working like this.

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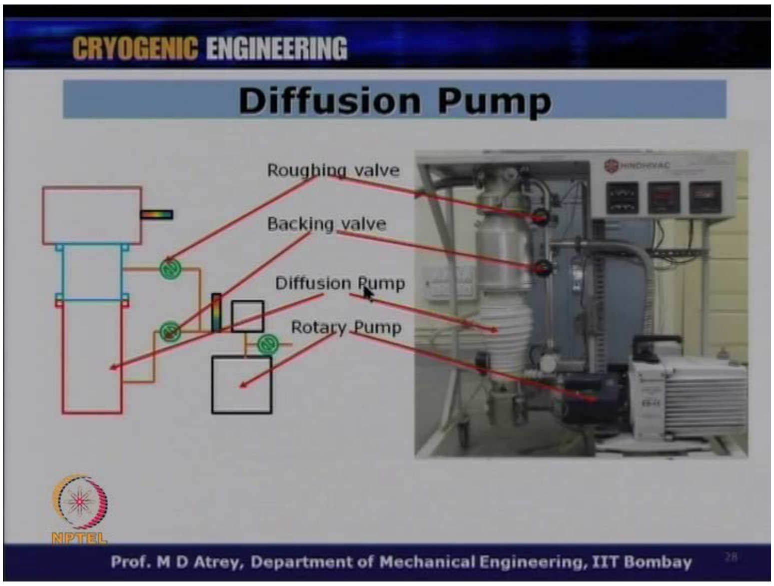

You can this actual diffusion pump over here. I have just given a picture and you can see, this is a diffusion pump here and this is a rotary pump. And, they are connected through these two valves. And, this is a roughing valve. I have just shown you the schematic. So, you can understand it better way. So, initially, I will start this Rotary pump; connect it to the space to be vacuumed to this roughing valve. And then, I have got a backing valve, which I will open once the molecular regime is established at this point. And, you can see the diffusion pump; this is a cooling coil at this. And, you have got oil and the heater at the bottom over here. So, one can understand entire working of a diffusion pump from this. And, you have got a rotary pump over here. So, this will make you understand the working of a Diffusion pump completely.

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Let us see a video here, which shows you two hoses: vacuum hoses a and b let us say. And, other side that the vacuum pump can stay away from this place; the space to be vacuumed can be fed away. And therefore, we have to have some hoses joined together, for which we have got some coupling mechanism. And, this is very important, because this one has to use this coefficient. So, what it has? It has got some kind of sealing in between. So, you can see some rubber sealing; you have got some brass ring on which this rubber sealing goes and stays over there. So, it is kind of hosing over here. And then, you have got coupling. And, this is what constitutes a kind of KF coupling here, which is normally used in connecting this vacuum hoses, which are made of stainless steel. And, you can see some corrugation also here. And, this is the way the coupling is actually compiled together. So, you have got a nut at the end, which actually puts them together. So, we just saw the coupling 1, 2, 3 part.

And now, if you see (Refer Slide Time: 41:45) a vacuum hose, which has got a diameter; and, this can be a KF-25; that means, the 1 inch kind of a thing. Similarly, you have got a 2 inch coupling also. So, whatever you want to use, you have got two hoses now. And, using this coupling now, we want to connect these two vacuum hoses. So, you can see how the rubber is held on this brass hosing. This will have the same ID as this and this will now be connected with this using this coupling together. So, let us go head. So, this is the sealing; this is the way you press it now here. So, this will have a ID matching over here; the internal diameter will match with this as you see. So, this is in perfectly aligned with this vacuum hose on this side and the vacuum hose on the other side also. So, I can put them together.

And now, this (Refer Slide Time: 42:47) coupling will hold all these three elements together: vacuum hose 1, vacuum hose 2 and the sealing material together. So, this is the way a KF coupling would be assembled and this is what will be used everywhere in all the cryogenic experiments. And therefore, the conductance of the entire connection now will change, because you have got two lengths brought together, because of various reasons. And, this is the way the two hoses of 1 meter lengths will be connected; at the other end, you have got a pump; and, on the other end, you have got let us say some vacuum jacket of which you have to take vacuum basically. And, this is the way the two vacuum hoses will be connected without having any leak through this with perfect sealing mechanism. So, this is the classification table.

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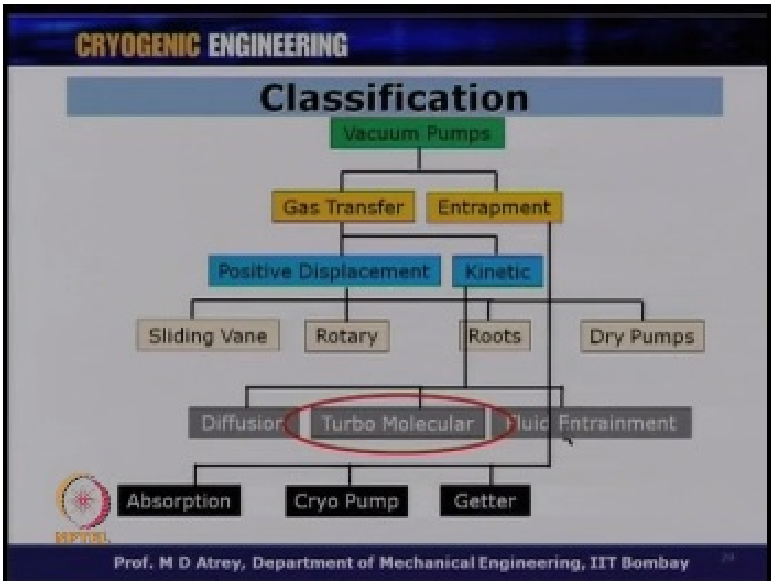

And, having seen how the diffusion pump works under the category of kinetic kind of pumps. Let us see now, how the turbo molecular pump works, because these two pumps are normally very widely used under the kinetic category, so has to obtain a vacuum level of minus 6, minus 7 of this sort basically. So, let us see how this turbo molecular pump works.

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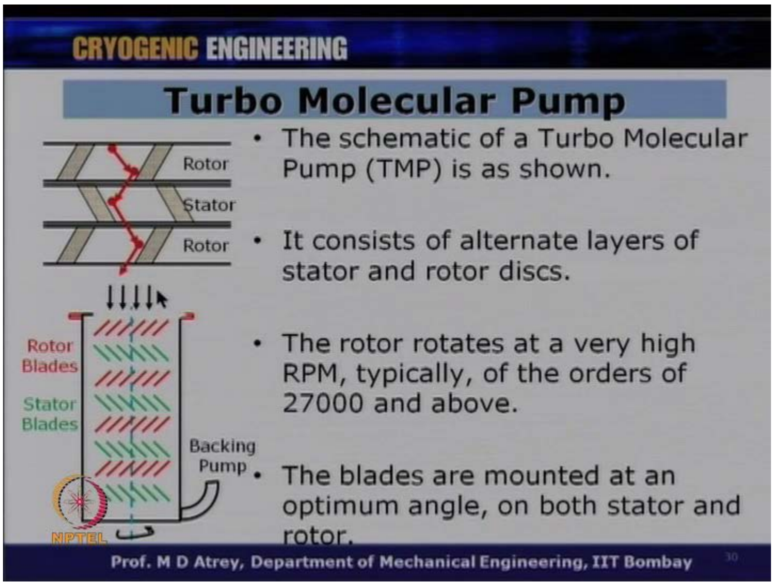

The schematic of a Turbo Molecular Pump – normally, it is referred to as TMP. In a short form, lot of people will call it as use a TMP. So, a Turbo Molecular Pump is normally called as TMP in colloquial language. And, this is the way it works. So, you got an arrangement like a rotor-stator-rotor-stator-rotor-stator like that. And, a rotor-stator would look like these blades, which can identify the rotor. There are other blades, which get identified as stators. And, they have got several rotor-stator-rotor-stator arrangements; the gas is transferred and delivered to the backing pump. And, this is how the Turbo Molecular Pump works normally.

A Turbo Molecular Pump (Refer Slide Time: 44:35) consists of alternate layers of stator and rotor discs. The rotor rotates at very high speeds; the stator remains constant; stator will not move; while the rotor will start moving. And, the rotor rotates at a very high speed, typically, of the orders of 27000 RPM and above; they are working at 60000, 70000, 1 lakh – that kind of RPM. Higher the speed, better it is, because as I told you, this is a kinetic category and this is a transfer of momentum. So, depending on the gas molecular size and depending on the kind of speeds, they get the mass into velocity. So, a momentum is going to be created, because of the mass into velocity.

The typical gases, which we use here (Refer Slide Time: 45:15) could be air, nitrogen, helium. And, each gas would have its own mass. To this mass now, we will give a momentum by giving a velocity. And therefore, the velocity has to be as high as possible. So, speeds at which these people work – the Turbo Molecular Pump works, is going to be very high – as high as possible; that is possible from design point of view. So, higher the speeds, higher the momentum; higher the gas molecular size or mass, higher is momentum. So, helium, for example, is a very light gas, a very small size molecule in the very small mass. And therefore, momentum transfer in that case is going to be less as compared to that of nitrogen. So, one has always TMP will be specifying the flow rate with respect to a particular gas, because the particular gas has got a molecule, will have a particular mass. And therefore, it is very important to see that normally the TMP or diffusion pumps, where momentum transfer happens, the speeds are mentioned in terms of nitrogen or a particular gas.

Now, here (Refer Slide Time: 46:13) we have got various blades: the rotor blades, the stator blades, the rotor blade and the stator blades. And, the blades are mounted at an optimum angle. There is an angle over here, which ensures that space to be vacuumed, the gas is going to move in downward directions. The molecule will strike against these blades. It will give a direction by the stator blade. Again, it will give a momentum by a rotor blade. Again, the direction given by a stator blade in order to see that molecule will not go back, but is always going down to the backing pump. So, the direction is given by the blade angle; and, the blade angles have to be correctly designed, manufactured optimum angles. And, these angles have to be ensured that they correctly exist on rotor as well as static blades; both the blades will have to have correct angle.

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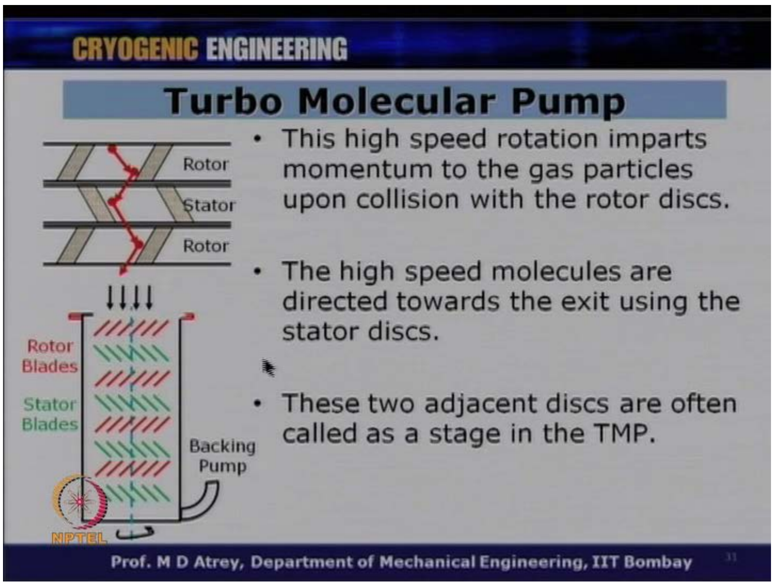

This high speed rotation imparts momentum to the gas molecules upon collision with the rotor discs. So, what is happening is this rotor is moving very fast and the gas molecule will come over there; and, this gas molecule will collide on the rotor discs. And, during this disc, the momentum of the rotor will get transferred to the gas molecule. And, it will get velocity; because of which, it will go to the stator and again the stator will give direction. Again, on the next rotor stage, it will get a momentum and again it will give a direction in such a way that the momentum is imparted in every rotor stage; while the stator stage ensure that it goes in a correct direction and ultimately it will go through a backing pump.

The high speed molecules (Refer Slide Time: 47:40) are directed toward the exit using the stator discs. These two adjacent discs are often called as a stage of a TMP. For example, one rotor and one stator will constitute one stage. So, you have got one stage, stage number 2, stage number 3, stage number 4; and normally, 6 to 7 or 8 stages could be there for a given TMP; not more than that. What is most important, you can understand that. First requirement is that they are rotating at very high speed; the rotor is rotating at a very high speed; and, the second is fabrication of these plates. The angle at which each stage is kept, at every stage, the angle will be different; every stage, the compression ratio will be different. So, the gas will come at minus 5. And, by the time it comes to the backing pump, the gas will be at minus 2 or minus 3 in these cases. This is very important – how this blades design will change across the stages; what the angle will change. And therefore, correct angle, correct fabrication is very important aspect of TMP. Fabrication requires lot of skills; because of which, you can understand the cost of the TMP also is exorbitantly high as compared to the diffusion pump.

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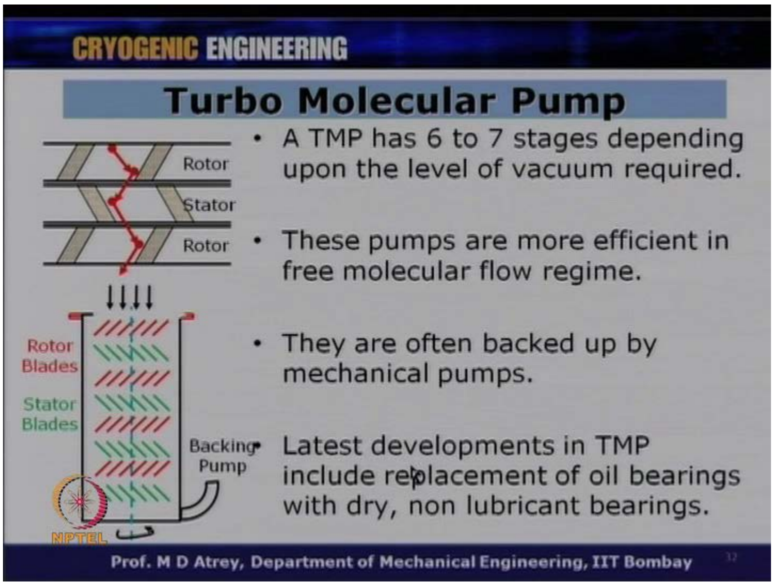

A TMP has 6 to 7 stages depending upon the level of vacuum required. These pumps are more efficient in free molecular flow regime. Again, as you know diffusion pump, they also work in a free molecular region. And therefore, you have to have a backing pump in order to take the gas and again dumping it to atmosphere ultimately. So, the TMP would deliver from minus 6, minus 7 to minus 2; from where, rotary pumps will take over as backing pump and they will deliver it to atmosphere ultimately. They are often backed up by a mechanical pump or a rotary pump.

Lot of developments are happening, because (Refer Slide Time: 49:13) they are moving at such a high speed. The bearings of TMP pump, the balancing of TMP pump are very important research topics. So, latest developments in TMP include replacement of oil bearings with dry, non-lubricant bearings. So, lot of magnetic bearings are there; noncontact bearings are there. Static bearing, dynamic bearing are the very important research activities happening in the design of Turbo Molecular Pump.

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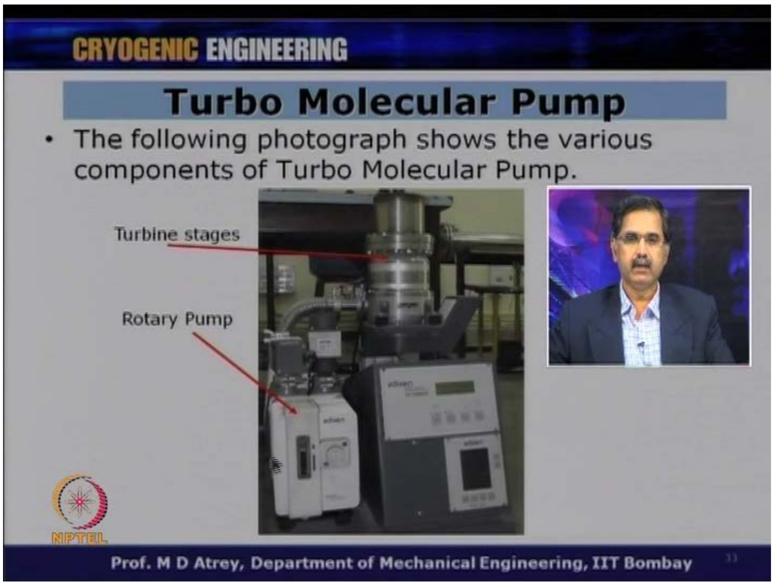

And, a typical Turbo Molecular Pump is shown over here. And, you can see that there is a Rotary pump on this side and there is a Turbo Molecular Pump, which houses all the stages here. So, you have got turbine stages, which are housed over here; you have got a rotary pump, which is kept at this point. So, there is a kind of a backing pump. And, ultimately, it is left to atmosphere. This is the way the TMP works.

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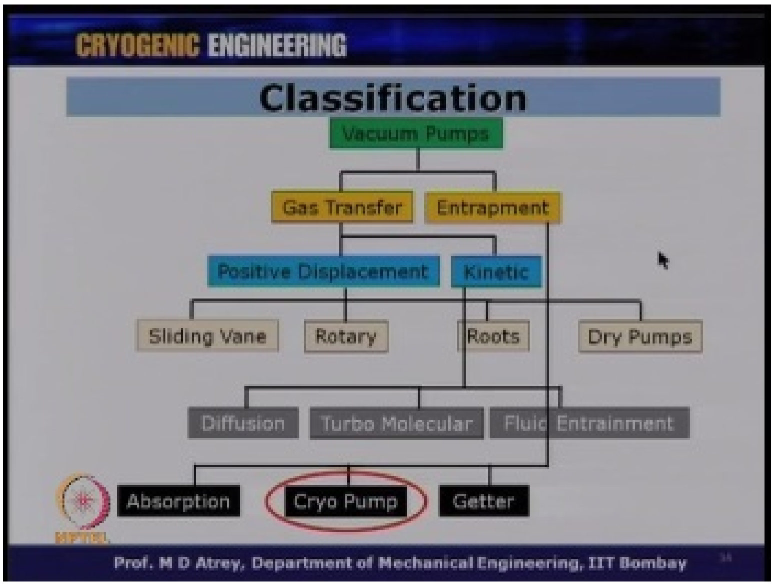

Let us come now to next kind of thing, which is… I am just going to give an example of entrapment and (( )) vacuum pump now. And therefore, under this category, we can see how a cryo pump works. So, we have seen now, gas transfer type of pumps. We will see entrapment; and, under entrapment, now, let us see how does a cryo pump work.

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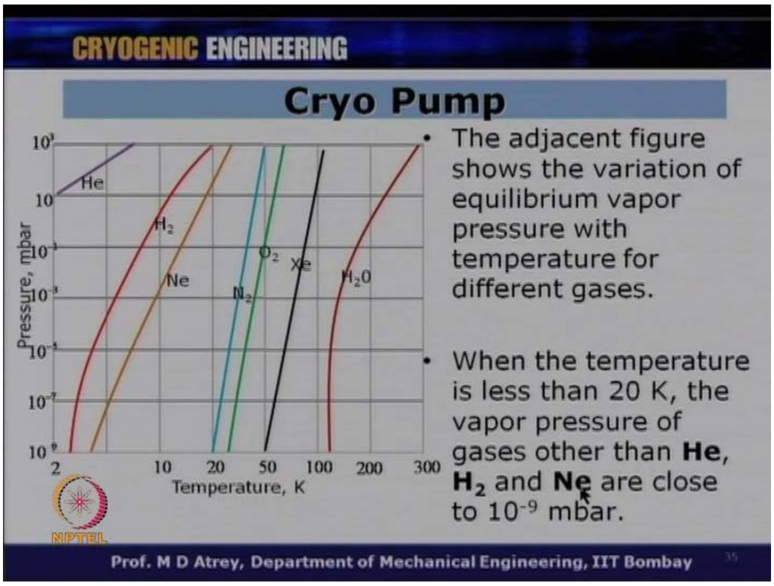

Now, how does a cryo pump work? Cryo pump basically works in loading of temperature and seeing to it that the gas vapor pressure is brought down; that means, the gas ceases to be in gaseous conduction, the gas gets actually frozen down, because of the lower temperature (( )) generated by a cryo pump. For example, if I am at 100 Kelvin, it ensures that water is at very low vapor pressure now; it is as low as minus 9; that means, it is not existent at all; that means, all the moisture in this case is completely frozen now; this is not in a gaseous stage at all. And therefore, there is no gas existent over here.

If I come down to 20 Kelvin, you can see that water, xenon, oxygen and nitrogen – all of these are (Refer Slide Time: 51:00) below minus 9 kind of a vapor pressure; that means, these gases have got frozen if I have got a 20 K surface exposed to these gases. So, at 20 K now, what are the gases over there? There are neon, hydrogen, helium; this cannot be taken care of. So, if I have got a surface, which is having 20 K temperature, it will ensure that the vapor pressure of all these gases – normal gases, which are existent in air, will be taken care of; that means, they all get frozen. And therefore, their vapor pressure is much below minus 9.

And, this is the (Refer Slide Time: 51:34) basic principle how the cryo pump works that, can you lower the temperature of the spaced therefore all the gases in that space will get frozen down? That means, they get cryo pumped. This is what the principle of a cryo pump is. The adjacent figure shows the variation of equilibrium vapor pressure with temperature for different gases. When the temperature is less than 20 Kelvin, the vapor pressure of gases other than helium, hydrogen and neon, are close to minus 9 milli bar; that means, you can get a vacuum pressure of minus 8, minus 9 easily. But, neon, hydrogen and helium, will still be in gaseous phase over there. But, as you know, they are the rare gases basically. But, you cannot take care of neon, hydrogen and helium at 20 K; their pressures are very high there. They could be at the power 3 milli bar kind of pressures.

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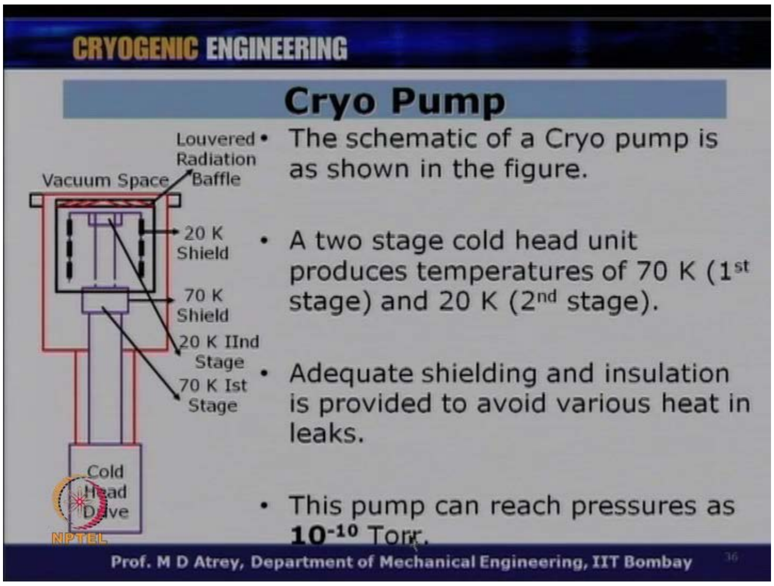

Typical cryo pump looks like that. It consists of a two stage GM cryocooler. So, you can see a two stage GM cryocooler, which works in a closed cycle manner. You can have a compressor running this cryocooler. The first stage of this cryocooler delivers around 70 Kelvin; the second stage of cryocooler delivers cooling effect at around 20 Kelvin. And, this works on a principle normally of GM type machine, which we have seen already how does it work. The schematic of a cryo pump is as shown in this figure. A two stage cold head unit produces temperatures of 70 Kelvin and 20 Kelvin at first and second stage respectively. Adequate shielding and insulation is provided to avoid various heats in leaks. This pump can reach pressures as less as 10 to the power minus 10 Torr, which is very good.

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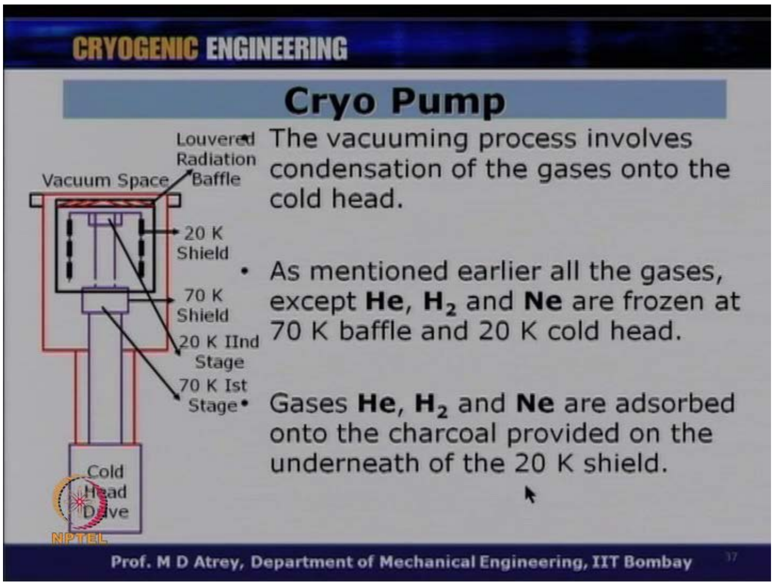

We can see now here the first stage is connected to this louvered radiation baffle; that means, this baffle is kept at around 70 Kelvin. And, the space to be vacuumed will be exposed over here. When the gas comes in a side, whatever moisture is there, because this is 70 Kelvin, this moisture will be trapped; it will get frozen down. And, we know that at 70 Kelvin now, all the moisture is taken care of. Now, the second stage – you can see, there is a shield over here and this is at 20 K surface. So, when this gas comes down, the remaining oxygen, nitrogen, xenon, etcetera, will get frozen down on this. And therefore, at this 20 K, this 20 K shield will take care of the other gases other than moisture, where the 70 K shield, which is connected to the first stage, it will take care of water vapor.

As mentioned earlier, all (Refer Slide Time: 53:53) the gases except helium, hydrogen and neon, are frozen at 70 K baffle and 20 K cold head. So, 70 K baffle and 20 K baffle will take care of all the gases, except helium, hydrogen and neon. Now, helium, hydrogen, neon, are basically going to be adsorbed on the carbon-charcoal paste, which is kept over here on the inside part of this inverted cup. One is the open cup like this to which baffles are connected; one is a closed inverted cup. And, inside part of this is going to be having a charcoal paste on this, on which helium, hydrogen and neon, will get adsorbed. So, all these other gases also can be taken care of by this adsorption technique on the activated charcoal. The gases like helium, hydrogen, neon, are adsorbed on to the charcoal provided on the underneath of the 20 K shield. And, this is the way cryo pump will take care of almost all the gases in this case. And, this is the way it works.

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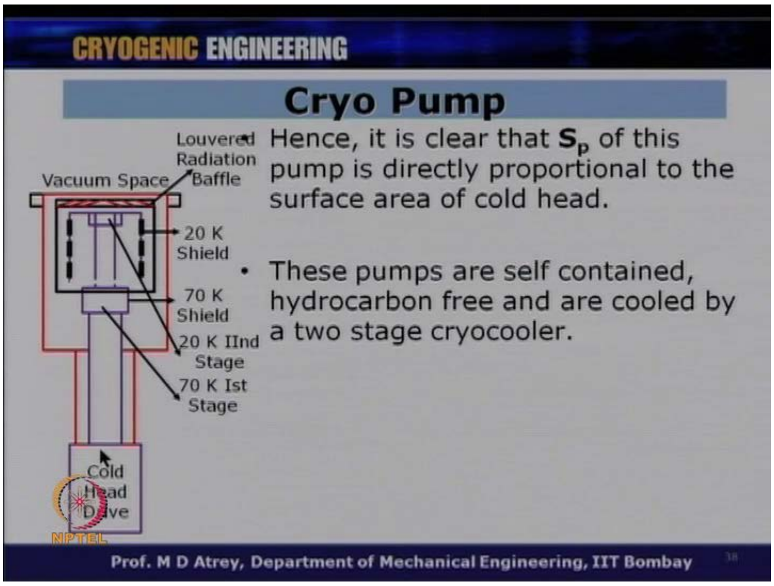

Hence, it is clear that the pumping speed of this pump is directly proportional to the surface area. More the surface area, you can have more gases that could be adsorbed or that could be trapped in this case. These pumps are self-contained hydrocarbon free and are cooled by a two stage cryocooler. There is no oil business over here. And therefore, it creates a very clean vacuum. And, this is the way they can be really used in application like semiconductor physics, microelectronics. Cryo pump is a very acceptable pump in this area, because they deliver very clean vacuum; there is no oil like what it is in diffusion pumps.

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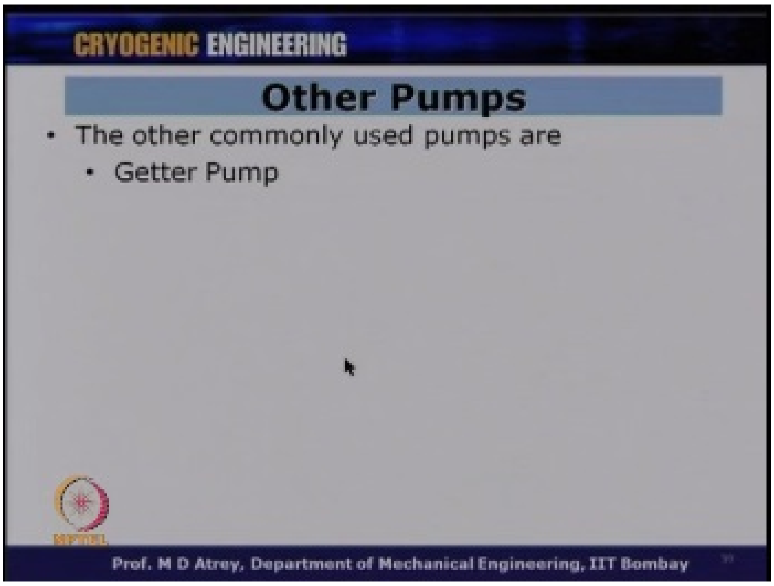

Now, there are several other pumps called… I will not going to detail, but getter pumps, spetarine pump, sublimation pump, adsorption pump. And, I would like you to go through the working of these pumps. They all come in kind of entrapment pumps that also could be sometimes used.

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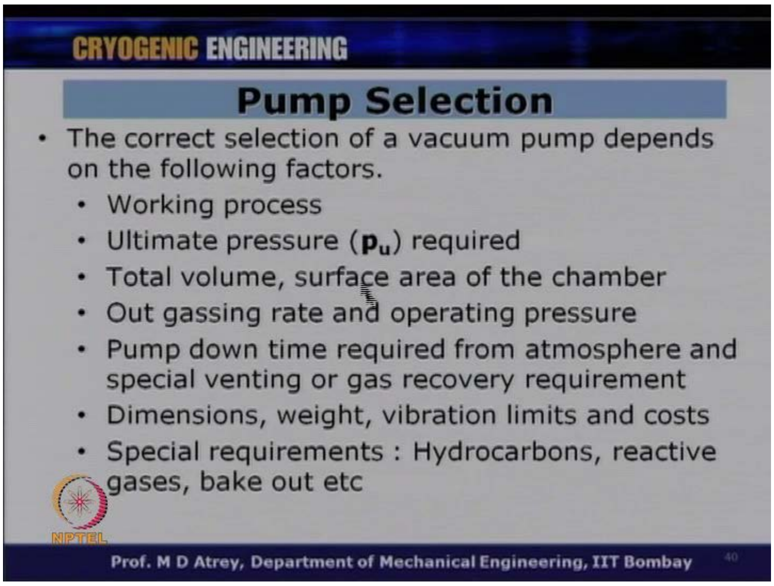

The pump selection is governed by various criteria. And, they are criteria – what is the working process? What kind of pump do you want to use? Do you want to use rotary pump, diffusion pump? As I said, we have got a clean requirement of vacuum; I should go for cryo pump and things like that. So, working processes; ultimate pressure required; total volume surface area of the chamber to be vacuumed; out gassing rate and operating pressure. Is there an out gassing possibility? Is there a painting on the inner part? Is there some coating on the outer part? All these things have to be seen. Pump down time required – that also will decide what kind of pumps that could be used. Dimensions, weight, vibration limits and costs also will decide what kind of pumps to be used. And, there are sometimes special requirement like hydrocarbon atmosphere, reactive gases, bake out, which will also decide what kind of pumps do we select in these cases.

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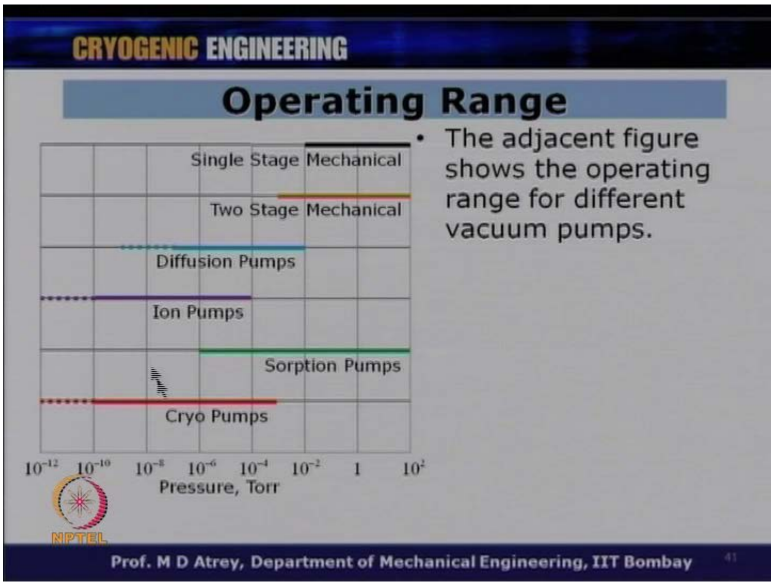

What we have seen in general is various pumps and various pumps have got different operating ranges. If I want to operate from here to here through minus 2, I can select only rotary pump. So, the adjacent figure will show the operating ranges of different vacuum pumps. For example, if I want to work with minus 2, I will have a mechanical or single stage vacuum pump. And, if I want to go up to minus 3, I can have a two stage mechanical vacuum pumps. If I want to go below minus 2 up to minus 6 or minus 8, I can go for diffusion pump; that means, I will require a backing pump in order to reach up to minus 2 first. This is what we have seen earlier.

And then, I have got different (Refer Slide Time: 57:00) ion pumps, which can take me down to minus 10 levels of Torr. And then, I have got various other pumps like sorption processes, which can bring to minus 6 pumps. And, there are other pumps like cryo pumps, which can operate from minus 3 to minus 10, give me clean vacuum. Several other pumps are there. All of them will have their operating ranges. But, what is important to see is what kind of (( )) pump to be uses and what criteria of that should be used, has to be understood with the working these pumps.

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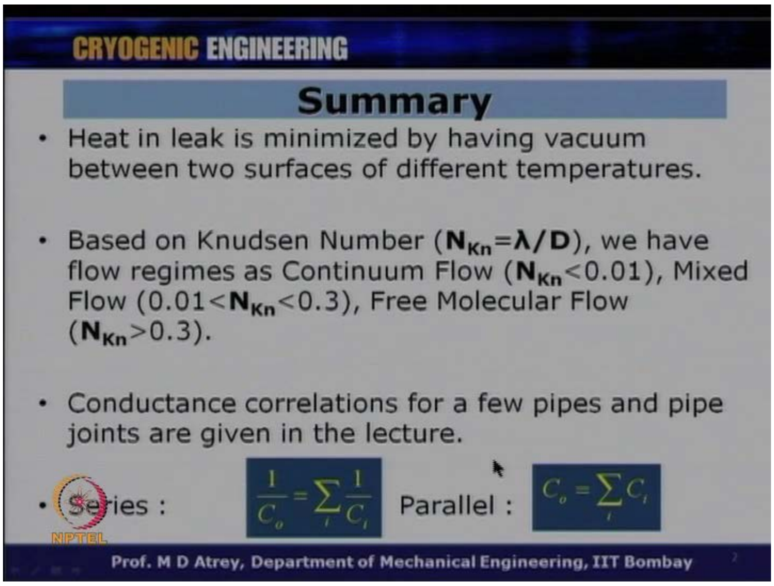

Let us summarize what we have learnt in this particular topic. We have found that heat in leak is minimized by having vacuum between two surfaces of different temperatures. We also defined a number called Knudsen Number, which is lambda by D. Based on this Knudsen Number, we have flow regimes as Continuum Flow when Knudsen Number is less than 0.01; we have got a mixed flow when the Knudsen Number is between 0.01 and less than 0.3; and, we have got a free molecular flow when Knudsen Number is 0.03 lambda by basically determine the ratio of mean free path through the characteristic dimension D. And, the lambda is defined as the length between the two subsequent collisions of the molecules.

The various conductance correlations we have understood. The conductance correlations for a few pipes and pipe joints are given in the lectures. And, we found that, based on these correlations, we can calculate conductance; based upon which, we can calculate the pumping speed and the system speed. And, you know that the conductances when put in series, you got this expression (Refer Slide Time: 58:31); and, conductances, when in parallel, we got this expression in order to calculate the overall conductance of these pipes in series and pipes in parallel.

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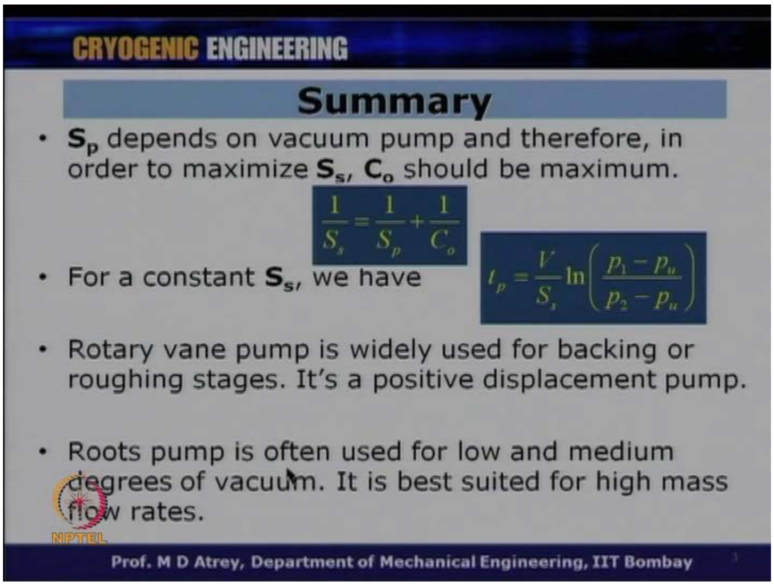

We know that the pumping speed S p depends on vacuum pump and therefore, in order to maximizes system pumping speed, we know that the conductance should be kept as maximum. And, S p and S s and C o get related by this formula, which is 1 upon S s is equal to 1 upon S p plus 1 upon C o. We have studied this formula in detail. For a constant S s now, we got an expression for time to create vacuum from the pressure p 1 to p 2; and, as S s is more, as the system pumping is more, we know that time to reach that particular vacuum is going to be less and less for a given volume be. Then, we have studied various vacuum pumps. We know that the rotary vane pump is widely used for backing or roughing stages; it is a positive displacement pump. Roots pump is often used for low and medium degrees of vacuum. It is best suited for high mass flow rates when you want the low vacuum to reach very fast or we have got a very big volume to be vacuumed.

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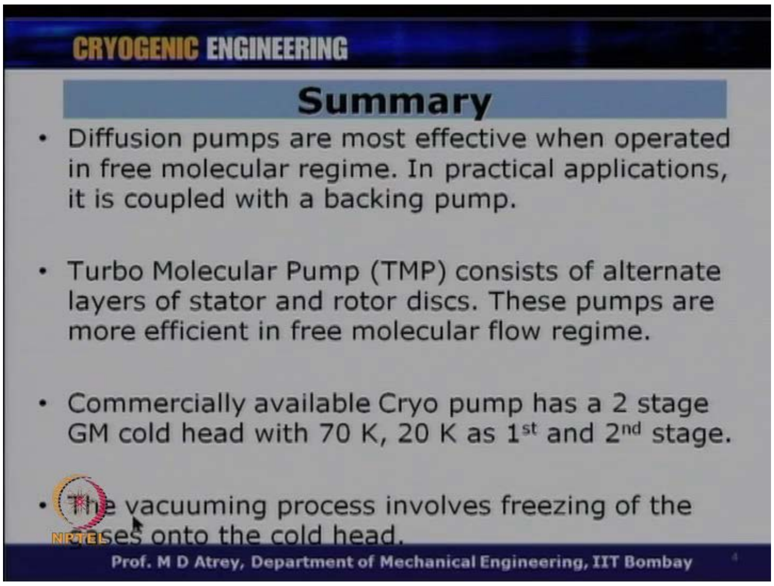

Then, we know diffusion pumps are most effective when operated in free molecular regime. In practical applications, it is coupled with a backing pump. Then, we have got TMP or Turbo Molecular Pump – it consists of alternate layers of stator and rotor discs. These pumps are more efficient in free molecular flow regime as diffusion pump. Then, we got a cryo pump, which gives us cleaned vacuum. When the oil is a question, always a clean vacuum is preferred using cryo pump. So, commercially available cryo pump has normally a two stage GM cold head or a cryocooler with a first stage around 70 to 80 Kelvin; while the second stage will be around 50 to 20 Kelvin – temperature on these two stages of this cryocooler. And, based on the temperature generated on this first stage and the second stages, various gases will be getting frozen on the surfaces. The vacuuming processes involve freezing of the gases on to this cold head and the vacuum is generated. This is in short the summary of the entire vacuum topic.

Thank you very much.