Cryogenic Engineering
Prof. M. D. Atrey
Department of Mechanical Engineering
Indian Institute of Technology, Bombay

Lecture No. # 37
Vacuum Technology

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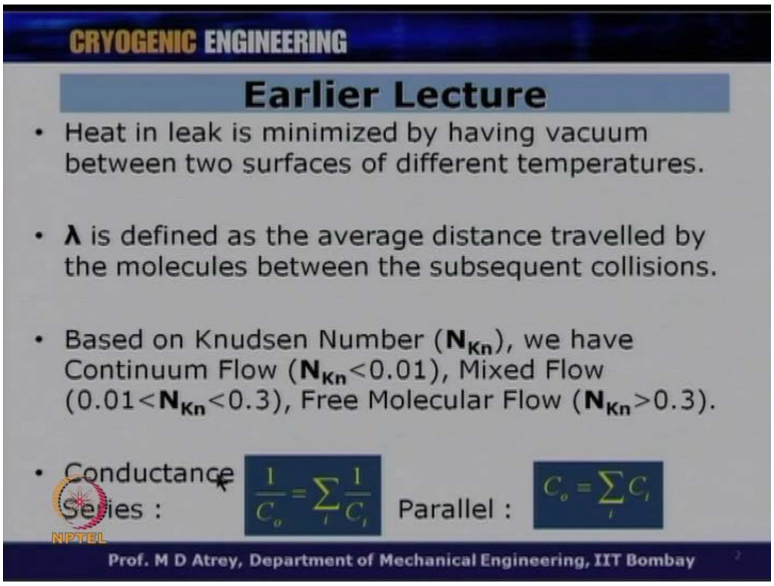

So, let us come to the 37th lecture on cryogenic engineering under the NPTEL program. The earlier lecture we were talking about vacuum, and during the earlier lecture we talked about heat in leak is minimized by having vacuum between two surfaces of different temperatures. Then we talked about lambda which is mean free path of the molecule, and lambda is defined as the average distance travelled by the molecules between the subsequent collisions. And we had seen that based on this lambda we had classified the different vacuum levels.

So, based on the Knudsen number, again we have got a number analogous to Reynolds number continue flow, we had Knudsen number which is equal to lambda by D; where D is the characteristic dimension. And based on Knudsen number N k n we had continuum flow when the Knudsen number is less than 0.01, we have mixed flow when the Knudsen number between 0.01 and 0.3, and we got a free molecular flow when Knudsen number is more than 0.3.

So, in normally in very good vacuum we will always encounter a situation when we got a free molecular flow, and we also studied what is this conductance, and when you found that conductance will depend on the length of the pipe, diameter of the pipe, the gas, the temperature, the pressure etcetera. We have got conductances in series; that means, we got a pipes in series, the conductance would get added like this.

So, one upon C 0 overall conductance of the entire pipe structure which will depend on as sigma 1 by C I, where I will go from 1 to 2 or 1 to 3 depending on how many pipes you have. So, 1 upon C 1 plus 1 upon C 2 plus 1 upon C 3 is equal to 1 upon C 0, and in that way we can calculate overall conductance. Similarly, if you have got pipes in parallel the conductance's will be added C 0 is equal to sigma c, they will be directly added to each other with that we will get a overall conductance for the parallel pipes. And this will be utilized ultimately in order to get the vacuum speed, the pumping speed and that is what we will see in this particular lecture.

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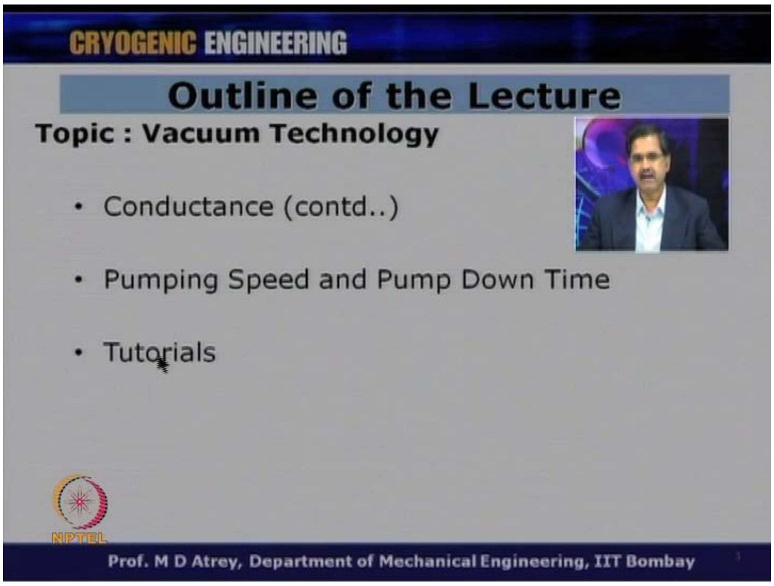

So, in this lecture now we will continue with what is conductance business all about, then we will come to the important parameters quite regularly used in vacuum technology, which is pumping speed and pump down time all right. So, we will come across what is this terminologist which are normally used in vacuum technology, and then we will have some tutorial based on this pumping speed, conductances, pump down time etcetera. And therefore, all this things which we are understanding in this particular lecture, we will have some tutorial based on it and we can have some values associated with all this parameters.

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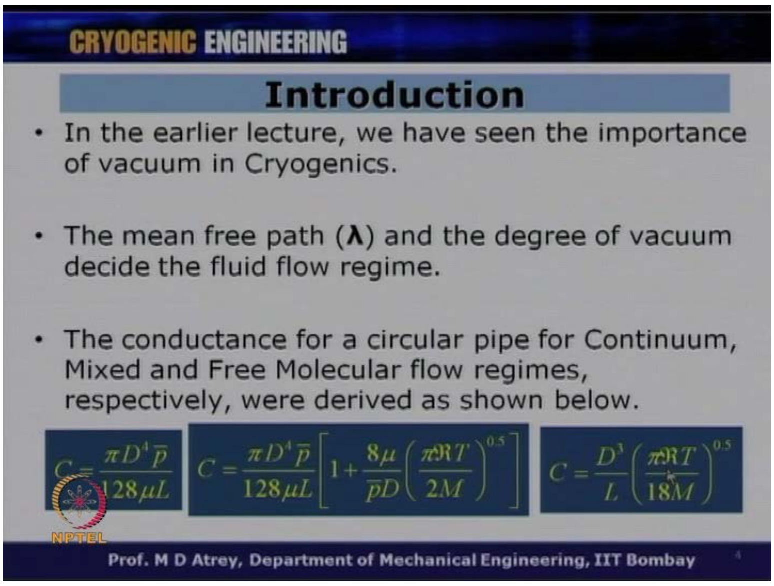

In the earlier lecture we have seen the importance of vacuum in cryogenics, we have seen the mean free path lambda and the degree of vacuum, we will decide the fluid flow regime all right. And then we have Knudsen number also in order to classify these different flow regimes.

The conductance for circular pipe for continuum mixed and free molecular flow regimes respectively, were derived as shown below. If we remember the derivation which we did last time, we found that conductance for continuum flow is proportional to D to the power 4, and this is what expression we had got at Poisson equation basically. Then for a mixed flow we had a conductance which is a typically a little mixed behavior, and you got a very not direct relationship between diameter over here, but it is inversely proportional to the length one can see, and diameter due to the power 4 is here in the numerator while D is there in denominator also. And when we come for a free molecular regime, the conductance is now proportional to D cube and inversely proportional to L.

So, these are the conductance's which we found that they vary with different diameters, they vary with lengths, they vary with pressures, they vary with temperatures and of course, the gas property like viscosity etcetera. So, using this formula depending on the flow regimes you are in, we will have to calculate for a given pipe of a given diameter and length, what is the conductance of that pipe? And this will determine ultimately, help us determining what is my pumping speed or what is my system pumping speed etcetera. And this is what we will see in this particular lecture.

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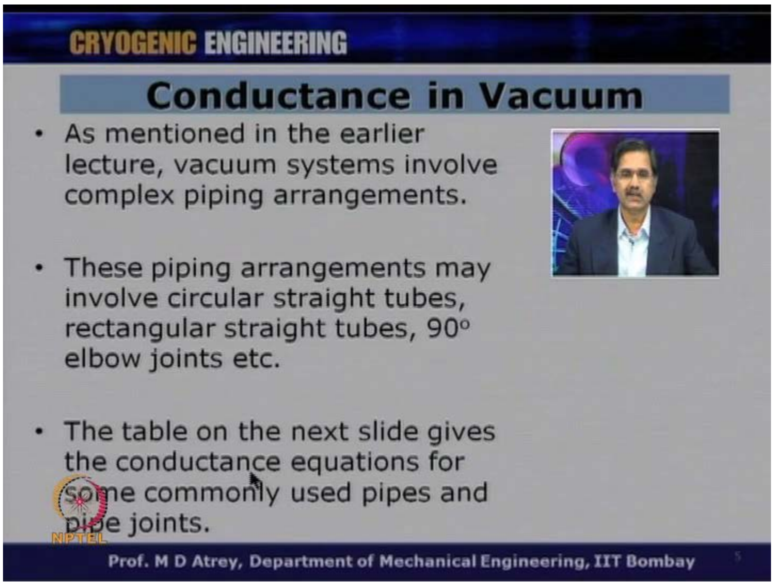

So, conductance is a vacuum as mentioned in the earlier lecture, vacuum systems involve complex piping arrangements. These piping arrangements may involve circular straight tubes, rectangular straight tubes, 90 percent elbow joints etcetera. And actually, lot of other structures which has not been mentioned over here, we can have some couplings also involved over here, we can have some bands over, they may not be 90 percent again all right.

So, in order to calculate the conductances for such mechanism, because I got a vacuum pump I got a system to be vacuumed, and in between I will have some piping arrangements alright. So, vacuum pump cannot directly go and sit on a system, the vacuum pump is going to be away from the system to be vacuumed and therefore, these piping arrangements effectively will determine, what is the conductance which is responsible to get particular system pumping speed?

So, if I got some structures which are circular straight tubes, rectangular straight tubes, or 90 percent elbow joints and many other possibilities, but I am just showing you three possibilities. Then there are some standard equations to be used, in order to calculate the conductance’s for these particular pipes, joints etcetera.

The table on the next slide gives the conductance equations for some commonly used pipes and pipe joints. And we have to use such correlations that are available to calculate the conductance in order to come to calculate overall conductance of the system.

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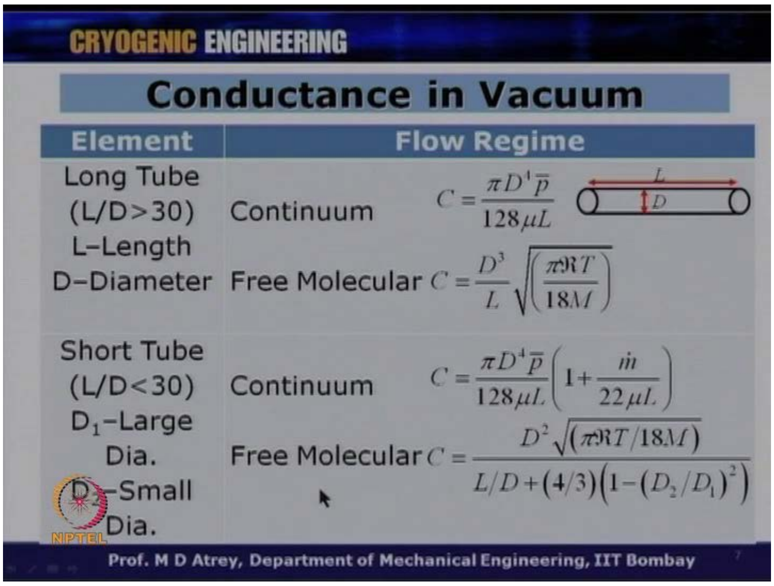

For example, we got a long tube and long tube is defined as when L by D is more than 30, so L is length D is diameter. And for continuum flow we have got a relationship as we have derived earlier as pi D to the power 4 p 125. So, use this equation to calculate conductance if we are in continuum region, or if we could prove that we are in free molecular region then you use this formula which we have ultimately derived alright.

So, use as such formula first find out what is the Knudsen number, ensure that you are in a free molecular region, mixed region or a continuum region, and use corresponding formula to calculate the conductance for that pipe for a given dimensions t D and L. If we got a short tube where L by D is less than 30, then again we have got different formula, and if we got a free molecular region we got a different formula again where D 1 and D 2, we can have two joints two diameters also having D 1 as large and D 2 as smaller diameter. So, use all this things in order to calculate the conductance’s for such given pipes.

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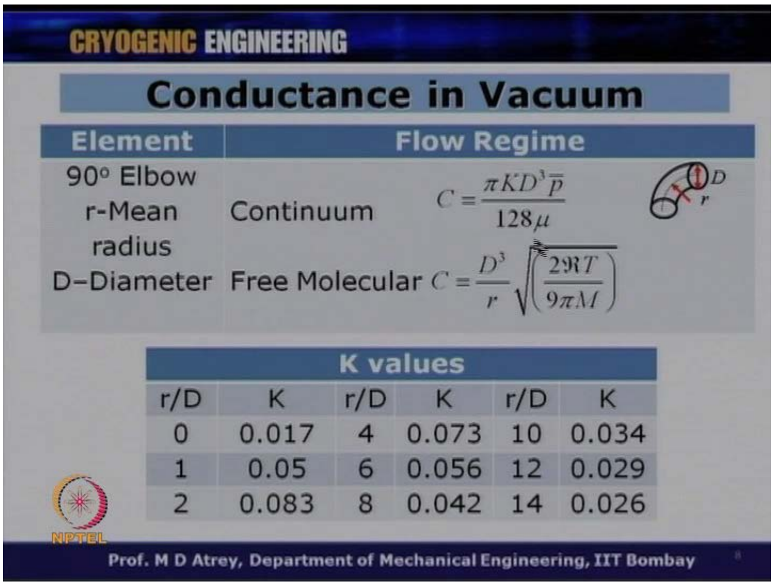

If we got a 90 percent elbow which may look like this, we can see that the gas flow in this direction, and you can see there is a you know reduce of curvature, and these are diameters of the pipe, and again we have got expressions for calculating the conductance for a continuum flow for a free molecular region, and the value of k which is showing up over here depends on particular r by D, this is basically get shown up early in the this only all right.

So, find out that calculate the value of conductance’s accordingly and put those values here. And for different structures therefore, for different pipes, for different joints, for different curved elbows etcetera, you calculate the conductance in this way, and effectively you will calculate; if there are pipes in parallel, if there are pipe in series one can calculate the overall conductance of this combination of pipes.

In addition to this we will have several couplings, we can have several non characterized kind of a items which could be placed in place or pipe of different structures also could be placed, and then correspondingly we will have a very big table that is available in literature which you have to look for, and you can get the conductance’s for those particular structures which are employed to connect vacuum pump to the system to be vacuumed.

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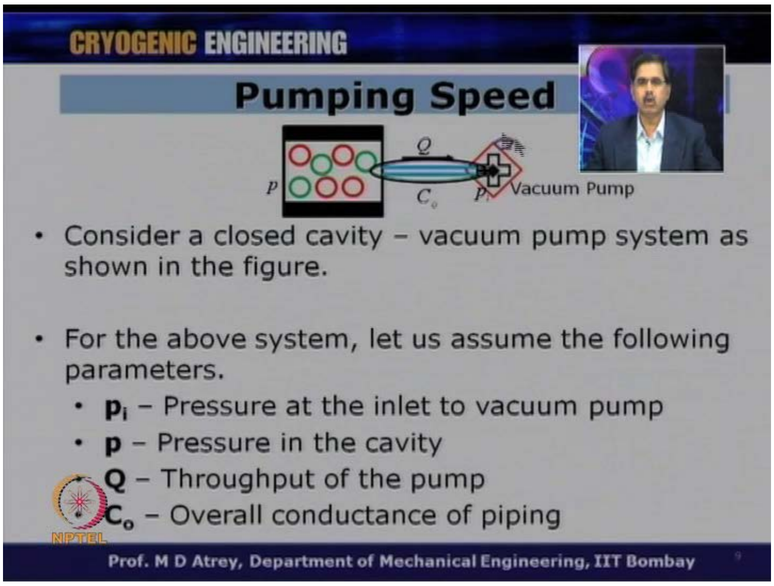

Now, let us come to know what this pumping speed is. So, what we can see here is a cavity or a cylinder which is shown to be vacuumed, and there is a vacuum pump kept on the right, the vacuum pump is a is a known device to me and therefore, vacuum pump will have known characteristics; however, this vacuum pump is directly not mounted on the system to be vacuumed, but it is connected to some piping arrangement and therefore, the conductance of this pipe also become very important.

So, consider a closed cavity and a vacuum pump system. So, closed cavity vacuum pump and connections given by pipes over here, this pipe can have different diameters, different elbows, different joints, and corresponding to that we will have a different overall conductance for this pipe. So, you can see a closed cavity vacuum pump system as shown in this figure, for the above system let us assume the following parameters.

P I is the pressure at the inlet to the vacuum system which is P i at this point, p is the pressure in the cavity. So, this p and this P i will be different, the vacuum at this level will be very, very high because I have got a vacuum pump here. So, the pressure at this point will be less while the pressure at this point will be little bit more, and how much more will depend on the conductance of this alright.

So, we know that we can suck the gas molecular from this only when that the pressure at this point is going to be less than the pressure at this point and therefore, this vacuum will have a different pressure P i, while this system to be vacuum or the cavity to be vacuum will have pressure little bit higher than what you get at the vacuum pump. Q is the throughput of the pump. So, so many bar liter per minute or pressure into liter per minute, what is the unit of throughput of the pumps which will be known to you. And the C o is the overall conductance of the piping. So, depending on the pipes that have been used, the couplings that have been used, the elbows that have been used will have some overall conductance of this pipe.

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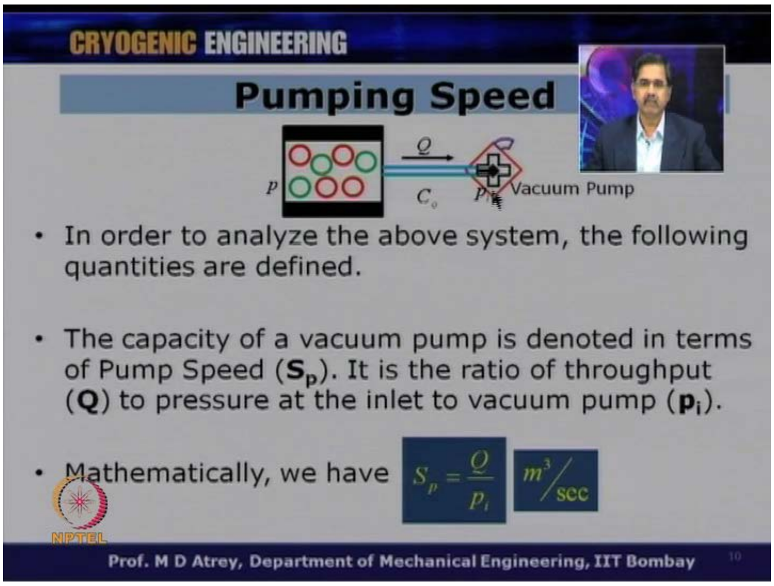

In order to analyze the above system the following quantities are defined, and what are those quantities? The capacity of a vacuum pump is denoted in terms of pump speed. So, we got a pumping speed S p and this is known to me, because the capacity of vacuum pump, when I buy a particular pump I should know what is its capacity. So, how many meter cube per minute, meter cube per hour, liter per minute, liter per hour that this particular vacuum pump can suck alright. And again this capacity normally is given in for a particular gas, let us say nitrogen normally it is defined as. So, every vacuum pump when you buy it will have its capacities defined alright, so a pump speed is normally defined for a given vacuum pump.

So, what do we define this pump speed as? It is the ratio of throughput Q to the pressure at the inlet to the vacuum pump alright. So, Q upon P i and therefore, we can see mathematically S p is equal to Q upon p i. So, whatever throughput it is basically getting right, pressure into volumetric flow rate divided by P i at this particular point, we will get that as a throughput divide by P i is going to be my pumping speed, and the unit of this will be like volumetric flow rate meter cube per second, it could be liter per minute, liter per hour depending on the kind of pump we have been talking about.

So, pumping speed as we said is a standard for a given pump, depending on the pumping speed cost of the vacuum pump also will increase or decrease. So, S p is equal to Q upon P i, P i is the pressure at the vacuum pump.

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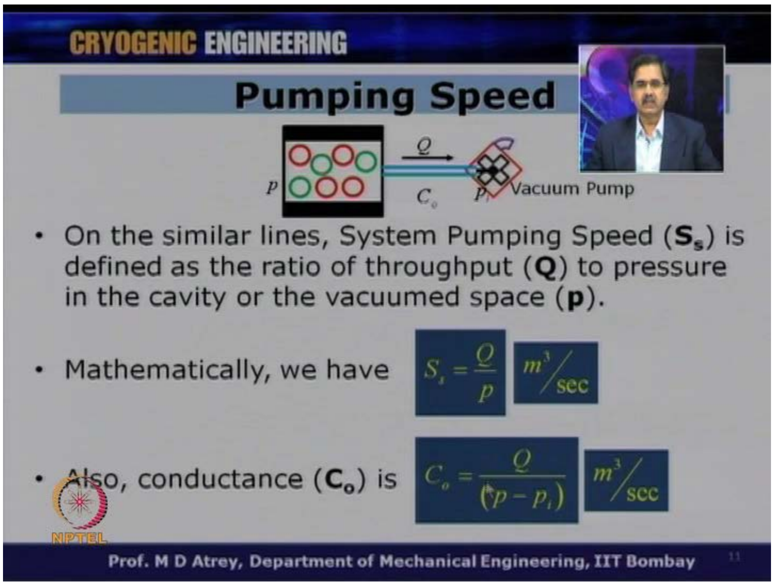

On the similar line this is a system pumping speed. So, we got a vacuum pumping speed which is the pumping speed normally refer to as, and then we had a system pumping speed which is specified for the system here, this is my system to be vacuumed, this is my vacuum pump I have been utilized, and this is the way I have connected this vacuum pump to the system.

So, on the similar line system pumping speed S s is defined as a ratio of throughput Q to pressure in the cavity or the vacuum. Now I am talking vacuum space; that means, I am talking about the system. So, this pressure as I have said is going to be more than pressure what you see at a vacuum pump. So, system ultimately what is important for me is what is my system speed, because I am interested in vacuuming in this particular cavity, to get this vacuum over here I am using this pump, but if I use a different connections as given over here my system pumping speed is going to be much different than what my vacuum pumping speed will be alright, and let us see how they are related basically.

So, mathematically we see that S s which is my system pumping speed is equal to Q upon p Q is the throughput, but the p is now the pressure of the system over here alright. So, this pressure is going to be little bit more as compare to what you get P i as this point. So, definitely what you understand from here S s is going to be less than s p, so system pumping speed is going to be less than the vacuum pump speed or the pump speed. Again the units are meter cube per second, liter per minute or whatever units you want to use.

The conductance now, everything depends what is the value of S s depending on the value of s p, but S p the pump is connected through the system to be vacuumed through a conductance all right. So, I can have a very large vacuum pump, but I can connect it through a very small cube and therefore, the conductance in this case is going to be very small and therefore, that will affect the system pumping speed. So, the conductance is given by Q upon p minus P i which is what we have seen earlier.

So, what is the difference of pressure across this piping? p minus P i this will determine what is my conductance as p is more than P i, and this is again unit will be conductance unit will be same as pumping speed.

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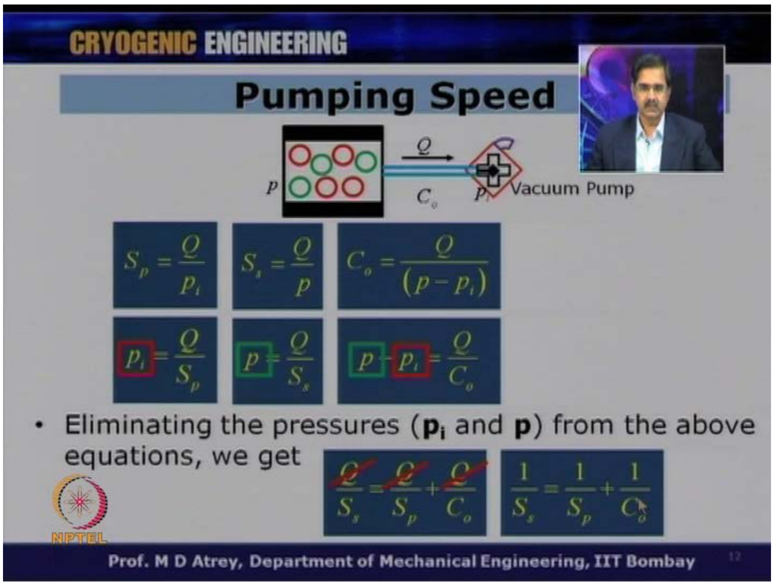

So, we know now S p is equal to Q upon P i, S s is equal to Q upon p and C 0 is equal to Q upon p minus p i. So, now I got a relationship between p P i p minus P i, and how are these related, how are this pressures related? P i is equal to now Q upon S p, p is equal to Q upon S s and p minus P i is equal to Q upon C 0, Q upon overall conductance.

So, if I put this values of p and P i over here, I will get the relation which is connecting now C 0 S s and S P, I get connection between pumping speed, system pumping speeds and overall conductance. So, if I did that eliminating the pressures P i and p form above equations what we get therefore, is Q upon S s is equal to Q upon S p and transpose you get little bit, I will get Q upon S s is equal to Q upon S p plus Q upon C 0, and I can eliminate Q q Q form this equations, and what you get ultimately is 1 upon S s is equal to 1 upon S p plus 1 upon C 0.

Now, this is a very important relationship which connects system pumping speed to the pump speed to the conductance of the pipe, which is going to be connecting my pump to the system. So, it depends on what is my pumping speed and what is my conductance, this two will determine together what is my system pumping speed. And therefore, these are very important relationship to decide if I want to design a particular system vacuum system to get a particular S s, I will have to worry about both these parameter S p as well as C 0, and let us see how do they show up.

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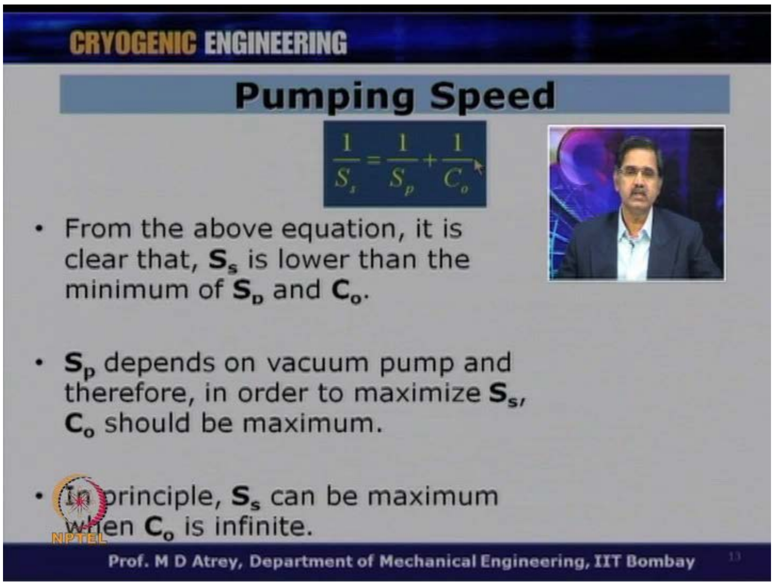

So, this is my relationship 1 upon S s is equal to 1 upon S p plus 1 upon C 0, from the above equation it is clear that S s is lower than the minimum of S p and C 0, this is simple mathematical thing, you got a reciprocal rule S s which is the resultant of S p and C o is going to be less than the lowest of these two, so if S p out of S p or C 0 whoever is lower than that value will be value of S s. Normally, I would like to be S s to be very high, but you have to understand that S s cannot be more than the low, I mean it will basically be depending on what is the lowest of this two alright.

So, S p depends on vacuum pump. Let us understand now, what is the parameter that dominates the value of s s. So, S p is the vacuum pump which I have bought and therefore, I know everything about S P, i know that so many liter per minute, or so many meter cube per second is what my pumping speeds of an available pump is all about. So, S p depends on a vacuum pump and therefore, in order to maximize S s, if I want to maximize S s I have to maximize my c o.

So, if I increase my C o I can have S s coming closer to the minimum of S p and C o. In principle, what could be the maximum value of S s? The maximum value of S s could be S p provided C o is infinite, if C o is infinite 1 by infinity becomes equal to 0 and we can say that 1 upon S s is equal to 1 upon S p, in that case we can say that the maximum value of system speed is going to be, can be equal to the pumping speed.

So, in principle S s can maximum be equal to S p, and S s can maximum when C o is infinite.

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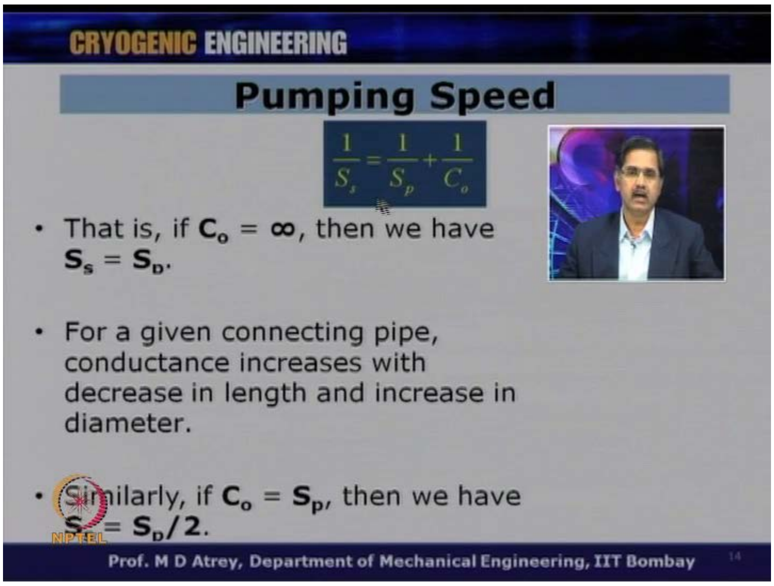

So, when C o is infinite what we get is this, if C o is infinite then we have S s is equal to S p. Can we have C o as infinite, is it possible? We will see that later.

For a given connecting pipe now conductance's increase with decrease in length and decrease in diameter. So, can I make my diameter infinite or length to be equal to 0? Then only my C o is going to be infinite. So, in principle I cannot do, so what I can do? I want to increase my diameter as much as possible, and I want to decrease my length connecting vacuum speed vacuum pump to the system to be vacuum to a minimum distance.

So, keep minimum length of a pump away from the system to be vacuumed, and keep maximum diameter of the connecting pipe. So, that the conductance is going to be higher in that case and therefore, S s can go as possible, but as you understood S s can maximum be equal to S p and not more than that. So, let us try to go as close as much to the value of s p, but everything then depends on what is my conductance.

Similarly, if C o is equal to S p. Let say in a case just an extreme case, if C o is equal to S p then my S s is going to be half of s p. So, you can see that if C o is equal to S p then we have S s is equal to S p by 2. So, go on increasing conductance as much as you can so that this parameter becomes very small, in that case my S s will approach to S p value, and that is what we want to ultimately achieve. So, my system pumping speed should approach the vacuum pump speed.

Now, having understood what is system pumping speed, what is pump speed, what is conductance all this thing having understood, let us now come to what is pump down time.

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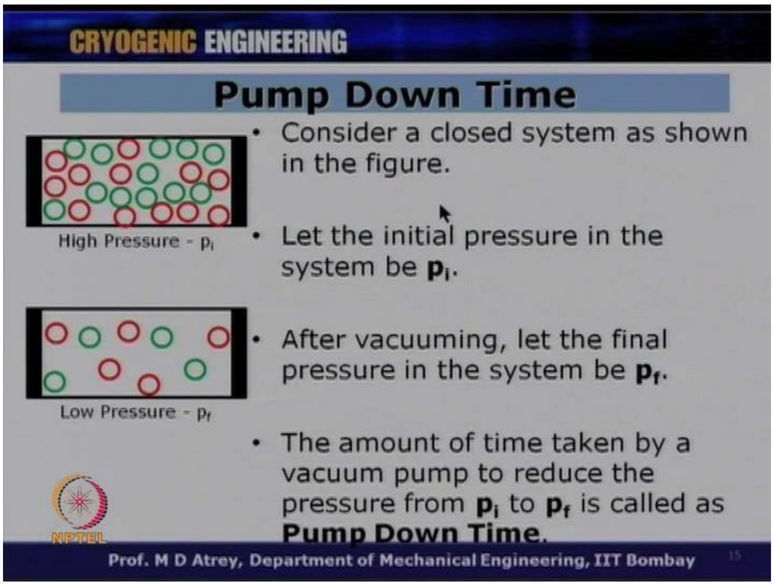

So, consider a closed system as shown in the figure, this is my high pressure to begin with, let the initial pressure in the system be P i, before I started vacuuming my pressure is going to be initial pressure which is P i, and after vacuuming I reach final pressure which is p f. So, I can see that less number of molecules over here, and this is my completely low pressure which I have got after vacuuming from P i to p f.

So, when I connect my vacuum pump to this unit, ultimately I reach the value of p f. And this time it will require lot of time basically, it will start sucking the molecules, and how much time it takes to reach the value p f will depend on the conductance I have used, the vacuum pump I have used and all those parameter will come into picture. So, the amount of time taken by a vacuum pump to reduce the pressure from P i to p f is called the pump down time. So, it will depend all the parameters, it will depend on the vacuum pump, it will depend on the conductance I have used to connect this vacuum pump to the to the system to be vacuumed.

So, all this parameters will determine what is my pump down time, and this pump down time is a very important criteria, because if I want to do an experiment which will last for only two hours and in one day I would like to do this experiment two or three times, my pump down time should not be more than two or three hours, I should get a vacuum within half an hour or 10 to 15 minutes and therefore, I have to design my vacuum system in such a way that I should get my vacuum p f, what is my pressure p f within 10 to 15 minutes or half an hour or something like that all right.

So, this a very important and it depends on what is my p f I am talking about, what is my conductance, how do I connect that conductance to the vacuum pump, and all those parameters will determine what is my pump down time.

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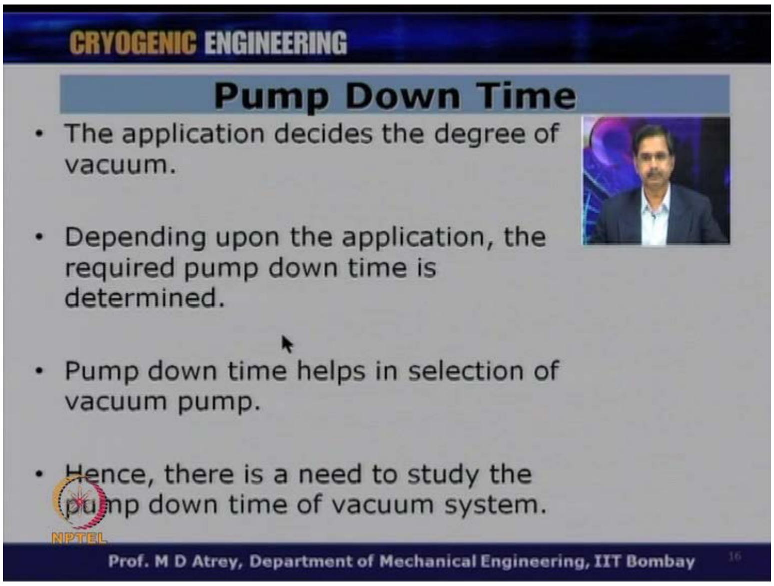

So, application decides the degree of vacuum. If I want to decide a particular experiment, that experiment will decide what degree of vacuum do I require, what is my p f requirement? What I want minus 5 tour, minus 6 tour or minus 3 tour vacuum levels, and this is what we call as degree of vacuum. So decide first, what is that lowest pressure I want, what is vacuum I want, what is degree of vacuum I want?

Depending on the application the required pump down time is determined. So, according to that I will decide what is my pump down time? Should I have 15 minutes, 20 minutes, half an hour, 2 hour, 5 hour, complete day all right? It depends on application; it depends on how big my system is also, because bigger the system bigger time it is going to take to pump down all the molecules all right.

So, pump down time helps in selection of vacuum pump. So, I have to decide what is my volume to be sucked, what is my volume to be vacuumed? According to that I will decide what my conductance should be and what my pump should be. So, ultimately depending on my application, depending on my pump down time I will decide the vacuum pump to be employed for this purpose.

So, the vacuum pump is, the pump down time is a very important criteria to decide a vacuum system, hence there is a need to study the pump down time of vacuum system. So, can I calculate this pump down time? And that is we are coming over here. So, if I know pump down time can I select a particular vacuum system or vacuum pump for a given operation and therefore, this parameter come down time is a very important parameter.

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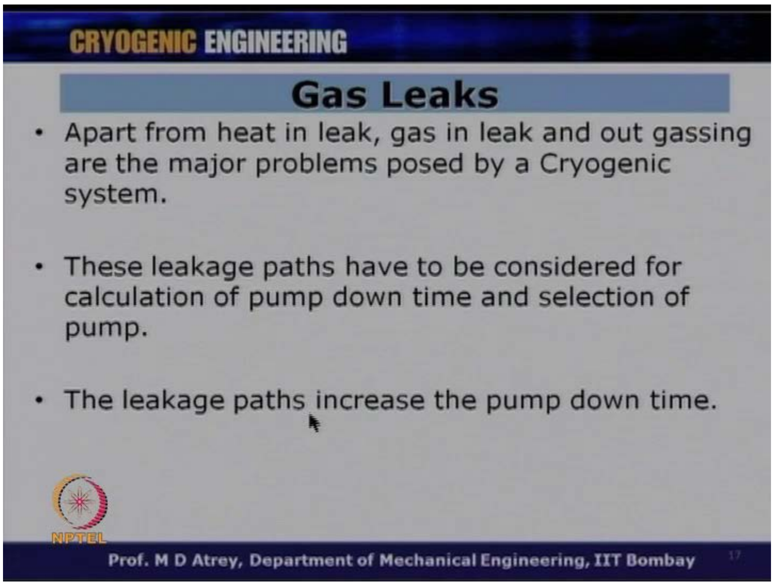

Now, this parameter will also depend on what are the leakages paths? The gas is going to get leaked over a period of time, and the gas is going to get leak leakage paths could be definitely there, as long as the fabrications happen you got always joints, you got some seal matters, you got a material which out gases and therefore, gas leaks is always going to be there.

So, apart from heat in leak, gas in leak and out gassing are the major problems posed by cryogenic system alright. So, there is during fabrications some gas has gone into the material and this will out gas over a period of time, this will come out over a period of time and therefore, there will be constant gas in leak in the system, and this has to be taken care by the vacuum pump.

These leakage paths have to be considered for calculation of pump down time and selection of a pump. So, I should know what are these leakages paths and what is this leakage quantity also, what are the flow rates also I should know. The leakage paths increase the pump down time, more the leakage path it will take more time to reach a required vacuum for a particular application. So, I should know all this leakage paths and I should know all this quantities that are leaking, and what are the gases also I should have an estimate for those things also all right.

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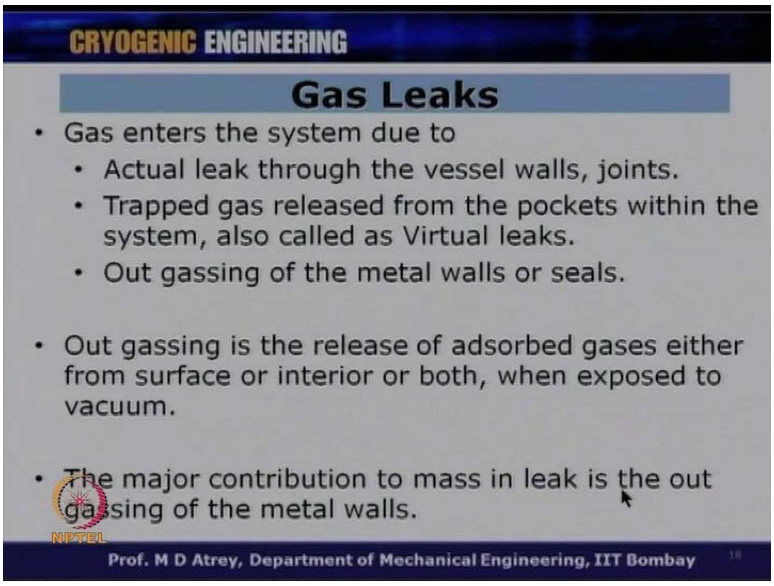

So, gas enters the system due to actual leak through the vessel wall joint so this should be minimized actually. So, you got a well it will have some leak; however, and whatever that leak is it has to be considered. So, actual leak through the vessel walls and joints, suppose you got a joint which is the mechanical joint or which has got a seal across oaring across it, then it will start leaking over a period of time, it will have some it is leak rate associated with that thing that also has to be considered while calculating the pump down time.

Then the trapped gas release form the pockets within the system also called as virtual leaks. So, there are material surface is there, and there are some trapped gases inside this material it will get released once you start vacuuming, that also has to be estimated. See this parameter become very important if we want to go down to minus 8, minus 9 kind of vacuum alright, so these are very important to be considered while calculating pump down time. Out gassing of the metal walls or seals and this is what you saw just talked about. All the non metals all the metals in a system will start out gassing, and we got some this out gassing quantities in available table also for vacuum technology.

So, one should know what are these out gassing rate for a given materialm for a given seal etcetera. All this have to be considered in order to consider gas leak, and in return it will basically taken into consideration to calculate the pump down time. Out gassing is the release of adsorbed gases either from surface or interior or both, when exposed to vacuum alright. It is a very slow process, out gassing happens over a period of time, over 6 month time, over a 1 year time, and it all depends on what fabrication the material has gone through and therefore, all this things have to be understood when we start designing for a particular application of vacuuming, and especially where vacuum is very plays a very important and crucial role.

The major contribution to the mass in leak is the out gassing, so out of all this parameter the out gassing is the very important parameter that has to be considered. The contribution from out gassing is going to be a major contribution to mass in leak, and that is why it has to be considered correctly while designing a particular vacuum system.

So, now let us understand how do I derive an expression for calculating pump down time?

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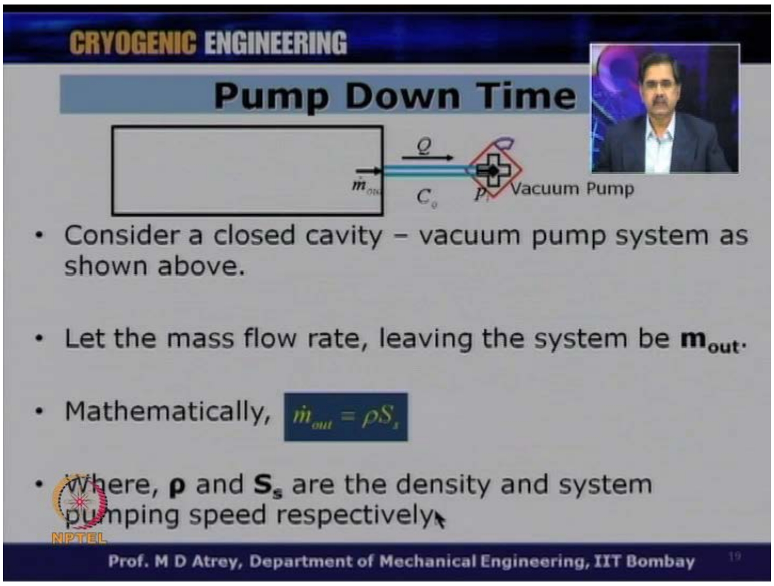

So, let us see this system, so considering the close cavity as shown over here with the vacuum pump system. So, you got a entire thing will be vacuum pump system a close cavity connected to a vacuum pump through a given conductance all right.

Consider a closed cavity vacuum pump system as shown above, and we have got two parameters, let the mass flow rate leaving the system is m dot out which is coming from over here and this is my system to be vacuumed, this is my piping which has got its conductance overall conductance as C 0, the throughput could be called as Q from here, and this is my P i which is the pressure at the vacuum pump or the vacuum level basically at the vacuum pump.

So, mathematically I will say m dot out is equal to rho into S s, what is my S s? S s is the system pumping speed, so depending on S s I got some meter cube per second multiplied it by k g per meter cube and therefore, what you get is a mass flow rate which is leaving the system which is m dot out inlet us say k g per second k g per hour whatever. So, m dot out is equal to density of the gas into S s alright, where rho and S s are the density and the system pumping speed respectively, please understand this clearly.

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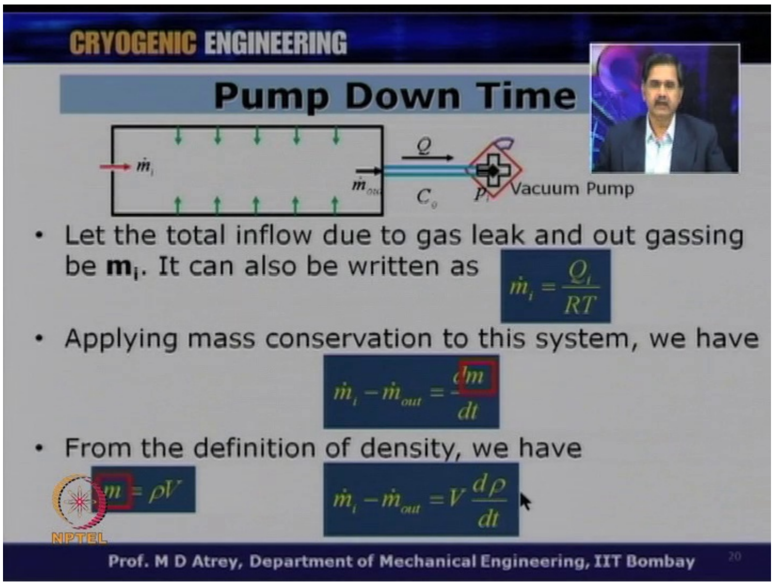

Now, similarly I will have some m dot i, and let the total inflow due to gas leak and out gassing be m dot i, it can also be written as m dot i is equal to Q I divided by RT. So, depending on heat in leak now, depending on the gas in leak in a system, so you got a several joints, we have got a several out gassing possibilities, and depending on all this seal materials used etcetera, we will have some Q i and therefore, as the result of which we will have some m dot i alright. And this could be again a constant or it could be a question of question of time, it could be dependent on time alright, so it can change with time also.

So, let the total inflow due to gas in leak and out gassing be m dot i, it can also be written therefore, as m dot i is equal to Q I upon RT. Now, applying the mass conservation to the system, so I am talking about system only the cavity to be vacuumed right now, where m dot i is mass in leak and m dot out is mass which is going out of the system.

So, we have m dot i minus m dot or is equal to D m by dt , and this is a very standard expression for flop conservation of mass basically. From the definition of density we have m is equal to rho into v, this is my volume and therefore, m is equal to rho into v and therefore, m dot i minus m dot out is equal to v into D rho by dt . So, if I write D m by dt basically, I can write D m by dt in terms of D rho by dt multiplied by volume.

So, now I got expression which is talking about D rho by dt and therefore, can I relate it to dp by dt now? Yes I can.

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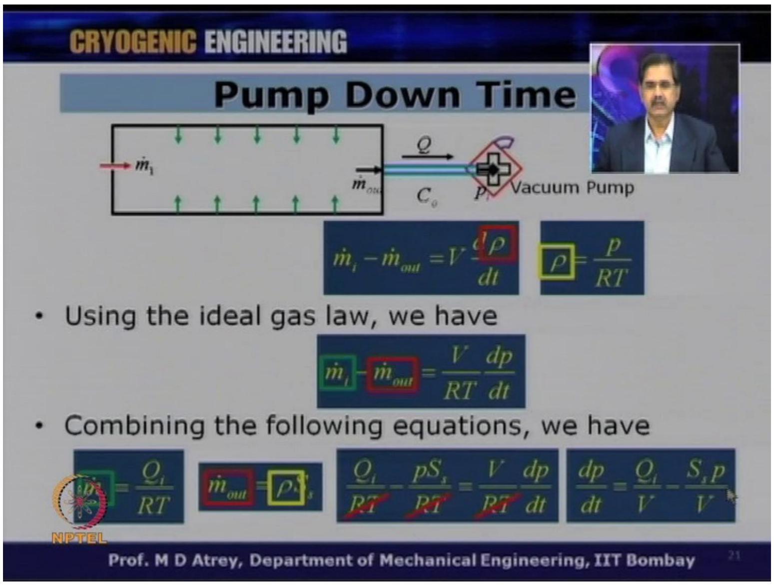

So, m dot i minus m dot out is equal to v into D rho by dt , which is the change of density with time using the ideal gas flow now what we have is equal to p v is equal to RT. So, we got p is equal to rho RT and therefore, now I got expression for rho in terms of p and RT, where RT could be considered to be the constants and therefore, now expression changes and I get an expression which is talking about on dp by dt which is the pressure change with time, and this is what we are aiming at basically when we are trying to vacuum this system out basically.

So, m dot i minus m dot out is equal to v upon RT, RT being constant is coming out of this and what we get is the dp by dt , we get expression for dp by dt now. So, combining the following equations now we have, we know that m dot i is equal to Q i upon RT, we know m dot out is equal to rho into S s this is what we have seen earlier, put those values over here what we get (( )) is equal to Q i upon RT minus replacing this rho as p upon RT what we have got here, we get p upon RT into S s that is p s upon RT is equal to v upon RT dp by dt and therefore, all the RT is going to get cancelled and what you get ultimately is dp by dt is equal to Q Q i upon v minus S s into p upon v.

So, you got a expression now which depends on system pumping speed, the pressure the volume to be vacuumed, and Q i which talking about basically the mass in leak throughput.

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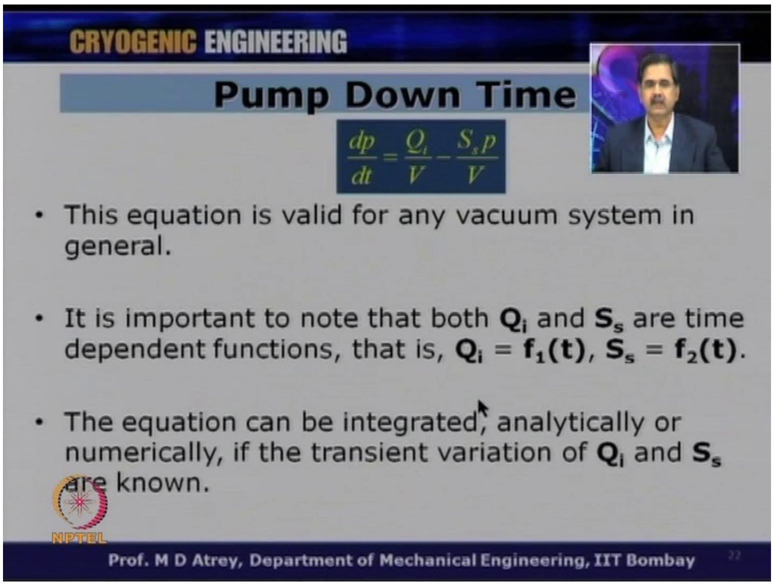

So, I got expression like this now, and if I want to now calculate the time to get a pressure from p 1 to p 2 I can basically integrate this, and this is what I will do some mathematical treatment of this.

This equation is valid for any vacuum system in general, for any vacuum system now which has got mass leak as given by Q i we got a system what we want, we got a system pumping speed is what we desired to have given volume of the cavity to the vacuum, and the pressure we going to talk about what are the vacuum level that we are talking for this volume, if I know this is my general expression for dp by dt , and then one can get pumping system pumping speed, and then I have to decide what my pump speed should be for in order to get my S s for a given pre requirement.

So, this it is a very general expression and whatever you want to do with this now, you can do all the mathematical treatment to this. It is important to know that both Q i and S s are time dependent functions. So, my mass in leak throughput can change with time, it can change because gas in leak because out gassing being dependent on time can change with time, also I can say my system pumping speed also could change with time.

So, I can write Q i as a some function of time and S s also is some function of time. So, if Q i is a f one of t, S s is function f two of t, basically to show the time dependence of this two parameters. The equation can be integrated analytically or numerically if the transient variation of Q i and S s are known. If I know the function f 1 all right, polynomial function or any other function if I know the dependence of Q i on time, then I can put that function in this value and then integrate it to get.

So, I should know basically some time dependent function of Q i, similarly I should know sometime dependent function of S s, and I could in then put this values put this expressions analytically in this particular expression and then integrate it, and I can get that time to get some pressure from p 1 to p 2 or P i to p f.

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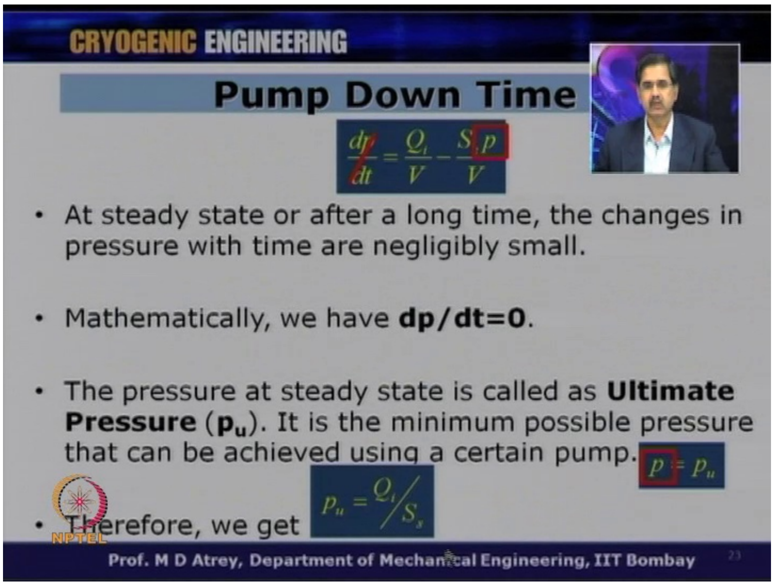

So, in this expression we say at steady state, so ultimately when I run this vacuum system for a long time, let us say many hours, many days depending on what is the volume we are talking about, what is the Q i we are talking about, and what is the pressure in our site is, what is my vacuum I am talking about.

So, at steady state I will found that I will find that after particular time there is no change in the value of pressure, my average some steady state value of the vacuum, in that case I will say dp by dt equal to 0 at that steady state. So, at steady state or after a long time the changes in pressure with time are negligibly small and therefore, I can say mathematically my dp by dt equal to 0 and therefore, if I say dp by dt equal to 0 I can say now, I can have a relationship between Q i and at that time I got a pressure as ultimate pressure, the pressure at the steady state is called as ultimate pressure p u. So, this p value has become my p u, it is the minimum possible pressure that can be achieved using a certain pump alright.

So, whatever vacuum system I have used, whatever conductance's I have used after connecting those, after running it for a long time what pressure I have got is p u, at that particular time I got dp by dt is equal to 0 and therefore, I got the pressure t as p u. And these are minimum possible pressure that I could get, minimum vacuum I could achieve using a certain pump and therefore, I will get p is equal to p u, and putting that value of p is equal to p u in these I will get a relationship now as p u is equal to Q i upon S s, cancelling v out here transposing on this side I get ultimate pressure that can be obtained depends on Q i and system pumping speed alright. So, Q i upon S s is what minimum pressure I can achieve, if I know the value of Q i can out this and I can get my p u value, if I know the system pumping speed put it over here and I can know that my ultimate pressure. ultimate vacuum that is possible with such a mass flow in leak throughput, and such a system pumping speed I can get a value of p u to be equal to this.

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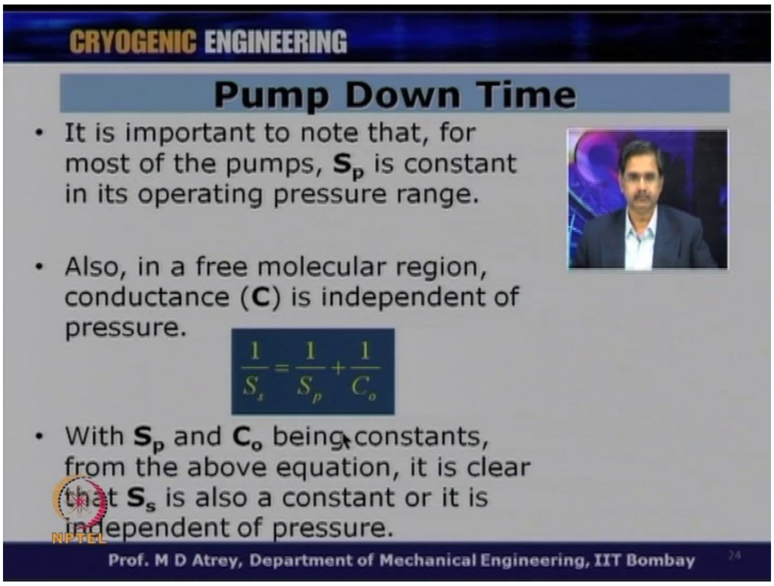

It is important to note that, for most of the pumps, S p is constant in its operating pressure range. This is the fair assumption to say that if I got a particular pump, it has got its own pumping speed and therefore, I will say that this pumping speed is constant right from when you keep the machine on and you fairly constant S p over a period of time alright. So, just fair assumption I will say that, for a given pump pumping speed remains constant; that means, S p does not depend it is not a function of time, S p is constant throughout.

Also, in a free molecular region, conductance C is also independent of pressure. If you see our expression, if my pressure is constant or if I am in free molecular region, C is because C depends largely on the gas properties, and C largely depends on diameter and the lengths the geometric parameters of that pipe which is going to be connecting the vacuum pump to the system.

So, I can say again that conductance is also not a function of time. So, S p is not a function of time, conductance is not a function of time and therefore, in this relationship in I can say 1 upon s is equal to 1 upon S p plus 1 upon C o, we can say from here if S p and C o are a constant from the above expression, it is clear that S s is also a constant or it is independent of pressure. I can… See S s can be a function of time depending on whether these two are function of time. If I know the time variance, time dependence I can put that in earlier expression, but because S p and C o are fairly constant with time, they do not depend on time I can say that S s also can be considered as independent of time; that means, S s is constant or it is independent of the pressure we are talking about all right.

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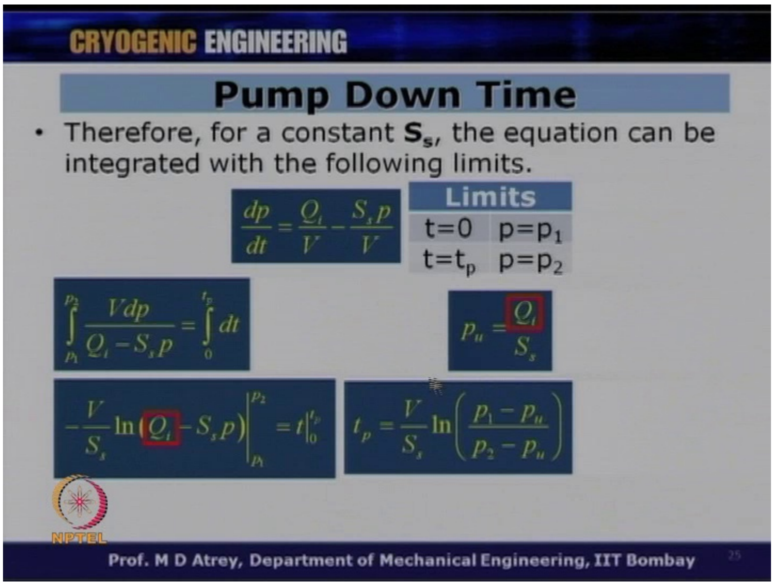

So, we can have this assumption of having system pumping speed as constant. Therefore, for a constant S s the equation can be integrated with following limits now. So, if you go to earlier expression now, I can assume S s to be constant and therefore, this is my expression. And we can now, if I want to find the time dependence on pressure, the only parameter which is depending on time will be in a Q i and therefore, my time will be at t is equal to 0 p is equal to p 1 let us say to begin with, and at t is equal to sometime any time I am talking about t p my p is equal to p 2 all right.

So, this is my time limit I am talking about, where the pressure changes from p 1 to p 2, where the pressure decreases from p 1 to p 2, and if I have integration therefore, I will have integration p 1 to p 2 v dp upon Q i minus S p p we can see from this expression, and ultimately I will have on this side only dt parameter basically. So, 0 to t p dt dt alright, transposing dt on one side and getting all other expressions on other side we can we can get this particular expression. And then I can solving using a simple numerical simple numerical, simple technique of solution solving an integration I can put Q i minus S s p is equal to to x and put the value of dp in terms of that, and then integrating and put some integration rules in place what I get is, minus v upon S s log Q i minus S p p in the limits of p 1 to p 2 is equal to t in the limits of 0 to t. So, just integrate based on available integration rules, what you can get is this expression. So, ultimately now put the value of p is equal to p 2 and p 1 in this expression and I will get parameter, and we know that p u is equal to Q y upon S s putting the value of p u also over there, replacing Q i as p u into S s in place I get an expression like this. So, I get t p is equal to now v upon S s log p 1 minus p u upon p 2 minus p u.

So, p 1 in a given time t p, pressure decreases from p 1 to p 2, while my ultimate pressure value is p u which is equal to Q i upon S s. I got an expression now which talks about pumping time, pump down time for a given volume to be vacuumed which S s as the pumping speed, which is constant it does not change with time, while the pressure is during this t p time comes down from p 1 to p 2, while the ultimate pressure that could be achieved is going to be Q y upon s s.

So, here is an expression I can now compete for a given S s, given volume what is the pump down time I can calculate for this expression. And this will be more clear when I do the tutorials I had alright. So, this is the expression for calculating the pump down time. So, what are more important expression is 1 upon S s is equal to 1 upon S p plus 1 upon C o that is the most important expression. And second is expression for pump down time.

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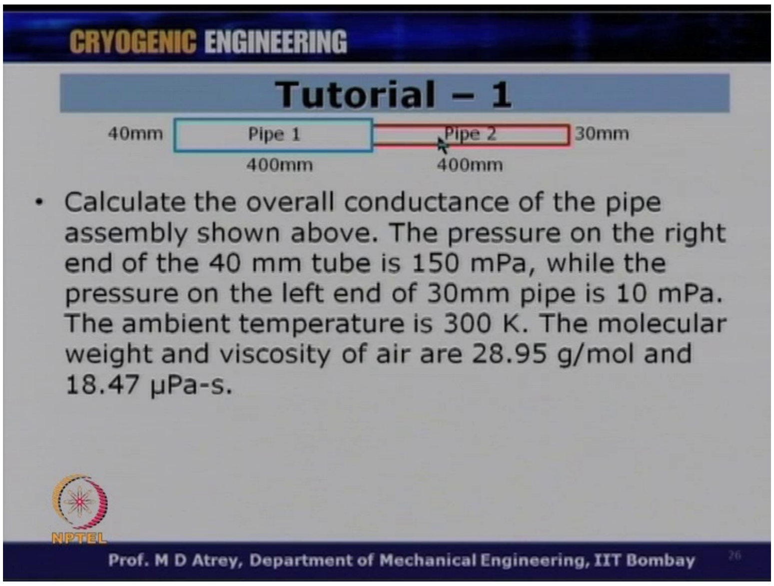

With this background now, let us have a look at the tutorials and wherein you can understand all the basics more clearly. So, tutorial 1, we have got two pipes of two different lengths and two different diameters in series, I think the lengths are same 400 millimeter, the diameters are 40 millimeter of 1 and 30 millimeters of 1 and they are connected in series. And first problem is to calculate the overall conductance of the pipe assembly shown above. The pressure on the right hand of the 40 millimeter tube is 150 mPa, 150 milli pascal on this side, while the pressure on the left of the 30 millimeter pipe is 10 mPa.

So, you can see that you got a 10 milli pascal and 150 milli pascal as two pressures. The ambient temperature is 300 Kelvin. So, we got one pressure on this side, we got one pressure on this side. The molecular weight and the viscosity of the air are given alright. So, basically it is a calculation of the overall conductance of two different diameters, pipes of two different links or same links.

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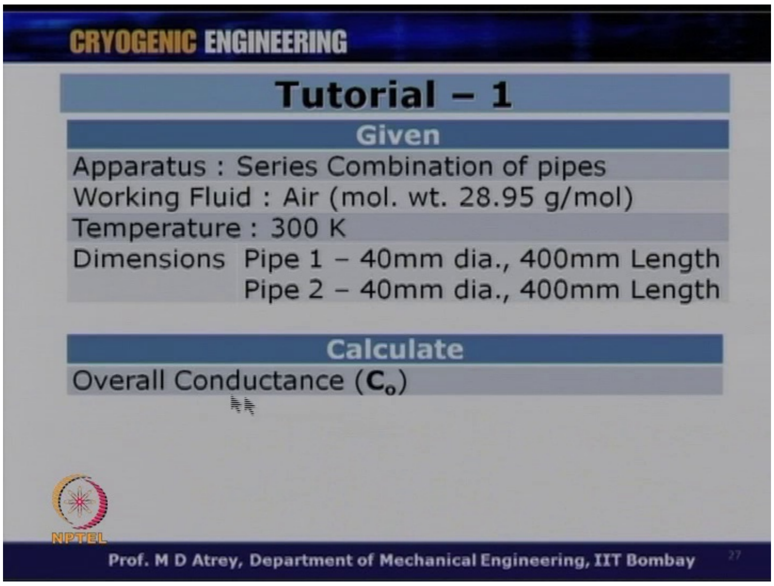

So, what you have apparatus is basically series combination of pipe, we know the working fluid, we know the temperature, we know the dimensions, 40 millimeter 400 millimeter length, pipe 2 40 millimeter 400 millimeter length.

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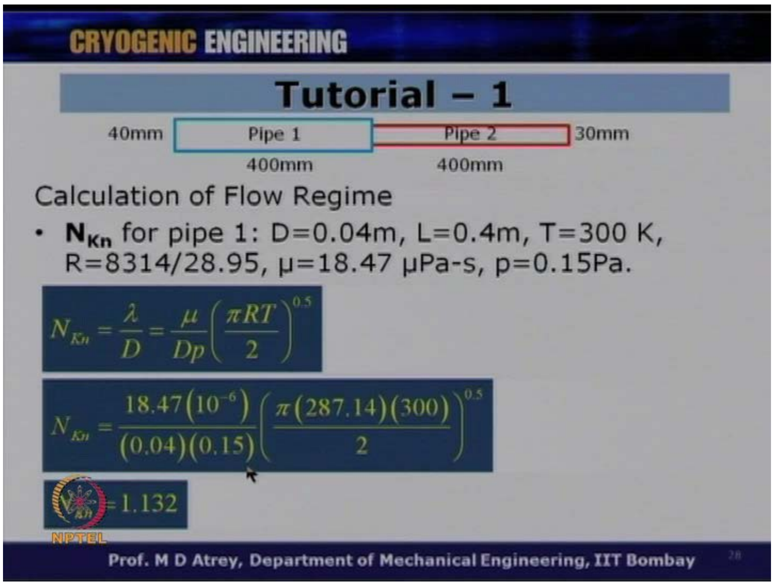

So, calculate the overall conductance C o, calculation of flow regime first in order to ensure in which flow regime I am, because depending on the flow regime I have to use the expressions for conductances.

So, first is Knudsen number for one, we know D is equal 0.04 meter, L is equal to 0.4 meter, t is equal to 300 Kelvin, r mu and p is known to me all right. So, the Knudsen number calculation is lambda by D, this is expression put those values all over here and I get Knudsen number as equal to 1.132, which means I am in free molecular region because Knudsen number is more than 0.3.

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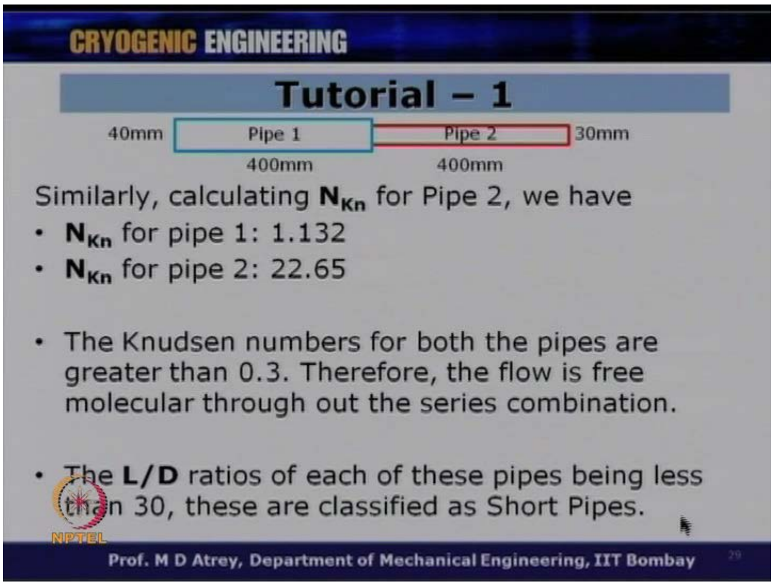

Similarly, I can do it for pipe 2 also, similarly calculating for Knudsen number for pipe 2 what we have is, Knudsen number of pipe 1 is 1.132, and Knudsen number for pipe 2 is 22.65 which is very high, we are not shown the calculations again and therefore, you can see that Knudsen number has been directly calculated for the pipe 2.

The Knudsen number for both the pipes are greater than 0.3. Therefore, the flow is freed molecular throughout the series combination. That is first thing to be established because that will give you now, what expression for conductance to be used from the available table.

The L by D ratios of each of this pipe being less than 30, these are classified as short pipes. We have got expressions for short pipe free molecular flow, and the expression for that conductance could be used for this cases.

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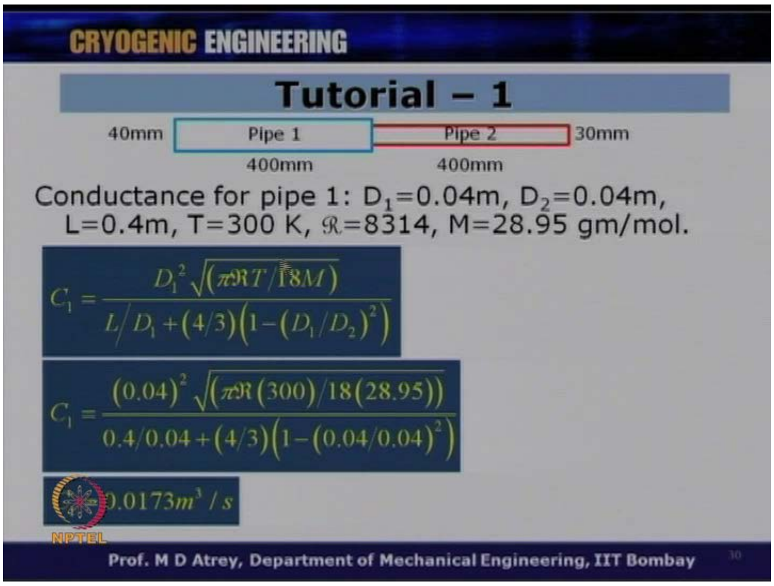

So, conductance for pipe which is D 1 0.04, D 2 is 0.04, L is 0.4, T is 300 Kelvin, and all this things are shown over here.

We have got C 1 for the conductance of the first pipe, put those values and get C 1 is equal to 0.0173 meter cube per seconds. I am not going through all these parameters, just go over the expressions for D 1 D 2 in the short formula could be used as 0.04 straight away.

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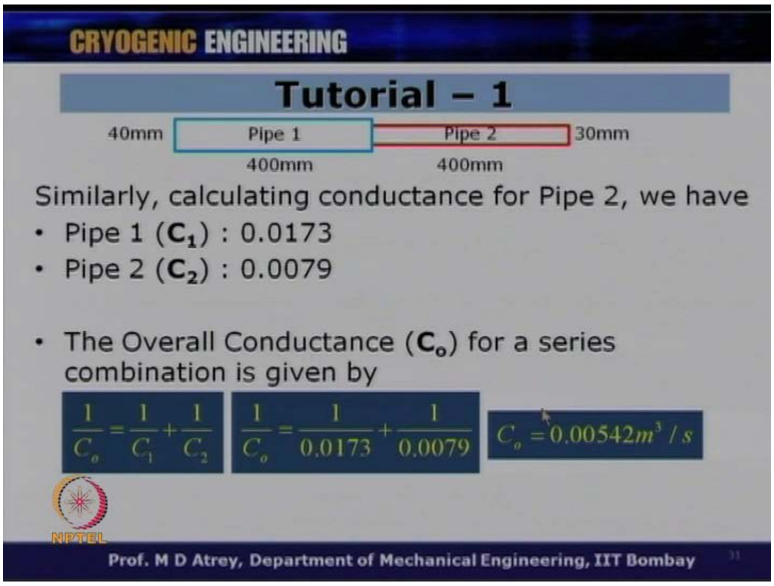

Similarly, calculate conductance for pipe 2 now, we got again pipe 1 as C 1 0.0173 and pipe C 2 we get 0.0079. The conductance for point the pipe C 2 is quite less as compared to what because the diameters are different.

The overall conductance now for a series combination is given as 1 upon C 0 is equal to 1 upon C 1 plus 1 upon C 2 and therefore, I can calculate the overall conductance by this formula is going to be 0.00542; that means I will get over all conductances now which is less than any of this two. So, which is less than point 0.017, which is less than 0.007 also.

So, as the result of this C 1 and C 2 I get over all conductances which is going to be less than even C 1 and C 2, and this is my final conductance now which could be utilized to calculate the system pumping speed, if I know what is the vacuum pumping speed is. So, this is my first tutorial to calculate the overall conductance for a series combination of a given pipe.

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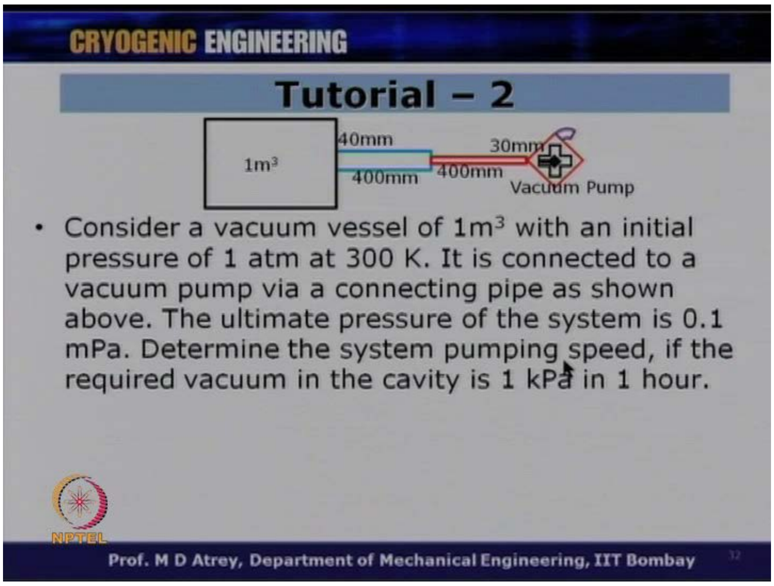

Now, tutorial is, if this arrangement what we have just seen is connected to vacuum a system of 1 meter cube volume, and I got a vacuum pump at the other end over here. So, now I can see that I got a entire system, which are known conductance which we are just calculated with the vacuum pump on one side, and system to be vacuumed on the other side.

So, my problem statement now, considers a vacuum system of one meter cube with an initial pressure of one atmosphere at 300 Kelvin. So, it is what all at atmosphere to begin with. It is connected to a vacuum pump via connecting pipe as shown above. So, it is using the same system which we have just calculated the C o for. So, it is connected to a vacuum pump

The ultimate pressure of the system is 0.1 milli pascal as shown over here. Determine the system pumping speed, if the required vacuum in the cavity 1 kilo pascal in 1 hour. So, I know what is my p u which is ultimate pressure, I know what my p 1 is which one atmosphere, I know what my p 2 is which is 1 kilo pascal, and I know what my t p is which is 1 hour. So, what is important to be known is, what is my system pumping speed, how much what is the system pumping speed for a given pump and for given values of pressures?

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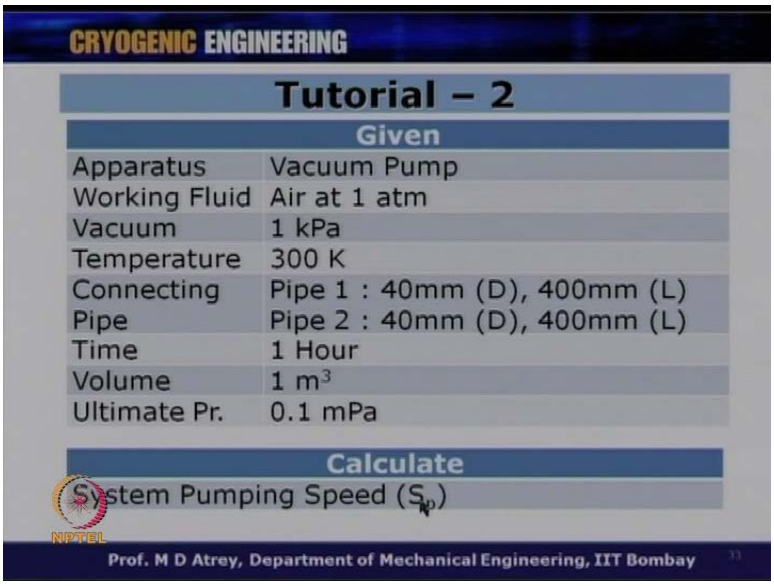

So, what is given to me? Vacuum pump system has been given to me, working fluid is air at one atmosphere, vacuum is 1 k P a, vacuum requirement is 1 k P a, then temperature 300 Kelvin, I have got a connecting pipe 440 millimeter, 400 millimeter 40 millimeter 400 millimeter, then time is 1 hour, volume is one meter, ultimate pressure is 0.1 milli pascal, system pumping speed is S p.

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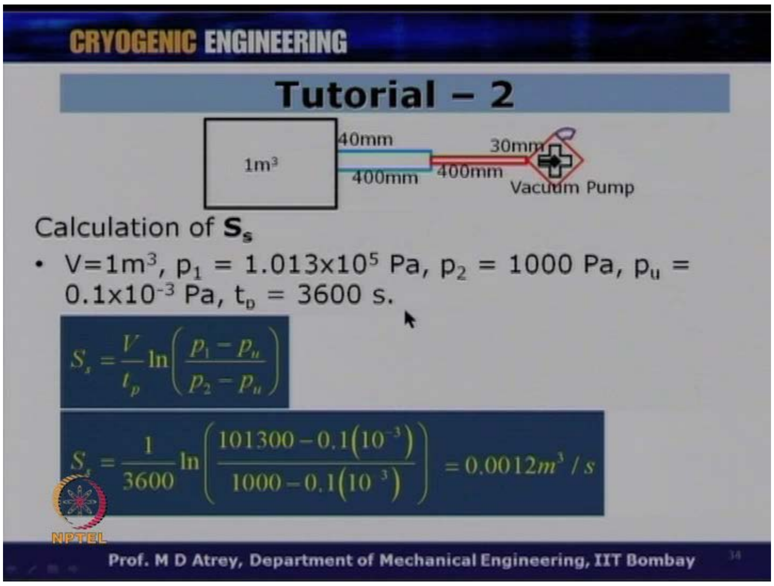

So, calculate the value of S s? So, what I know is all this parameters are known to me, v p 1 is 1.013, one atmosphere to begin with into 10 to the power 5 pascal, p 2 is 1000 pascal alright, then p u is ultimately what is the 0.1 milli pascal which is 0.1 into 10 to the power of minus 3 pascal, and t p is given as 1 hour which is 3600 second. So, I know p 1, p 2, I know p u. So, all the things in the formula is known to me. So, I got a formula which is S s is equal to v upon t p log p 1 minus p u divided by p 2 minus p u, I know almost all the values and I can calculate what my S s is. And therefore, I can put the values over here, and I can get my S s to be equal to 0.0012 meter cube per second, this is my system pumping speed is.

So, if I know system pumping speed, if I know the conductances over here, I can now calculate my pumping speed or vacuum pump speed required for this particular operation, so that I can have t p to be equal to 3600.

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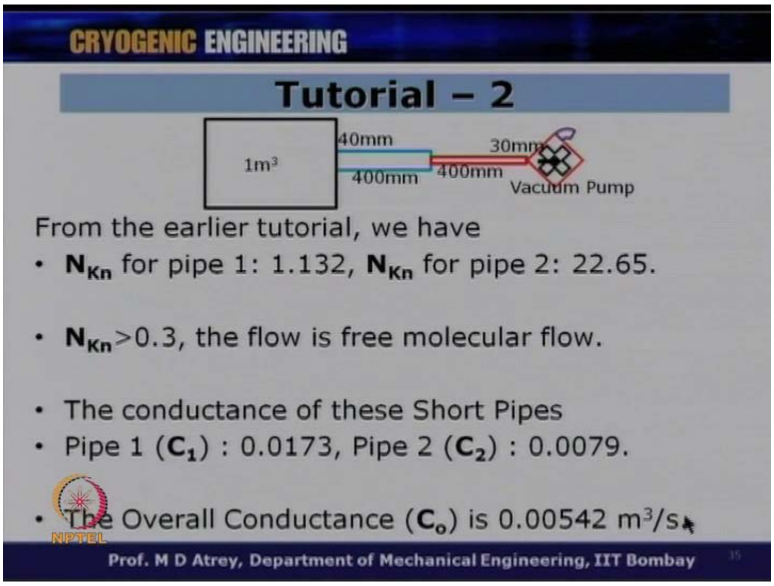

So, from the earlier tutorial we have understood that Knudsen number for pipe 1 is 1.132, Knudsen number for 0.2 is 22.65, Knudsen number is more than 0.3 and the flow is free molecular region, this is what I know. Also I know the conductance of these short pipes, and the conductance for pipe 1 is this, conductance for pipe 2 is this, as the result of which we have got over here conductance C o as 0.00542 meter cube per second.

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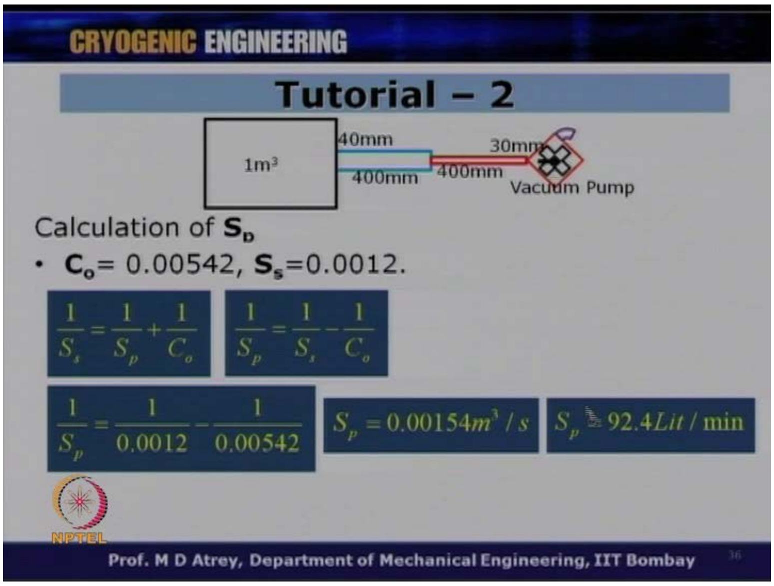

So, if I were to connect all this parameter together, I got the relationship of calculating my S p. What is required for that, is to know what is my overall conductance, and is to know what my system pumping speed. I know both these parameters and therefore, I got expression now 1 upon S s is equal to 1 upon S p plus 1 upon C 0 and therefore, from there I get 1 upon S p is equal to 1 upon S s minus 1 upon C 0 all right. So, put the value of system pumping speed, put the value of conductance, and I will get now what my S p should be, what my pumping speed is should be.

So, 1 upon S p is equal to 1 upon 0.0012 minus 1 upon 0.00542, putting this value I get my pump speed to be equal to 0. 00154 meter cube per second all right. So, S p is going to be 0.00154. So, this is my pumping speed and therefore, converting that into liter per minute S p is 92.4 liter per minute. So, I should choose such a pump now, which is having the pumping speed around this approximately, ideally, theoretically we are talking about.

So, actually I should collect all the out gassing in a connections here, also here and therefore, I should have a pump which has got a pumping speed more than these, at least 50 percent more than these and therefore, this will give me first calculation to understand for a given pump, if I want to do vacuuming from a given p 1 p 2 in 1 hour, with this such a connections over here I should have a pump of capacity 92.4 liter per minute. And this is the way we do these initial calculations, and then put all the reality factors in this in order to decide which pump I should buy. With this we got the summary of the lecture.

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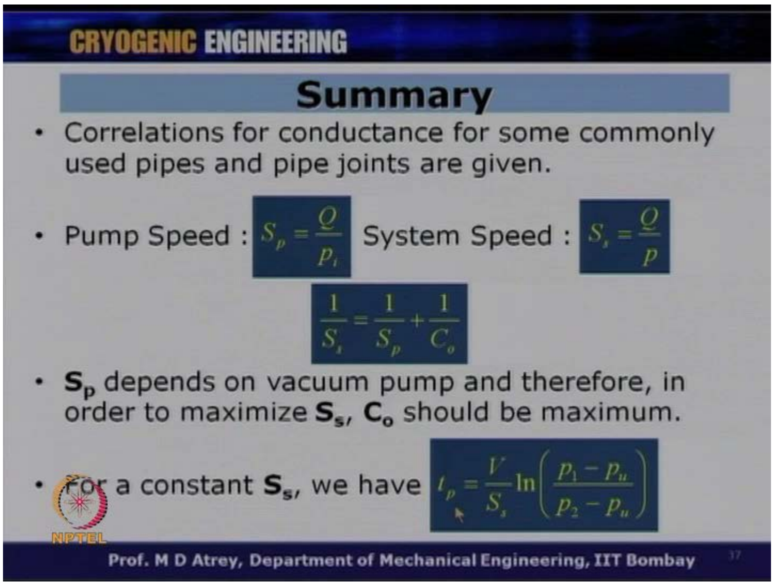

Correlations for conductance for some commonly used pipes, and pipe joints are given. So, you got a short pipe, long pipe, you got a elbow, and we know that conductances is expression for this, if you want to know more such expressions you will have to refer to some vacuum books, where you can get some intricately shift t points and thing like that, where you can calculate the conductance for such a joints such joints and such pipes also. We know that the pumping speed is given by S p is equal to Q upon P i, and we know that the system speed is nothing but which is equal to Q upon p, where p is my pressure in the system, while P i is the pressure near the vacuum pump.

We also know the relationship between S s and S p, and 1 upon S s is equal to 1 upon S p plus 1 upon C 0, from we understood that maximum S s can be equal to S p if C 0 is infinite, if conductance infinite S s can maximum is equal to s p, but S s can never be more than S p all right. So, this is the maximum relationship that S s can be equal to pumping speed only.

S p depends on vacuum pump and therefore, in order to maximize S s C o should be maximum. So, my conductance or the connection on the pump to the vacuum system has to be of a bigger diameter and minimum length, if required this pump should be directly mounted on the system to be vacuumed, there is no point in having a low conductance in this.

So, if I got a very high pumping speed, there is no pointing in decreasing pumping speed by connecting it to some capillary tube or something like that. I should ensure that this pump directly sits on the system to be vacuum, so that my C o is actually closed to infinite value, and that is the way in practice the decisions will be done.

For constant S s we have an expression as t p is equal to v upon S s log p 1 minus p u divided by p 2 minus p u, and this is the expression which we use to calculate the pump down time for a given volume v to be vacuumed from p 1 to p 2. Thank you very much.