Cryogenic Engineering
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Module No. # 01
Lecture No. # 34
Cryogenic Insulation

Welcome to the 34th Lecture of Cryogenic Engineering under the NPTEL program.

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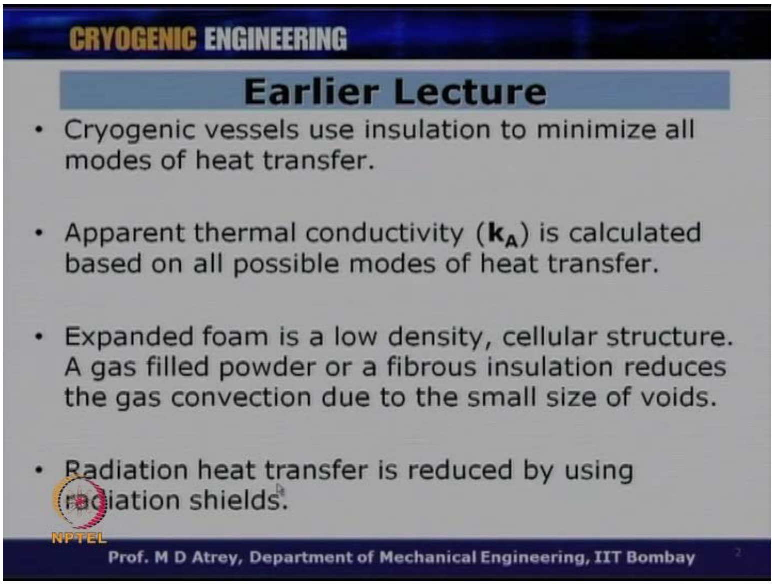

In the earlier lecture, we were talking about insulation, and what we had covered were the following points. We found that cryogenic vessels use insulation to minimize all the modes of heat transfer. Basically, they should be designed to minimize all the modes of heat transfer. The apparent thermal conductivity, and we had defined this apparent thermal conductivity KA, and it is calculated based on all the possible modes of heat transfer. It takes into account the conduction, convection, radiation, etcetera, and based on all these modes of heat transfer, value of KA is normally calculated.

We found out that expanded foam is a low density cellular structure. A gas filled powder or a fibrous insulation reduces the gas convection due to small size of voids. We also found that the radiation heat transfer is reduced by using radiation shields, and I had shown with this with an example that if I put many shields, the radiation heat transfer gets reduced.

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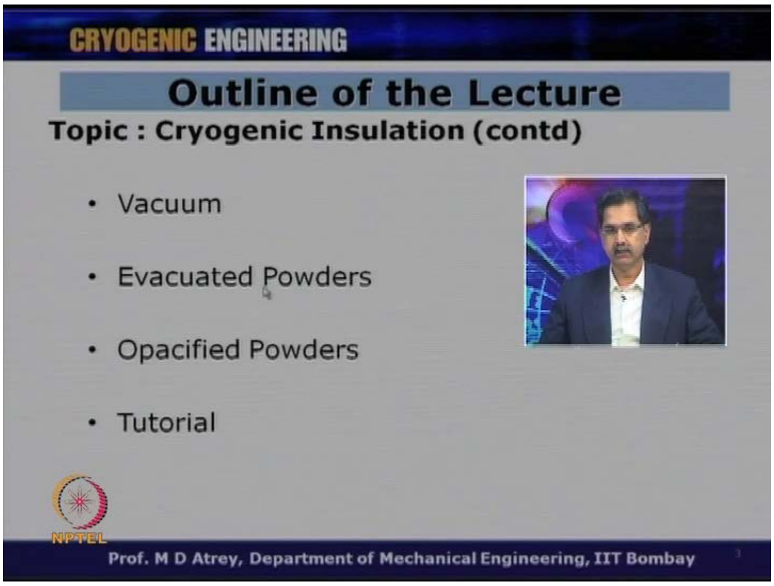

Extending this further, the topic is cryogenic insulation, and what I am going to talk in this today's lecture is Vacuum, Evacuated Powders, Opacified Powders, and we will have a small tutorial in order to compare the performances of these different insulations.

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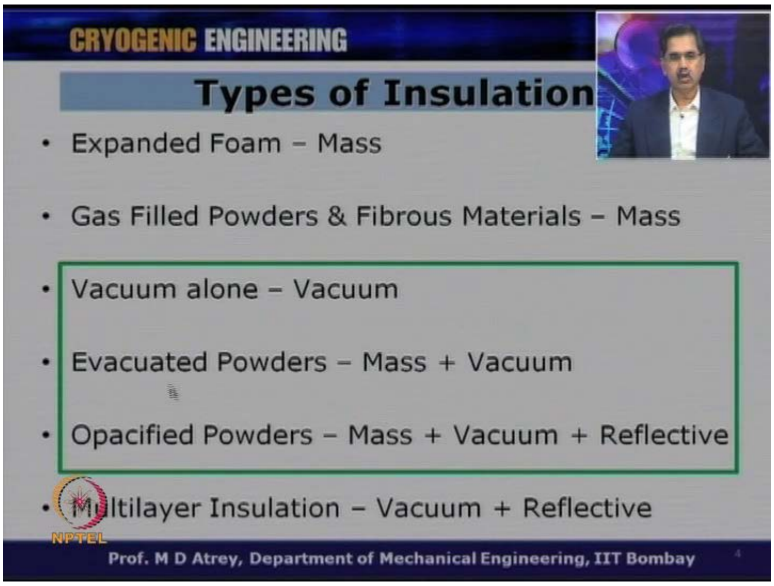

Just to go back and just to let you know how many types of insulations we are studying, and we went through expanded foam, which is a mass type of insulation. Similarly, gas filled powders and fibrous materials; and both these things were covered during the last lecture. And now we are going to cover the vacuum alone, evacuated powder, opacified powder, and then in the next lecture, we will have multilayer insulations. So, what is going to be covered in this lecture are all these three possible insulations.

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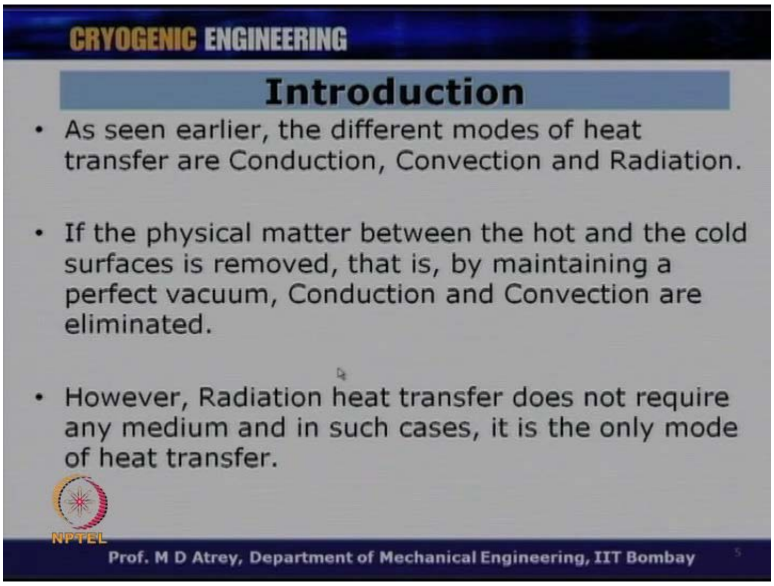

So, as seen earlier, the different modes of heat transfer are conduction, convection and radiation. If the physical matter between the hot and the cold surfaces is removed, that is; by maintaining a perfect vacuum, Conduction and Convection are eliminated. So, if I have a vacuum between hot surfaces or two different surfaces of different temperatures, the medium air or any gas for that matter, which would cause gas conduction or any other type of conduction and convection because of the movement of the gas, this will be completely eliminated. So, what this can be assured by having a perfect vacuum; However, what will remain now will be radiation.

So, however, radiation heat transfer does not require any medium and in such cases, it is the only mode of heat transfer. So, if I have got a vacuum between two surfaces, conduction and convection modes of heat transfer will be eliminated, while, what will remain now is going to be only radiation heat transfer, which depends on the temperatures of the two surfaces.

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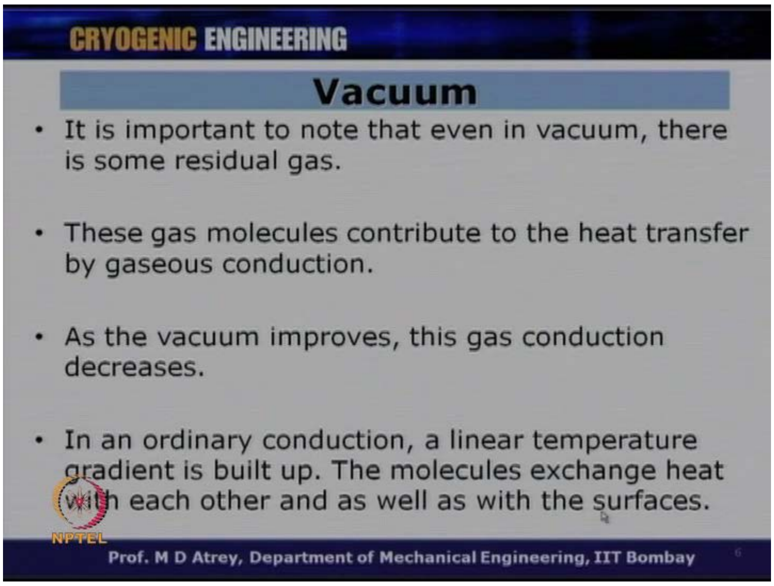

So, let us come to the vacuum first, and as we just found that, even if the vacuum is there, the radiation heat transfer will be there. It is important to note that, even in vacuum, there is some residual gas. Now, this is an additional aspect I had not talked about. So, depending on the kind of vacuum, depending on the level of vacuum, there will be some gas, and this gas also would cause some gas conduction. These gas molecules contribute to the heat transfer by gaseous conduction. In comparison, this gaseous conduction the quantity is going to be very very less; however, depending on the quality of the vacuum, depending on the degree of vacuum, these gas molecules will contribute towards heat transfer by the mechanism called gaseous conduction which will depend on the conductivity of the gas.

As the vacuum improves, this gas conduction will decrease. Naturally, if the vacuum is more and more, it's better and better, the amount of gas between the two surfaces would be less, and therefore, the gas conduction will be less. So, we can find that the gas conduction quantity will actually be related to the kind of vacuum, we will have between the two surfaces.

Now, in an ordinary conduction, when we are talking about general conduction, a linear temperature gradient is built up. You know that a surface is at T 1, surface is at T 2   and if I got some medium having a conductivity K which is constant, then we will have a linear temperature gradient across the two surfaces. The molecules we are talking about having gas between the two surfaces, the molecules exchange heat with each other and as well as with the surface. So, these molecules are basically responsible to conduct heat from surface at T 1 to the surface at T 2.

Each molecule will conduct the heat to other molecule, and in this way, conduction would happen depending on the gas conductivity, and ultimately these molecules will actually touch the walls, touch the surfaces, and therefore, the heat will be transferred from surface number 1 to surface number 2.

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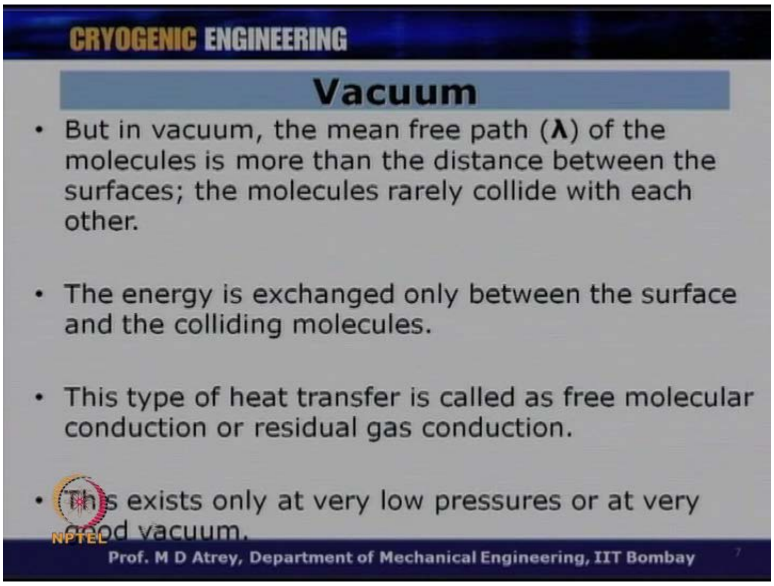

But in vacuum, if I am going to talk about a very high vacuum, very high order vacuum, then it basically is represented by something called as mean free path lambda. In vacuum, the mean free path lambda of the molecules is more than the distance between the surfaces. The molecules rarely collide with each other. This is very important to understand.

If I have got a very high vacuum or very good vacuum, the number of molecules between these two surfaces will be very very minimum. I mean, they could be of the order of 4 or 5 or some number basically. In that case, the molecule to molecule conduction will be completely eliminated or is assumption that the molecules will never emit the molecules, it will always emit the wall directly; that means, the collision between the molecules will be avoided, will not be there, if the mean free path that is; the distance between the two collisions, the time between the two collision, the length between the two collisions is going to be comparable with the length of the two surfaces or the distance between the two surfaces. In that case, the molecules will rarely collide with each other.

Now, the energy is exchanged only between the surfaces and the colliding molecules. The molecules will not collide with molecules. The molecules will directly collide on the surfaces and therefore, whatever heat transfer we had said that it occurs because of molecule to molecule conduction will not occur over here. It will be molecule; one molecule will take heat from surface 1, and it will directly bring this heat to surface number 2, and this is what we are going to talk about. This type of heat transfer is called as free molecular conduction or residual gas conduction.

Please understand that, the free molecular conduction or residual gas conduction, whether it occurs or not, is going to be completely dependent on the vacuum level because this vacuum level will determine what is the mean free path of the molecules. If the mean free path is very large, as compared to the distance between the two surfaces, we will have free molecular conduction or residual gas conduction. And this is one of the losses that will be encountered in vacuum, when vacuum is used as insulation. This exist only at very low pressures or very high vacuum or at very good vacuum. That is what we are talking about.

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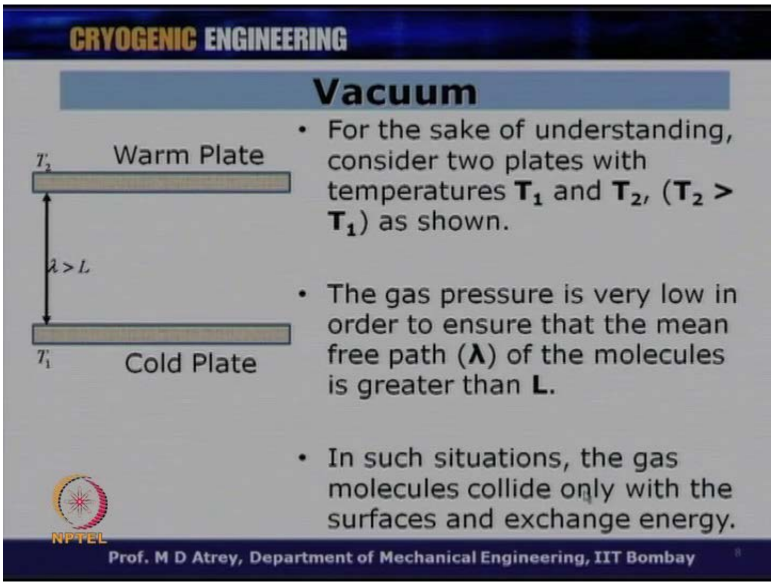

Now, let us understand the mechanism of this free molecular conduction. For the sake of understanding, consider two plates with temperature T 1 and T 2 as shown in the figure. So, here, we have got a warm plate which is at temperature T 2 , and here, we have got a cold plate which is at temperature T 1, and we say that lambda; which is a mean free path is more than the distance L. That means, these molecules in between these two surfaces will never collide with each other. The molecules coming from this surface from the warm plate will straightaway meet the cold plate without having any molecules in between for collision, all right.

So, mean free path for these molecules is more than the characteristic length; that is L which is between the two surfaces. And we found that T 2 is more than T 1. So, Conduction will occur and the heat will be brought from this warm plate by the molecules when the molecule hits to the cold plate, it will bring this heat and dump it on the cold plate, then again from cold it will go to warm plate, and this will continue. And let us analyze the motion of a simple molecule in this case.

The gas pressure is very low, in order to ensure that the mean free path lambda of the molecule is greater than L. Therefore, lambda is more than L; which means that, it is in free molecular conduction zone. In such situation, the gas molecules collide only with the surfaces and exchange energy.

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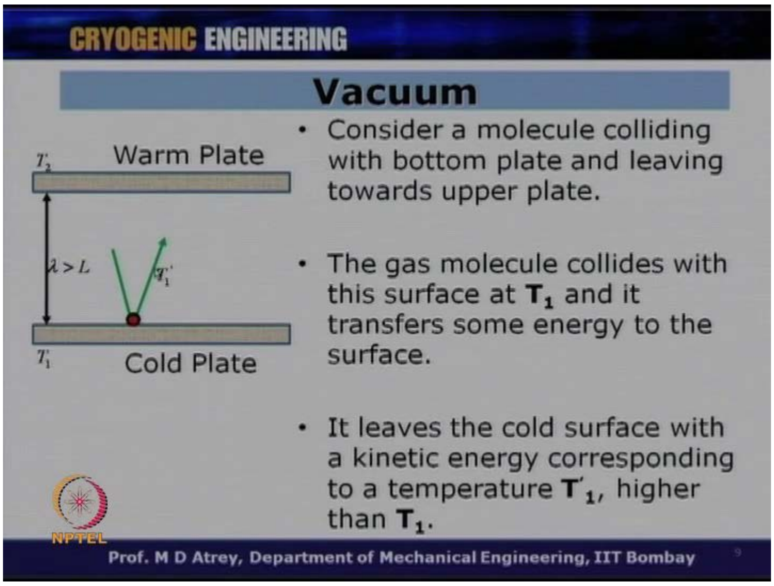

So, consider a molecule colliding with the bottom plate and leaving towards the upper plate. So, let us see a molecule which is shown by this red spot. The molecule has just hit the cold plate and this cold plate is at temperature T 1, and what is you understand from here is this.

The gas molecule collides with this surface at T 1, and it transfers some energy to the surface, all right. So, this gas molecule which is coming from warm plate, it will bring some energy and it will dump this energy on the cold plate which is maintained to be at T 1 temperature. Now this gas molecule then, having dumped the heat on the cold plate, it will leave this plate at a different temperature than the cold plate temperature. So, it leaves the cold surface with a kinetic energy corresponding to a temperature T 1 dash which is higher than T 1.

So, why so? It is not leaving at T 1 because the heat transfer is not perfect, because they could not get time to have a thermal equilibrium between the molecule and this cold plate. So, naturally the gas would leave at a higher temperature than this cold plate. It will not be able to attain the lowest temperature of T 1 because the time spent by this molecule on the wall is going to be very very less. So, when it leaves the surface, it will leave at a temperature T 1 dash and not T 1.

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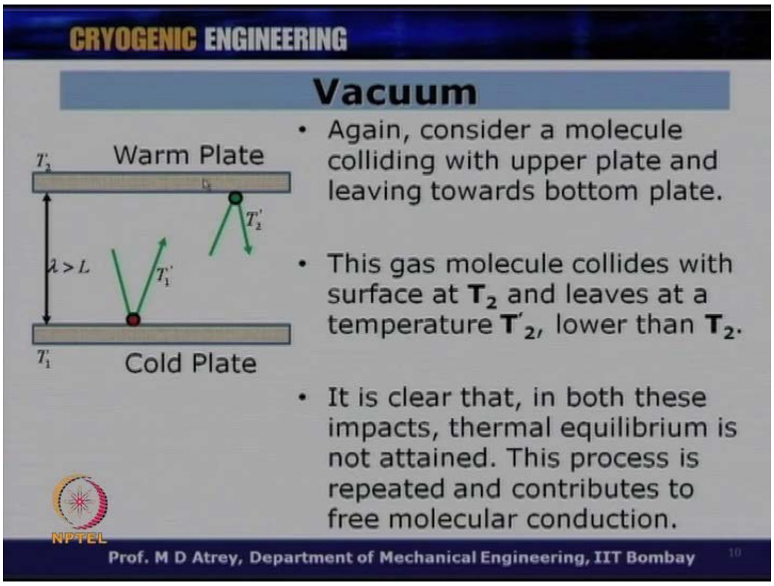

So, this was…, this is what we just analyzed for the cold plate. Now, let us see what happens at the warm plate. So, again consider a molecule colliding with the upper plate, and leaving towards the bottom plate. So, here, a molecule comes and hits the warm plate, and now the molecule color; we have shown a different one , blue one . This gas molecule collides with the surface at T 2 . So, this surface temperature is maintained at T 2. The molecule now will leave this plate at a temperature which is T 2 dash, which is lower than T 2.

Again with the same reasoning what we gave for the cold plate, they will not be in thermal equilibrium or the time that is given for this molecule to have heat transfer over here, will not be sufficient enough, and its temperature will not reach to T 2, but it will leave this plate at a temperature which is lower than the warm plate temperature T 2 and therefore, it would leave at T 2 dash.

So, what we found that at cold plate, it leaves at T 1 dash, at warm plate its leaves at T dash. T 1 dash is going to be more than T 1, while T 2 dash is going to be less than T 2. If there is a perfect thermal equilibrium, this T 1 dash should have been equal to T 1, this T 2 dash should have been equal to T 2.

It is clear that, in both these impacts, thermal equilibrium is not attained. The process is repeated and this contributes to free molecular conduction. So, this molecule again will come from T 2 dash, it will come to the cold plate, again would leave at T 1 dash, and this process will go on happening forever. As long as the temperature is maintained at T 2, the warm plate temperature, as long as the temperature of the cold plate is maintained at T 1, this process will get repeated, the molecule will leave at T 1 dash, cold plate the molecule will leave warm plate at T 2 dash, but the heat transfer would happen in this manner.

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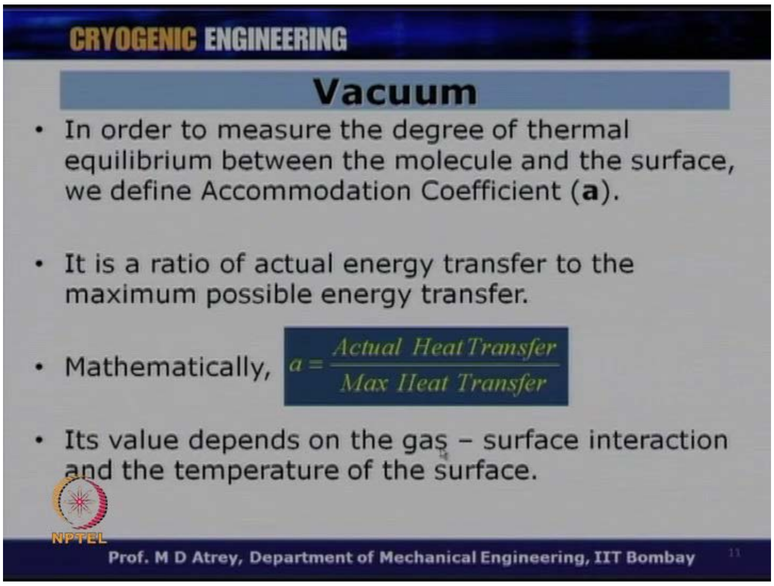

Now, what is important to understand is, why does this happen and who is responsible for that. In order to measure the degree of thermal equilibrium between the molecule and the surface, we define a parameter called accommodation coefficient given as a. This accommodation coefficient will tell you, what is the difference between T 2 dash and T 2, what is the difference between T 1 dash and T1, T2 dash and T 1. So, this will be defined by this accommodation coefficient and it will depend on what kind of gas you are talking about at what temperatures you are going to talk about and thing like that will dominate this parameter called accommodation coefficient. Let us see what it is.

So, accommodation coefficient is a ratio of actual energy transfer to the maximum possible energy transfer. Like heat exchanger effectiveness, when the molecules of different temperature let us say T 1 heats the surface at e 1, it will leave at T 1 dash. So, actual energy transfer is going to be less than maximum possible energy transfer, and this ratio is going to be defined as accommodation coefficient. So, mathematically we can write, a is equal to actual heat transfer divided by maximum heat transfer. Its value depends on gas-surface interaction, and of course, the temperature of the gas. So, it will depend on a actually type of gas, the gas surface interaction and the temperature of the surface.

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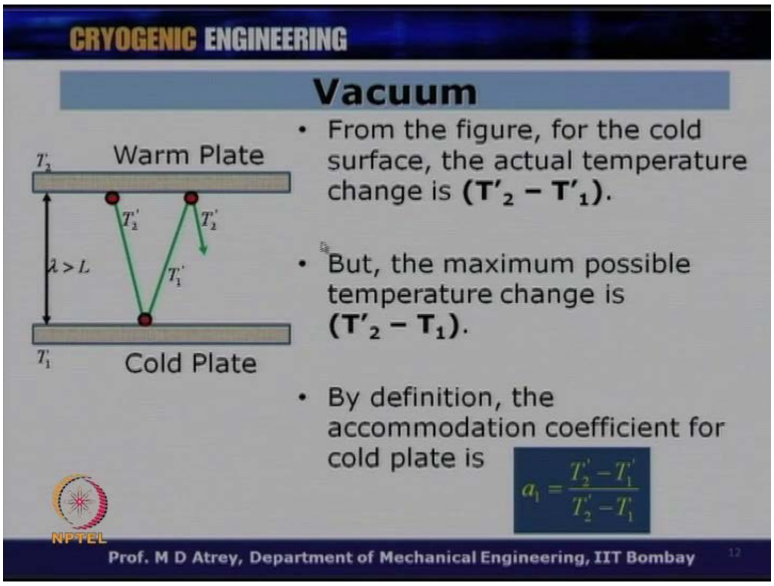

So, again looking at the same plate, now we see that the molecule is leaving at T 2 dash, hitting cold surface which is maintained T 1, leaves this surface at T 1 dash, again hits the warm plate, leaves at T 2 dash, again it will come here and leaves at T 1 dash and this process will continue.

So, from the figure for the cold surface, if I talk about the cold surface, the actual temperature change is T 2 dash minus T 1 dash. For the cold surface, the gas is coming at T 2 dash while it is leaving at T 1 dash. So, the change in temperature of the molecule is going to be T 2 dash minus T 1 dash, while the maximum possible temperature change could have been the gas is coming at T 2 dash, then it would have actually attained if there was a perfect heat transfer, it could have attained the temperature of T 1. So, the maximum possible heat transfer would have been T 2 dash minus T 1. So, actual temperature change was T 2 dash minus T 1 dash, and maximum possible change was T 2 dash minus T 1.

So, by definition now, the accommodation coefficient for the cold plate is going to be A 1, let us have for cold plate A 1, T 2 dash minus T 1 dash divided by T 2 dash minus T 1. If we find that the mass of the molecule remain the same, the C P of the molecule remain the same. Therefore, it will come only in the ratio of the temperature differences.

The numerator shows actual temperature change divided by denominator shows maximum possible temperature change. Now, we can repeat the same thing for the warm plate also. So, this is what is going to be defining the A 1 at a cold plate temperature, accommodation coefficient at a temperature T 1. Now, let us see what is the accommodation coefficient at the warm plate which is maintained at Temperature T 2.

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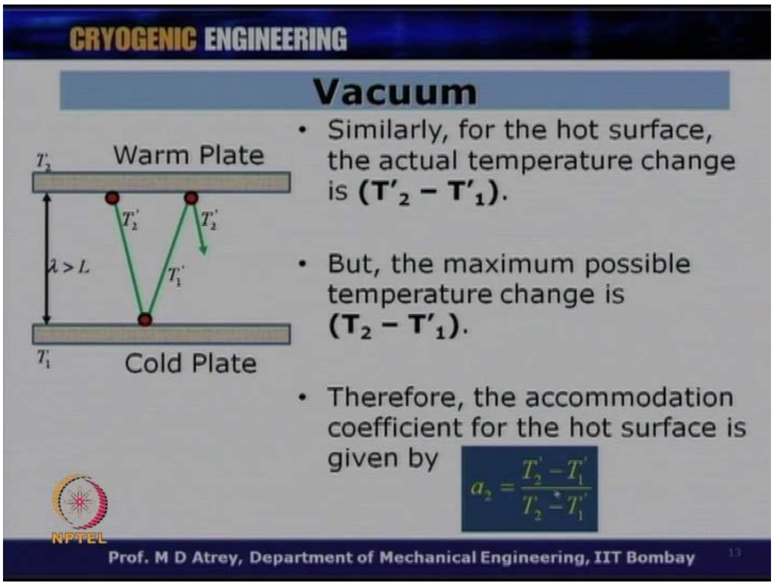

Similarly, for the hot surface, the actual temperature change again is going to be T 2 dash minus T 1 dash. So, actual temperature change for both the surfaces is going to be the same while what changes is the denominator which is the maximum possible temperature change, but the maximum possible temperature change is going to be in this case now, the gas is leaving this at T 2 dash. So, therefore, the maximum possible, when the gas is coming at T 1 dash the T 1 dash, the molecule should have attained the maximum temperature up to T 2 while it leaves at T 2 dash because of the imperfect heat transfer. So, the maximum possible temperature change could have been T 2 minus T 1 dash. So, this is what we call is denominator.

Therefore, the accommodation coefficient for the hot surface is given by A 2. So, A 2 is for the warm plate which is maintained at T 2 temperature, which is going to be T 2 dash minus T 1 dash divided by T 2 minus T 1 dash. So, we have defined now accommodation coefficient for plate 1 and accommodation coefficient for plate 2 which are maintained at T 1 and T 2 temperatures.

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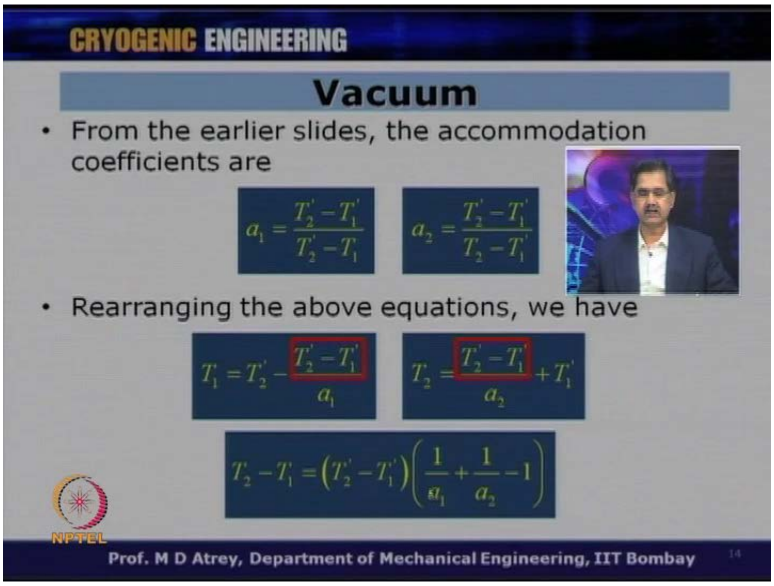

From the earlier slides, the accommodation coefficients are A1 as T 2 dash minus T 1 dash divided by T 2 dash minus T 1, while A 2 is going to be T 2 dash minus T 1 dash divided by T 2 minus T 1 dash. So, rearranging the above terms what we get is now, if I write in terms of T 1, I will get T 1 is equal to T 2 dash minus T 2 dash minus T 1 dash divided by A 1; if I look from A 1 definition, and I can define T 2 from here from definition of A 2 which is T 2 equal to T 2 dash minus T 1 dash upon A 2 plus T 1 dash. So, I am just rearranging these terms to get expression for T 1 from A 1, and T 2 from A 2. From this now, again I can rearrange terms because I can see that T 2 dash minus T 1 dash terms are common over here, and therefore, if I got T 2 minus T 1, if I say difference of temperature which is T 2 minus T 1, then I can take T 2 dash minus T 1 dash as common which will give me 1 upon A 2 plus 1 upon A 1 minus 1 .

So, from here, I can define that T 2 minus T 1; I can I am relating basically T 2 minus T 1 to T 2 dash minus T 1 dash, and there's one more parameter is coming which is 1 upon A 1 plus 1 upon A 2 minus 1.

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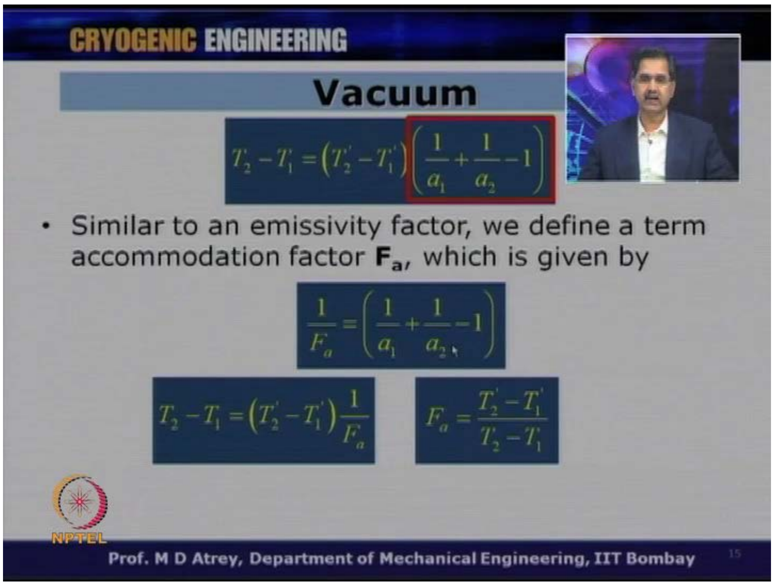

So, again if I rearrange these, what I get is a parameter which is basically like emissivity factor; similar to an emissivity factor if you have got two surfaces which have got emissivity of e 1 and e 2, then we say that the net emissivity Fe will be 1 upon e 1 plus 1 upon e 2 minus 1. Similarly here, similar to an emissivity factor, we define a term accommodation factor Fa will be which is given by 1 upon A 1 plus 1 upon A 2 minus 1.

So, 1 upon Fa is equal to 1 upon A 1 plus 1 upon A 2 minus 1. So, if I know accommodation coefficients for both the surfaces, I can now calculate accommodation factor which is Fa. A 1 and A 2 are accommodation coefficients, while Fa is the accommodation factor. So, how do I write this expression as now incorporating this accommodation factor?

So, T 2 minus T 1 is equal to T 2 dash minus T 1 dash into 1 by Fa. So, Fa is equal to which is accommodation factor; T 2 dash minus T 1 dash divided by T 2 minus T 1. So, now, this is a general expression which could be used to calculate Fa or I calculate F a from A 1 and A 2 and it could be realized it could be basically used to calculate the actual heat transfer that is going to occur because of free molecular conduction.

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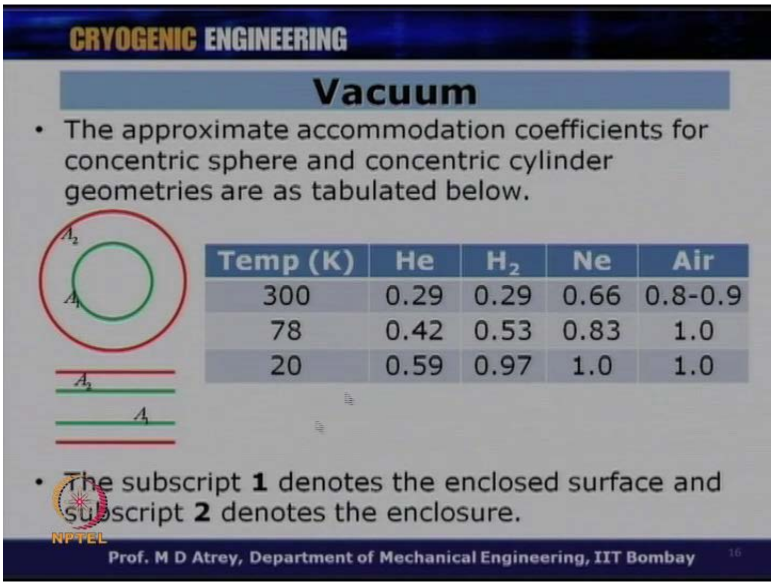

The approximate accommodation coefficient for concentric spheres and concentric cylinder geometries are as tabulated below. So, what you can see, if I have got a cylinder A 1 and A 2 maintained at temperature T 1 and T 2, and we can see that I have got different temperatures 300, 78, 20 or A 1 and A 2, and then we have got different gases helium, hydrogen, neon, air, and what you can see that as, at a particular temperature, if the gas changes or if the gas becomes heavier and heavier, the accommodation coefficients at this temperature has increased, while if the temperature decreases for a particular gas, the accommodation coefficient increases.

When there is an increase in accommodation coefficient, it is basically because of better and better heat transfer between the molecule and the surface. So, actual heat transfer is getting better and better as compare to maximum possible heat transfer, all right. So, this is what the subscript 1 denote the enclosed surface, while subscript 2 denote the enclosure.

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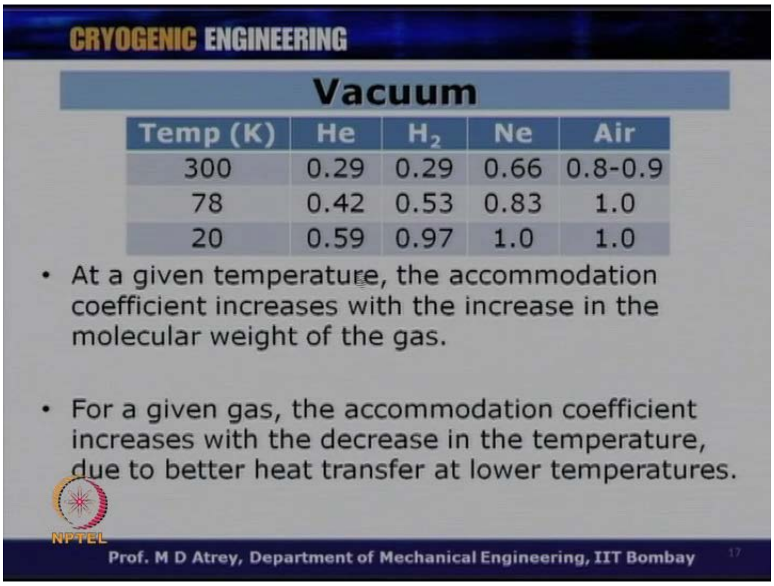

So, from this table what we see, at a given temperature, the accommodation coefficient increases with the increase in the molecular weight of the gas. For a given gas, if I see a given gas, the accommodation coefficient increases with the decrease in the temperature due to better heat transfer at lower temperatures. So, this is what we just saw from the table.

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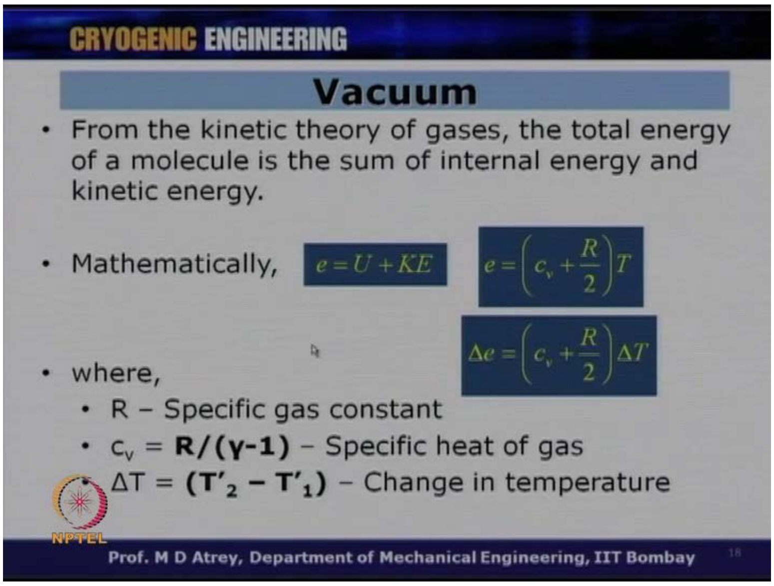

Now, let us come to further calculations. So, the kinetic theory of gases, the total energy of a molecule is the sum of internal energy and kinetic energy. By neglecting other energies, we can say that mathematically, e is equal to U plus KE. This is what is given by kinetic energy theory of the gases. Now this e is equal to U is equal to C v into T; we know that. So, I can write this as C v plus R by 2 T. Kinetic energy is half RT, while internal energy U is C v T, all right. So, I am just writing those values, and therefore, delta e is equal to C v plus R by 2 into delta T; where R is specific gas constant, C v is equal to R upon gamma minus 1, which is gamma is nothing but c P by C v, and delta T is nothing but actual delta T which is T 2 dash minus T 1 dash, this is why we are doing that thing? We are basically calculating the energy transfer happening because of this free molecular conduction.

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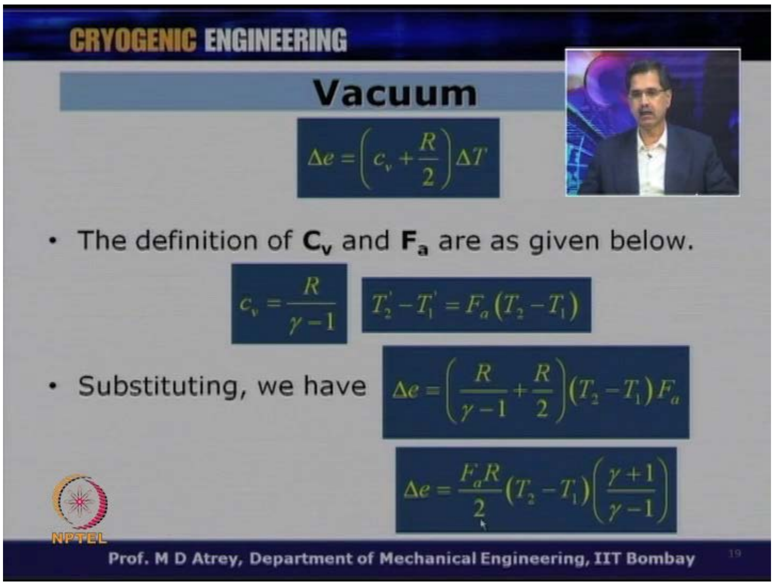

So, taking this further, delta e is equal to C v plus R by 2 delta T. The definitions of C v and F e are given as below. C v is equal to R upon gamma minus 1; again this is known from kinetic theory of gases, while we know the Fa is defined as T 2 dash minus T 1 dash is equal to Fa into T 2 minus T 1. Putting these values over here, we get delta e expression, I will put C v by R upon gamma minus 1 and I will put the value of Fa over here.

So, I have got now delta T over here. So, I am replacing the delta T by Fa into T 2 minus T 1. So, rearranging these terms, I will get, delta e is equal to Fa R; I am just taking R common from here and evaluating this bracket Fa R upon 2 T 2 minus T 1 into gamma plus 1 divided by gamma minus 1.

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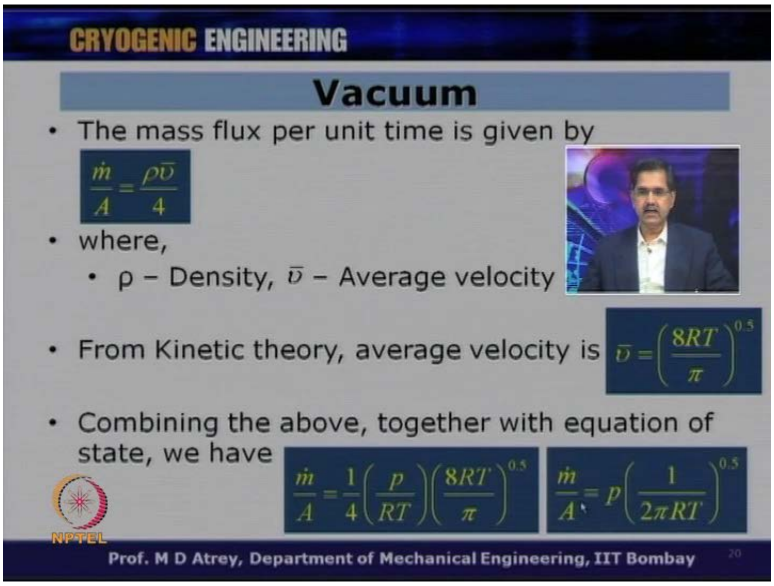

Now, if I want to calculate mass flux per unit time is going to be m dot upon A which is nothing but rho into velocity of the gas. So, rho is the density, v is the average velocity of the gas and this will give you basically the mass flux.

So, from kinetic theory of the gas, the average velocity; the value of v bar average velocity is given by 8 8RT upon pi to the power 0.5 or square root of 8R T by pi. Putting this value over there, combining the above expressions, we can find out what is m dot by A. So, m dot by A is equal to replacing this rho by P upon R T. So, by assuming the ideal gas equation, we've got rho is equal to P upon R T, 1 by 4 and putting the value of v bar I get this expression, and rearranging, I get R T and R T gets canceled m dot a is equal to P into 1 upon 2 pi R T to the power 0.5.

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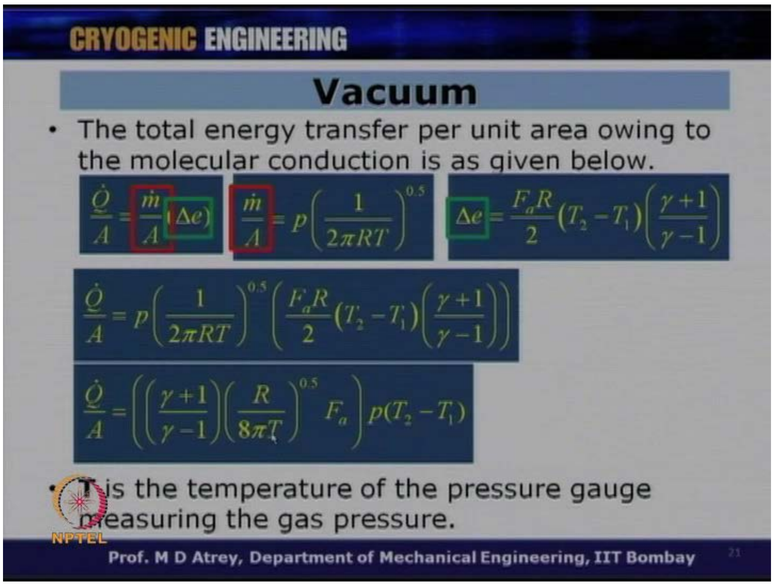

Once I get the value of m dot e, the total energy transfer per unit area owing to molecular conduction is given by Q by A is equal to m dot a into delta e. I am basically interested in calculate this Q that amount of heat transfer that occurring that that is occurring because of the molecular conduction. So, what is the m dot A? We have just found out. What is the delta e? We have calculated. Putting those values, m dot A is equal to this; delta e is equal to this.

Putting this value over here, replace this m dot A by this, replace the delta e by this parameter, I will get an expression for Q by A. Just rearranging that, I will get Q by A is equal to this expression. You have got a big bracket over here multiplied by P which is the pressure into T 2 minus T 1. T is the temperature. This T is the temperature of the pressure gauge measuring the gas pressure. So, wherever I am measuring this P, this T is going to be corresponding temperature at where the pressure is measured.

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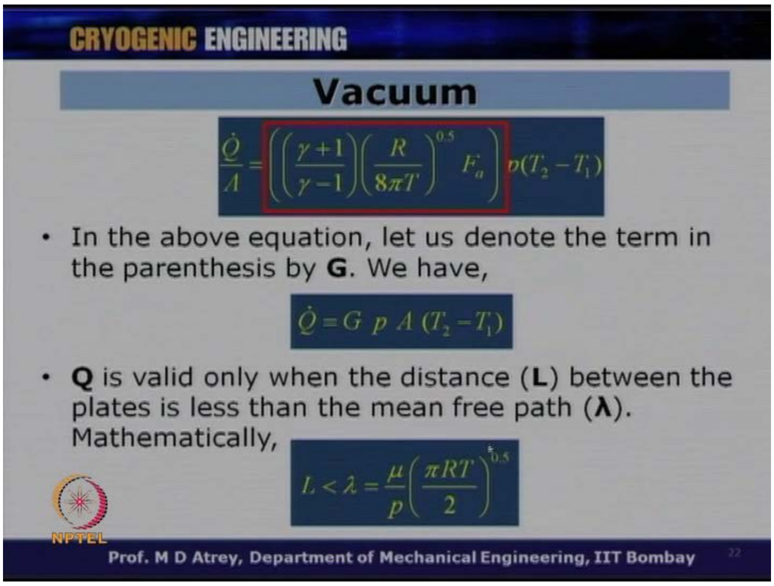

So, rearranging these terms again, I will call the entire bracket as G; because in this bracket you can see there are lots of constants. Gamma is a constant, R is constant, the specific gas constant gamma is specific to the gas. Again temperature is constant because I am measuring pressure at that particular point, while Fa is also going to be constant. If I know the temperatures of the surfaces and if I know the gas by knowing accommodation coefficient A 1 and A 2 I can calculate Fa there. So, this bracket is more or less constant. I can call this bracket as G. So, my Q is equal to now G into P into a into T 2 minus T 1, and this is what is going to be my heat conducted because of the free molecular conduction.

So, Q is valid only when the distance; the point to be noted is that this equation is valid for molecular conduction feature. So, Q is valid only when the distance L between the plates is less than the mean free path lambda. Mathematically, lambda is going to be given by this, and we say that L is less than lambda. Lambda will depend on the gas properties and the temperature and the pressure of course.

So, we first find out lambda, compare that lambda only with the characteristic length L, and decide if we lie in the free molecular conduction region. If lambda is going to be more than L, if the mean free path of the gas is going to be more than L; that means, there is no gas molecule to molecule collision. The molecule is going to hit to the surface straight, then I am sure that I am in this region, and lambda is more than L. Having ensured that, then I can apply this equation to calculate heat conduction by residual gas or I can calculate residual gas conduction.

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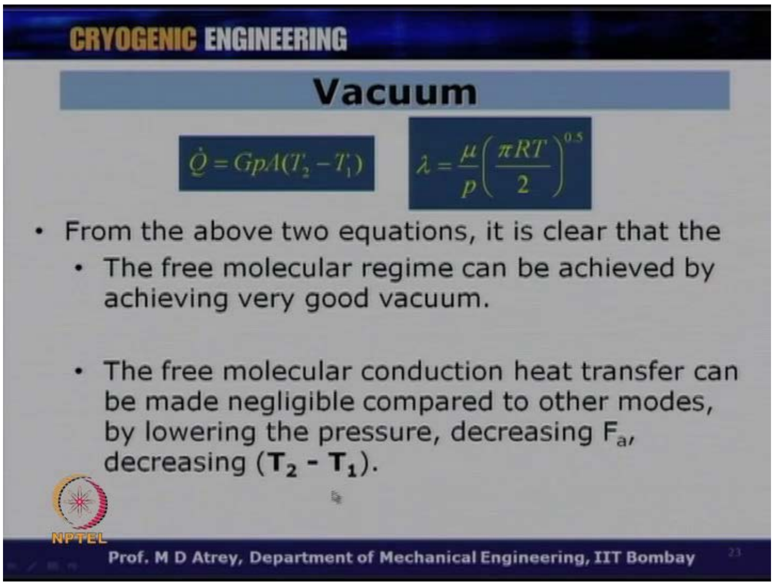

So, Q is equal to G into P into A into T 2 minus T 1. What is this G? G talks about the perfect the gas and takes care of the accommodation coefficient, P is the pressure, A is the area, and T 2 minus T 1 is the temperature difference of the two plates. Now, I am not bothered about what is T 2 dash and T 1 dash because that has already been taken into account by this Fa; which has been enclosed in the value of G, and the lambda value is given by this expression.

From the above two equations, it is clear that the free molecular regime can be achieved by achieving very good vacuum. As the pressure goes on reducing; that means, as the vacuum get better and better, the value of lambda is going to increase, and when lambda is going to be more than L, we are going to be in free molecular regime, and therefore, then I can use this expression to calculate residual gas conduction.

Also one can understand from this expression that the free molecular conduction heat transfer can be made negligible compared to other modes by lowering the pressure. So, if my P value is directly to P, if the P value is much lower; that means, you got a perfect and perfect vacuum, you ensure that there are hardly any molecules then, which will cause the free molecular conduction.

So, if I reduce the pressure, my Q is going to be much less. If I reduce the T 2 minus T 1, my Q is going to be perfectly less. So, we can understand that the free molecular conduction heat transfer can be made negligible compared to other modes by lowering the pressure, by decreasing the value of Fa or by decreasing T 2 minus T 1, and this is what the formula we will use to calculate free molecular conduction.

So, now let us come to evacuated powder. We have seen earlier, what happens when we use pertile powder. We have also seen what happens when we can use vacuum. Can we have these two together? So, basically the idea is now to have powder, but then evacuated powder is what makes more sense in order to reduce radiation, also in order to reduce conduction. So, let us see, what is this evacuated powder.

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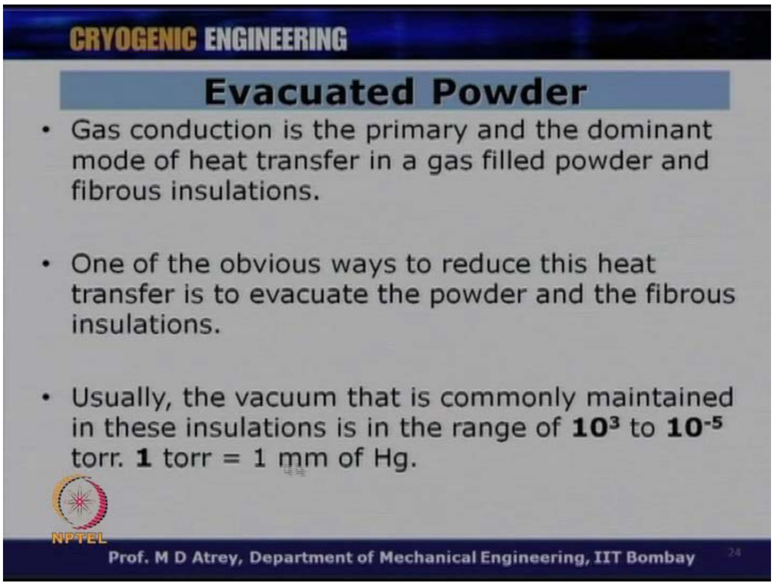

So, gas conduction is the primary and the dominant mode of heat transfer in a gas filled powder and the fibrous insulations. And this is what we had seen earlier, when we got a pertile powder which is a gas filled pertile powder, we have got a gas conduction as one of the dominant modes of heat transfer and of course, the solid conduction also. One of the obvious ways to reduce this heat transfer is to evacuate it. So, if I want to get rid of this gas conduction, and as I have just seen that if I have a perfect vacuum also, I have got a very good vacuum, then the gas conduction will be minimized in that case.

So, one of the obvious ways to reduce this heat transfer is to evacuate the powder and the fibrous insulation. So, just remove whatever gas is there, but for that you have to have a perfect vacuum now. So, one can have a perfect vacuum now. So, what remains is only powder in that case, and usually the vacuum that is commonly maintained in these insulations is in the range of 10 to the power 3 to 10 to the power upon minus 5 torr. So, we can this is not a vacuum actually, what you can see is that 10 to the power minus 5 is a good vacuum and this is not a good vacuum. This is what the range could be normally in such insulations, and what is this torr? We will talk about this torr more when we deal with vacuum, but for the benefits just understand that 1 torr is equal to 1 millimeter of mercury. You know that 760 millimeter makes 1 atmosphere and we are just talking about 1 millimeter of mercury now which is equivalent to 1 torr.

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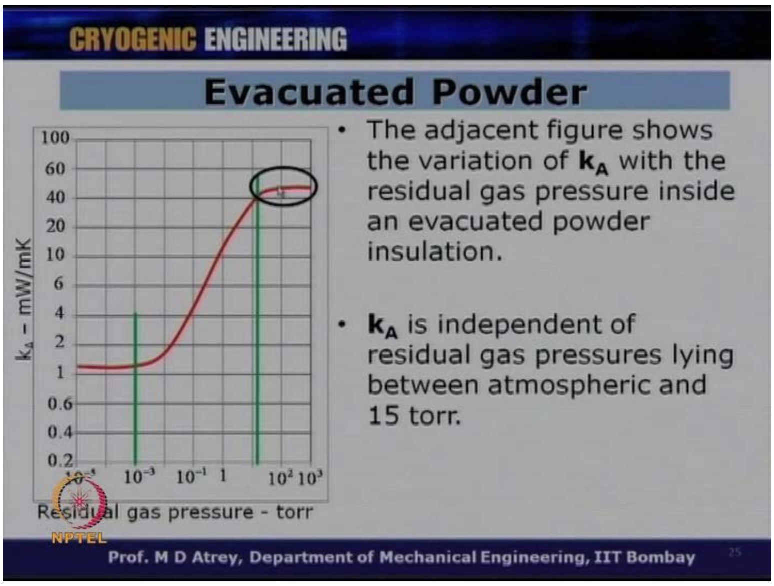

So, this is what if I plot the apparent thermal conductivity with residual gas pressure in torr, this is what the conductivity curve would look like. What is this? The adjacent figure shows the variation of KA- apparent thermal conductivity with the residual gas pressure inside an evacuated powder insulations. So, I have put as insulation and evacuated powder, and if I vary the pressure, if I evacuate this powder, the pressure in the powder will go on reducing, and according to this reduction in pressure, the apparent thermal conductivity of this evacuated powder will go on changing and it will taking such a S kind of a shape, all right. So, let us see how it behaves.

So, if I talk about this region which is from atmospheric pressure to around 15 torr, 15 torr means millimeter of mercury column, and atmosphere is around 760 millimeter of mercury column. So, you can see from 760 to 15 torr, KA is hardly changing. The value of conductivity is very high. This is in milli watt per meter kelvin. The conductivity value varies around fifties kind of a thing, and we found that KA is independent of residual gas pressure between the temperature pressure range of atmospheric to 15 torr.

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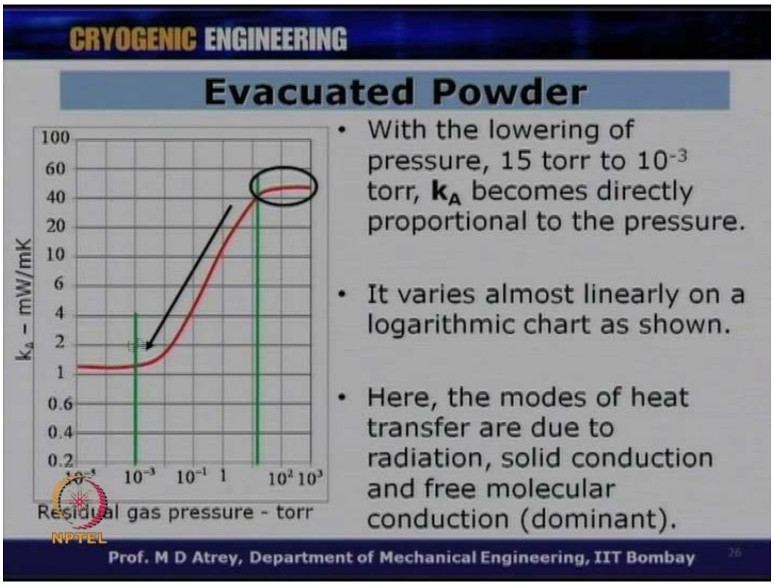

If you reduce the pressure further from 15 torr to let us say 10 to the power minus 3 torr, we can see that the apparent thermal conductivity is linearly changing. With the lowering of pressure from 15 torr to 10 to the power minus 3 torr, KA becomes directly proportional to the pressure. We have got a almost a straight line, and therefore, it showing a linear variation or linear decrease, if I decrease the pressure from 15 torr to 10 to the power minus 3 torr. And this is a very important thing.

Having reached this lowest value, so, it varies almost linearly on the logarithmic chart as shown over here. Here in this case now, the modes of heat transfer are due to radiation, solid conduction, and free molecular conduction. So, depending on the kind of vacuum you are having, you will have solid; we are not talking about this region because it is a gas filled order actually, isn’t it; because it is a gas pressure, while now we are evacuating this pertile powder, if about any powder basically, and now the modes of heat transfer will be due to radiation, solid conduction, and free molecular conduction, but in all these things, free molecular conduction is going to be dominant because the vacuum is not very good from 15 torr to 10 to the power minus 3, and we have just found that you have not possibly gone into free molecular conduction region. Here you could be causing lot of heat because of the molecular to molecule collisions in this case because the vacuum is not very very good.

So, in this region because there are you know powder, radiation will be minimum because the entire is occupied by the powder. There will be solid conduction, but maybe the free molecular conduction in this region depending on the kind of vacuum we are talking about is going to be dominant mode of heat transfer.

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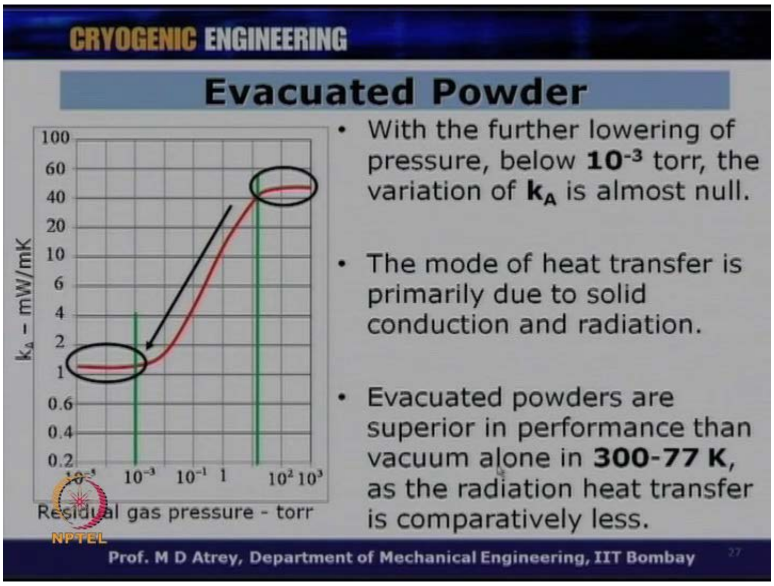

Now, if we decrease further below 10 to the power minus 3 torr and let us go up to 10 to the power minus 5 torr with the further lowering of pressure below 10 to the power 3 torr, the variation of KA is almost minimum. So, here I have reached the minimum value of KA; apparent thermal conductivity, and bringing the vacuum further down will not help towards out of improving or decreasing the value of apparent thermal conductivity.

So, normally the vacuum in this using a powder will be in this region 10 to the power minus 3 to 10 to the power minus 5. So, here I would have taken, the molecular conduction will be minimum in this case now because we got a very high order of vacuum. The modes of heat transfer is primarily due to now solid conduction because now there is a powder and there is a solid conduction because of the material of powder and of course, the radiation because we got two temperatures, two different surfaces at two different temperatures, but what has been taken care of is the free molecular conduction. It will be minimum free molecular conduction in this region.

So, if you at all you have a good vacuum, at all you want take care of the molecular conduction, you should be in this region. The vacuum should be below 10 to the power minus 3 alright. So, evacuated powders are superior in performance than vacuum alone. If you have got a vacuum alone, then you have got a radiation of heat transfer which is proportional to 300 to the power 4 minus 77 to the power 4; however, in this case, because there is a powder, the radiation parameter is going to be minimum, and the molecular conduction has also been taken care of.

You got a apparent thermal conductivity of around 1 or 2 or 1.1 or 1.2 like that as compared to that vacuum which could be higher in the same temperature region of 300 to 77 because in 300 to 77 Kelvin, the vacuum the radiation heat transfer is going to be maximum for vacuum alone, while in evacuated powder, the radiation heat transfer is going to be comparatively less alright.

So, evacuated powders are superior in performers than vacuum alone in 300 to 77 Kelvin as the radiation heat transfer is comparatively less in this case. So, if I want to have liquid nitrogen, and if I want to have a container or liquid nitrogen around which I would prefer to have evacuated powder rather than having only vacuum around it as insulation, I will have a powder which is evacuated powder and evacuated powder will take care of radiation heat transfer from 300 to 77 kelvin in that case. Please understand this points.

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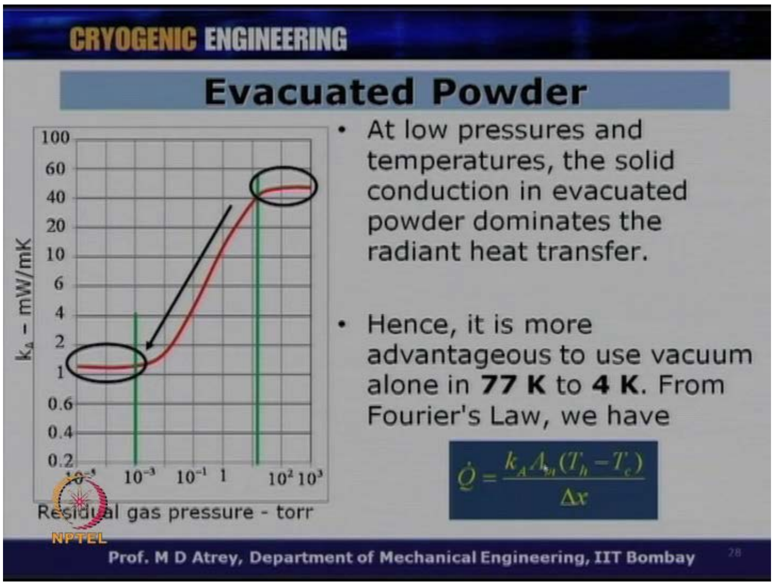

However if I go at very low pressures and very low temperatures, now using this evacuated powder, the solid conductions in evacuated powder will dominate the radiant heat transfer. Radiation heat transfer will be there, but now if I go for lower temperatures, the solid conduction with the powder material is going to be dominant and therefore, in this temperature range when I am going very I am going to go for lower temperatures, the evacuated powder may not help. They are definitely better up to 77 Kelvin or liquid nitrogen temperature range. Hence it is more advantageous to use vacuum alone in 77 to 4 Kelvin .

So, if I have two surfaces at 77 and 4, I may have to go for vacuum alone as compared to evacuated powder in this temperature range. Now from the Fourier's law, we have Q is equal to K into d T by d x. So, we have got a instead of K, we have got an apparent thermal conductivity and value of Am is going to be decided whether we going to have a cylinder or we going to have spherical surfaces.

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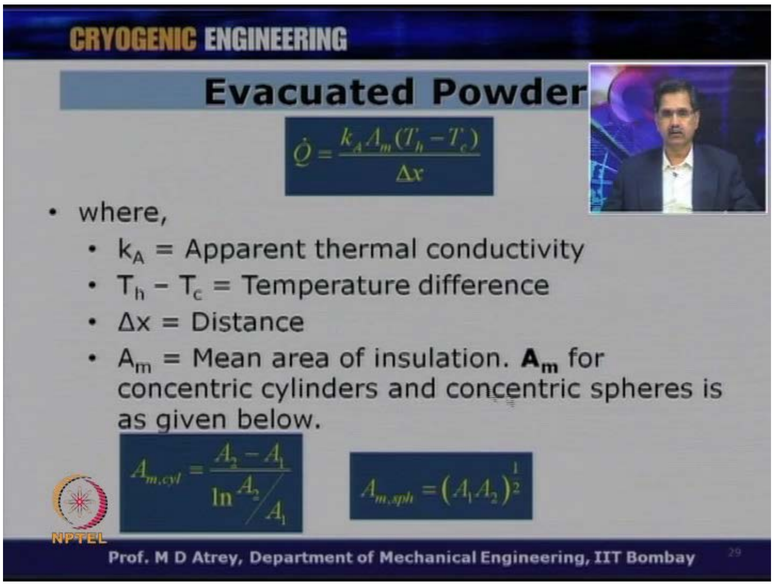

So, Q is equal to K into A into d T by d x where K A is apparent thermal conductivity T h and T c are the temperature differences, delta x is a distance in the two temperatures surfaces having T h and T c are temperatures while A m is a mean area of insulation and Am for concentric cylinder and concentric spheres as given below.

So, for cylinder, it is A 2 minus A 1 divided by log A 2 by A 1, and for sphere is going to be under root of A 1 into A 2 or A 1 into A 2 the power half. I will put this area in this equation, I will get the value of apparent thermal conductivity and I will calculate the conduction, the loss due to this conduction.

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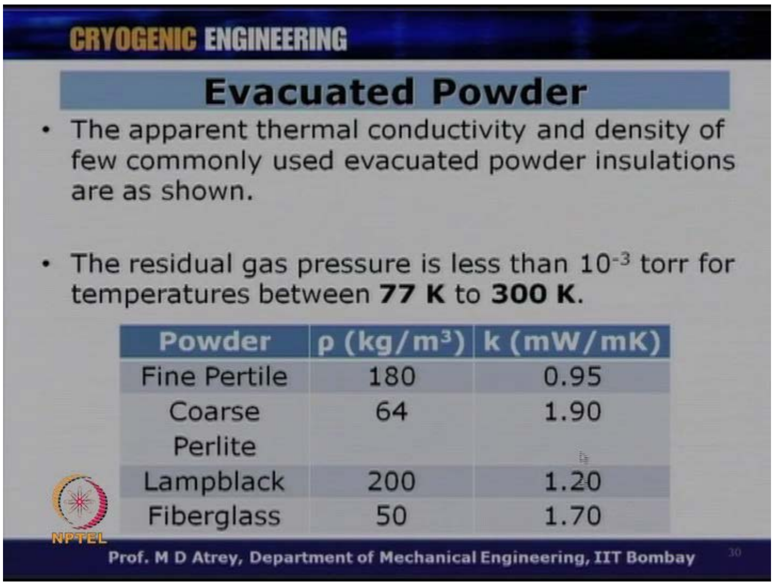

The apparent thermal conductivity and density of few commonly material are given over here. So, you can see now for 300 to 77, I got pertile coarse pertile lampblack fiberglass and I got a conductivity value of 0.95, 1.9, 1.2 between 1 to 2 kind of thing for evacuated powder.

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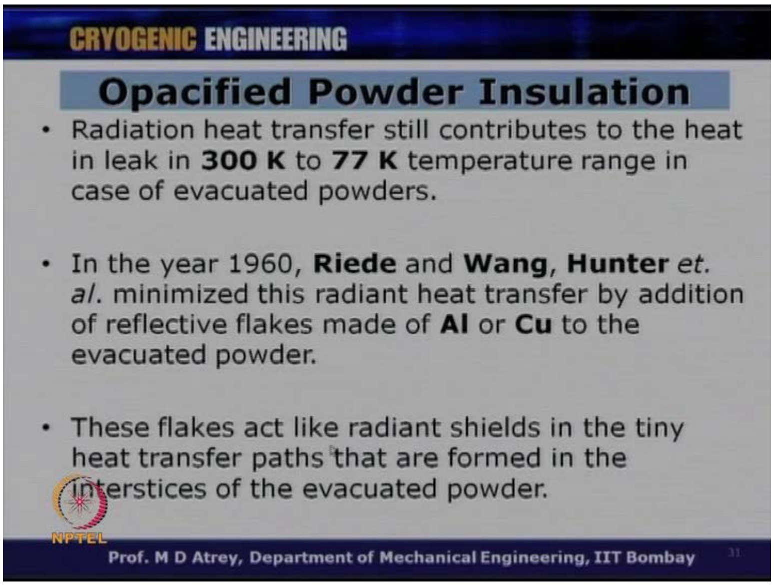

Let go to opacified powder insulation. The radiation heat transfer still contributes to the heat in leak in 300 to 77 K temperature range. In case of evacuated powder, we have just see in that thing radiation heat transfer still existence over there, if I want to get rid of that, comes opacified powder.

In the year 1960, Riede and Wang Hunter et.al minimized this radiant heat transfer by addition of reflective flakes made of aluminum and copper to the evacuated powder. So, if you put the flakes of aluminum or copper, it will stop radiations reaching the internal surfaces. These flakes act like radiant shields in the tiny heat transfer paths and are formed in the interstices of the evacuated powder and therefore, they will prevent this radiation also further.

So, I can I am reducing now all the modes of heat transfer using powder we have got a opacified powder which will now block even the radiation reaching the lower surfaces.

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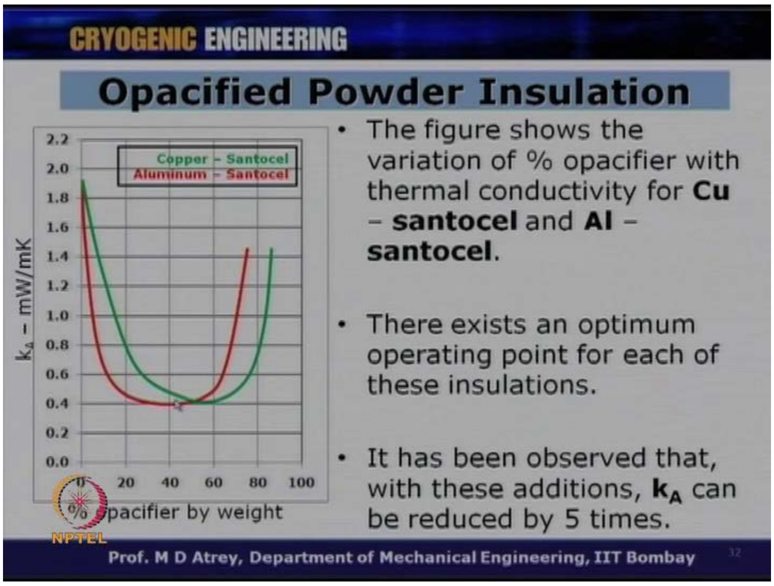

So, these are the apparent thermal conductivity for opacified powder in relation with how much opacifier by weight has been used, how many aluminum flakes, how many copper flakes have been used as a percentage of the total insulation material.

So, figure shows the variation of percentage of opacifier with thermal conductivity for copper or santocel is called as commercial length and aluminum santocel. So, you can see that there exists an optimum operation point for each of these insulations. So, if I use 40 60 case, the opacified ways forty percent out of hundred percent, my apparent thermal conductivity has come 0.4 which was 1.5 or 2 earlier; that means, I have reduced my apparent thermal conductivity be almost 5 times.

Similarly, if you have copper santocel, I can go for 60 percent opacifier by weight and again I can reduce the apparent thermal conductivity to 0.4. It shows that by taking care of this radiation heat transfer mode in the evacuated powder, by adding some aluminum flakes or copper flakes, I can reduce my apparent thermal conductivity further down, to around very low 0.4 and this is what we are talking about optimum value.

It has been observed that with these additions KA can be reduced by 5 times you should go on adding this opacifier further, then you will have more and more conduction also because number of opacifiers has increased, and therefore, there will be minima somewhere in between. You can just go on adding that thing because as the opacifier weight goes on increasing there are more and more flakes now and they might start touching each other because of which you will have a solid conduction path increase in that case.

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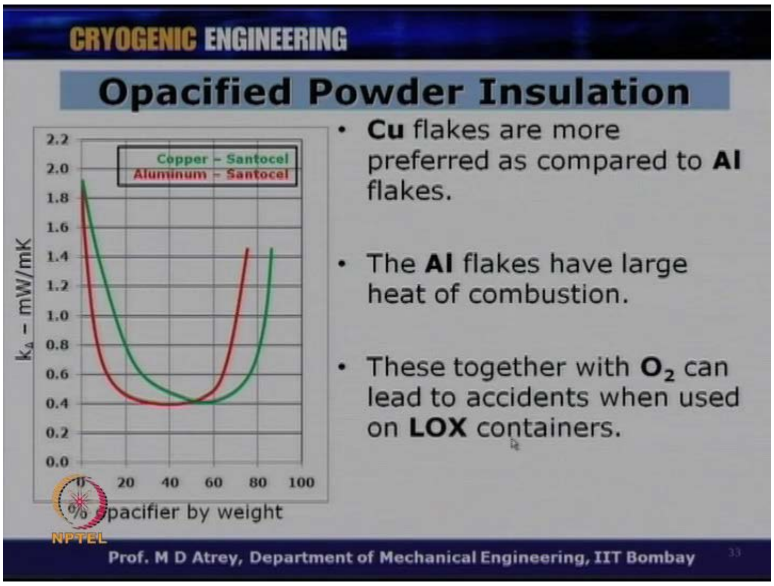

Copper flakes are more preferred as compared to aluminum flakes; the aluminum flakes have large heat of combustion and that is why copper flakes are preferable. These together with oxygen can lead to accidents when used in LOX condition; therefore aluminum should not be use or normally is not used.

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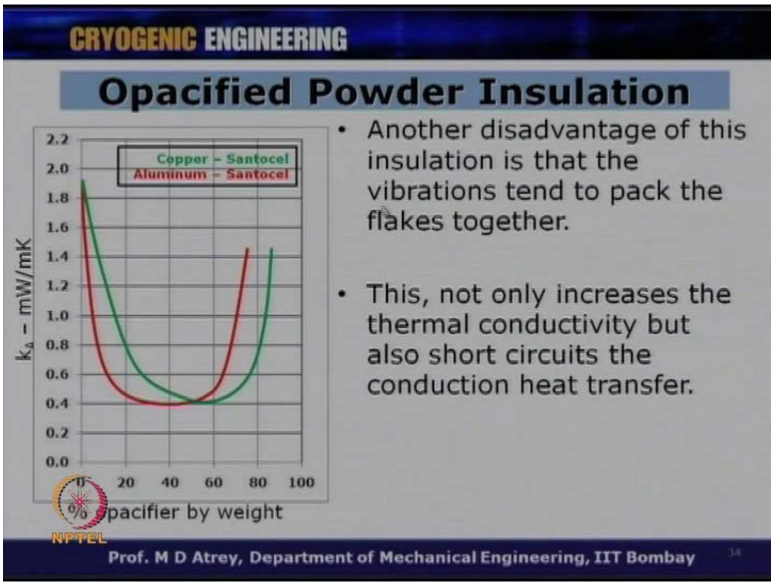

For the disadvantage; one is, we talked about copper is preferable. The another disadvantage of using opacified powder is the vibrations tend to pack up the flakes together. If you are carrying let say some cryogen in a moving container or in a mobile container, over a period of time, this flakes can come together. The vibrations can tend to pack the flakes together and therefore, you will have certain zones where flakes are plenty, while certain zones are there while flakes are not existence, and therefore, radiation in that case can reach directly to the low temperature surface which is not advisable, while only in one area, radiation might get plot.

This not only increases the thermal conductivity, but also short circuits the conduction heat transfer. So, lot of flakes together means we have got a more conduction happening out there. So, one has to ensure that this flakes are even the distributed first thing and also ensure that there are no vibrations given to this particular vessel which is having a insulation of opacified powder, but if you got a vibration, then this problems can be faced over a period of time.

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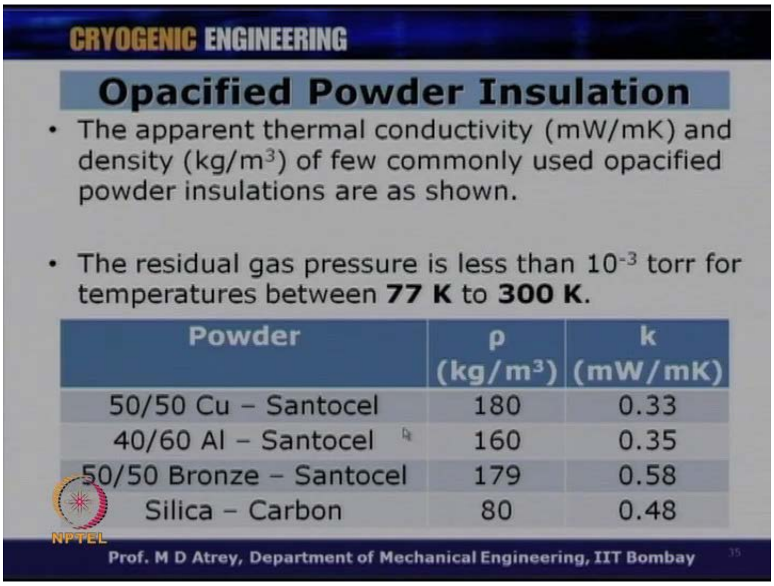

The apparent thermal conductivity and density of few commonly used opacified powder insulations are as shown. The residual gas pressure is less than minus 3, and we are talking about temperatures of 300 to 77 Kelvin and you can see here, you got a copper santocel, you got a aluminum santocel, you got a bronze santocel, and you got a silica carbon combinations for different densities, and you can see the apparent thermal conduct is 0. 33, 0.3 5, 0.58, 0.48.

So, what was between 1 to 2 for evacuated powder got reduced now 0.3 to 0.6 in this conductivity range , mille watts per meter Kelvin. So, we could how from here that having this opacifiers in the evacuated powder, the apparent thermal conductivity has decreased by almost 5 times, and therefore, opacifiers are preferred, but then we have got a conditions like you know not having vibrations, having it you know evenly distributed and thing like that.

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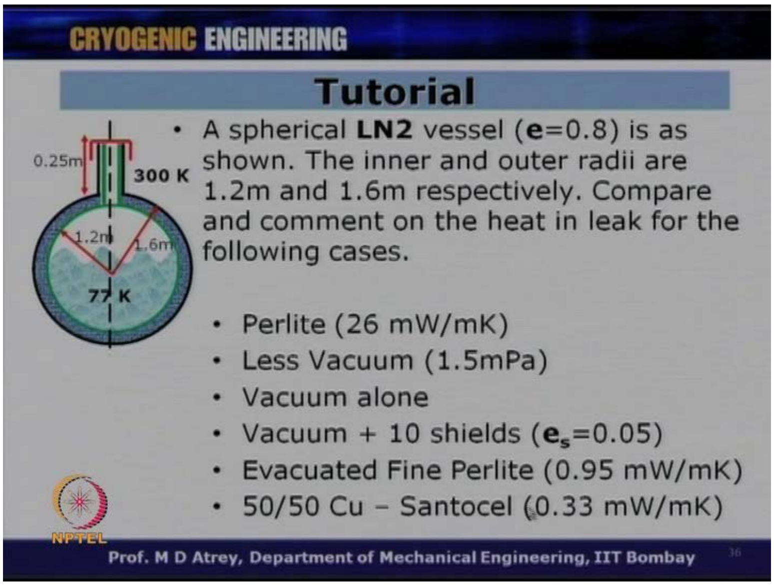

With this background now, having studied vacuum, vacuum plus radiation in earlier case, pertile powder, evacuated powder, opacified powder, I would like to have a small tutorial to understand the comparative effects of all these insulations, for which I will taken a little practical problem, and let us see this practical problems and apply all this equations which we have use earlier, which we have derived earlier to understand the losses using different insulations.

So, the problem statement is, a spherical liquid nitrogen vessel and this vessel has got emissivity of 0.8 for the both surfaces, emissivity of 0.8 is as shown over here. The inner and outer radii are as 1.2 meter and 1.6 meter. So, it is pretty big vessel. Compare and comment on the heat in leak for the following cases.

So, you have got a pertile powder which has got 26 mille watt per meter Kelvin as apparent thermal conductivity, then we have got a case where the vacuum is maintain between two surfaces. Pertile is removed and we got a vacuum, and the vacuum is of the order of 1.5 mpa. Then we have got a vacuum alone; this also vacuum alone, but the vacuum level is 1.5 mpa, while here is good vacuum or a perfect vacuum in this case.

Then we got a vacuum plus 10 shields, and the shield emissivity is as low shield as low emissivity 0.05. Then we got a evacuated fine pertile which had got 0.95 mille watts per meter kelvin and as apparent thermal conductivity and we got a copper santocel 50-50 where the apparent thermal conductivity is 0.33 mille watts per meter Kelvin.

So, I would like to put these values over here. Get apparent thermal conductivity for different insulations and compare the heat that is being conducted or heat loss that will occur using this insulation, and come out with a perfect insulation that one can recommend from this study.

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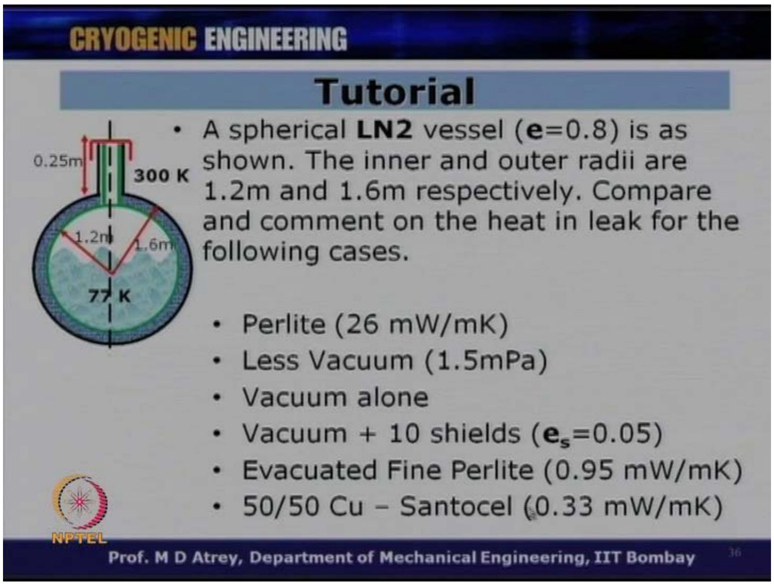

So, what is a tutorial? The given is spherical vessel which has got a emissivity of 0.8, working fluid that is the liquid nitrogen, that is why temperature is 77 Kelvin of the inner vessel while 300 Kelvin which is a ambient temperature for the outside vessel, and we have to calculate the heat in leak for this six different insulations for with data regarding apparent thermal conductivity has been given. The shape factor between the two container is assume to be 1, fine.

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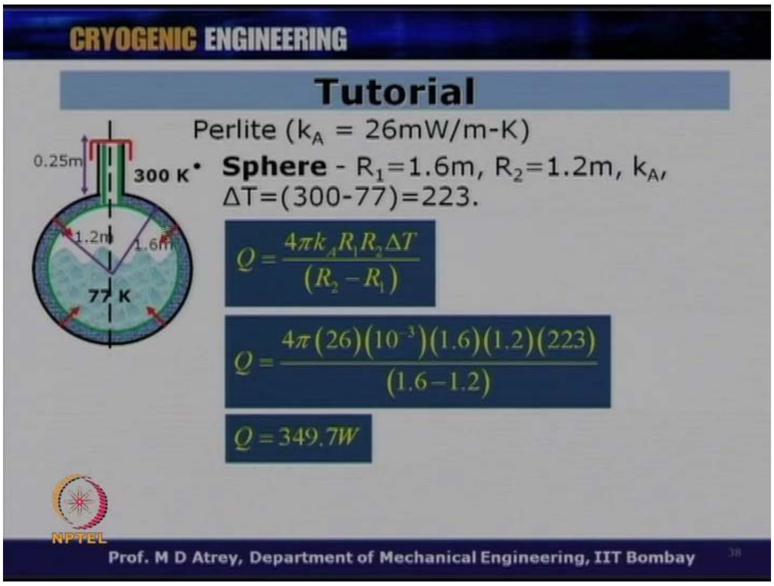

Let us have first pertile for which apparent thermal conductivity is 26 mille watt per meter kelvin. So, we have got a sphere here, which has got a R1 of 1.6, and R 2 of 1.3. R 1 is for outside and R 2 is for the inside vessel, apparent thermal conductivity has been given, delta T is 300 minus 77 which is 223. Find out the Q by this formula; 4 pi K R 1 R 2 delta T upon R 2 minus R 1.

So, this is what K into A into d T by d x. This is what the formula to be used. Put those values 4 pi into 26 mille watts. So, you know take care of all the units in such problems. Let us have meters everywhere R 1 and R 2, delta T, R 2 minus R 1 over here, what we can see that Q is equal to 349.7 watts which is fantastic; which is very high heat in leak in this case.

So, if we just have pertile powder between to this vessel, which is at 300 to 77 Kelvin, we will have 349.7 watts of heat in leak happening. R 1 and R 2 a crossed two surfaces.

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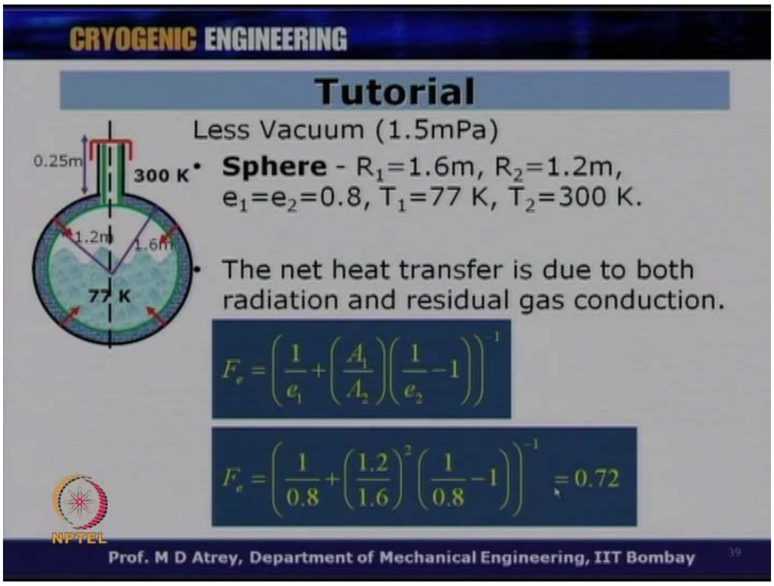

Now, if you got a less vacuum of 1.5mpa only, again we can apply, but now in this case, will have free molecular conduction, but before that we have to worry about are we in free molecular conduction region for which we have to calculate lambda.

The net heat transfer is due to both radiation and residual gas conduction, and if I want to calculate residual gas conduction, if I want to calculate radiation first, I will calculate what is my emissivity factor which is 1 upon e 1 plus a by A 2 1 upon e 2 minus 1. Putting value because both emissivity e 1 and e 2 are 0.8, I can get the value of Fe is equal to 0.72.

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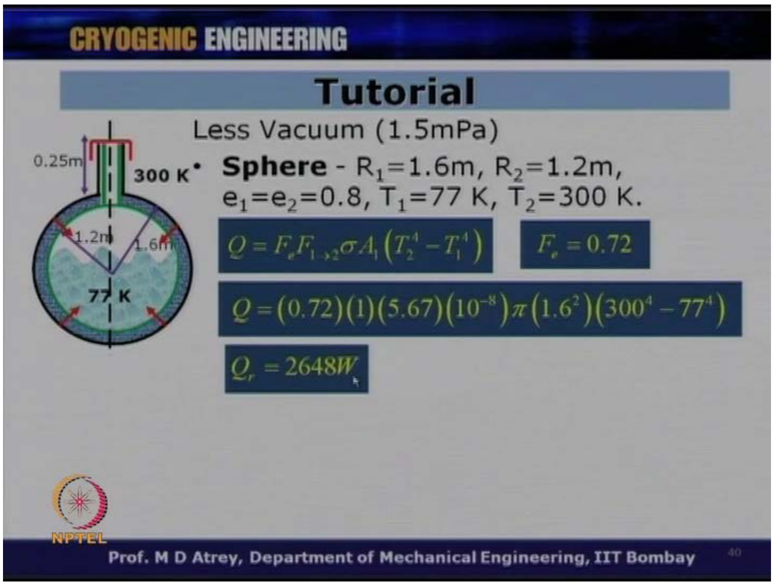

So, less vacuum, and if I want to calculate radiation now, I will have this formula; Q is equal to Fe into shape factor sigma which Stefan Boltzmann constant into A 1 T 2 the power 4 minus T 1 to the power 4. Fe I have just calculate to be 0.72. Put those values over here. I will get Q radiation is 2 6 4 8 watt 2648 watt which is much higher than the pertile powder over here.

So, we can see that vacuum alone is not going to helpful at all in this region. Only pertile powder is much better than having only vacuum in this region.

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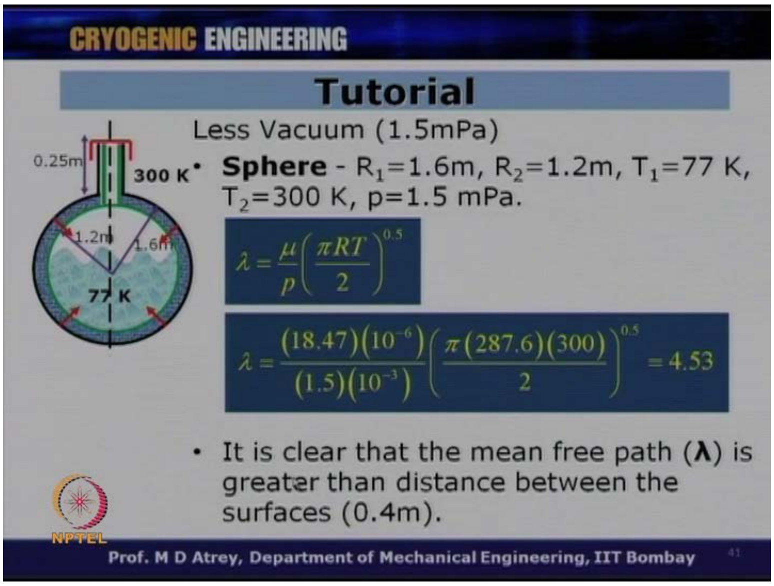

In addition to this radiation, because of the vacuum, we will have even the residual gas conduction. So, for that let us establish whether we are in free molecular conduction for which we will calculate lambda, putting the value of different properties and temperatures, I get lambda to be 4.53 meter which is much higher than R 2 minus R 1, alright. It is clear that mean free path lambda is greater than the distance between the surface which is 0.4 meter, and therefore, we establish that we are in free molecular conduction region, and therefore, I can apply the formula which we have derived.

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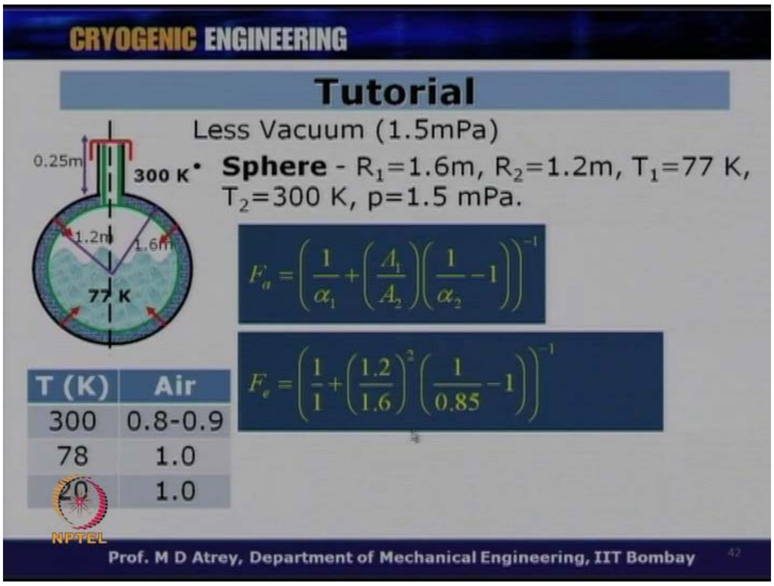

Let us have accommodation coefficient for two temperatures. So, 300 K, I can have a accommodation coefficient 0.8 or 0.9, and around 78 Kelvin we got a accommodation coefficient of 1 for air which is what we say lies between the two. I can calculate now accommodation factor which is given by 1 upon alpha 1 plus A 1 by A 2 1 upon alpha 2 minus 1 inverse, put the value of alpha 1 as 1 alpha 2 as 0.85, I will get accommodation factor as 0.91 .

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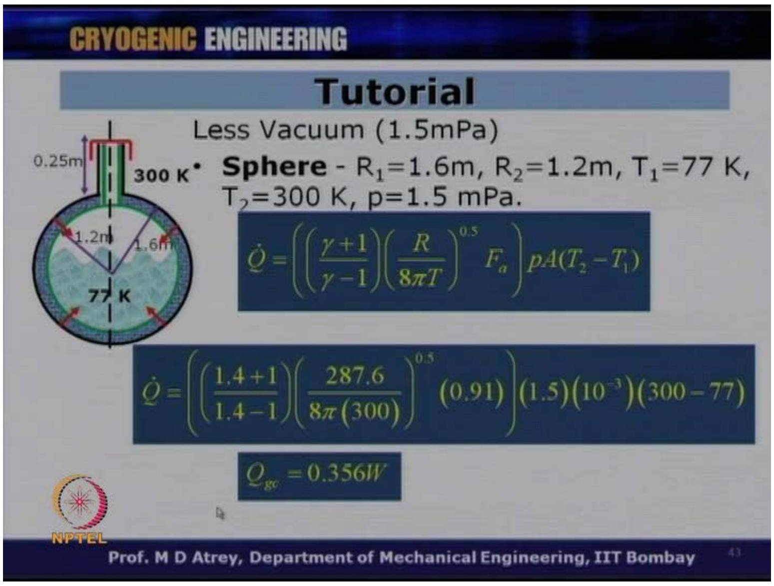

So, now I can calculate my Q because of free molecular conduction, put all the values over here. I know all the values, put the value of Fa, put the value of pressure which is 1.5mpa, put the value of area, and I get T 2 minus T 1 over here. So, by getting all this parameters, I will get Q is equal to 0.356 watts over here, alright, which is much less than event the radiation heat transfer when we have vacuum. So, total heat transfer will be what happened in radiation plus gas conduction or residual gas conduction.

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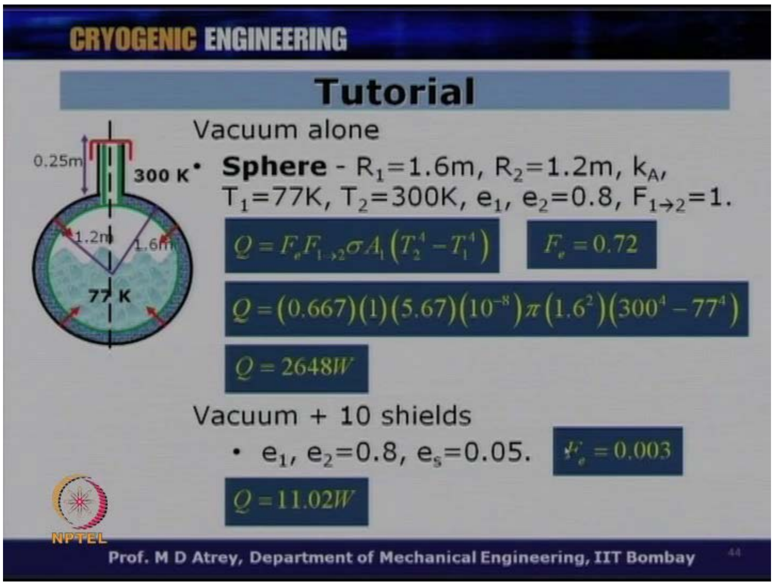

If I got vacuum alone, then I will have the same formula, and I will get only 2648 watts, but if I had now vacuum plus 10 shields, then I can apply the formula using shield emissivity of 0.05, and my Fe now will get reduce from 0.72 to 0.003. So, if I can allow to have 10 shields in between, my emissivity factor comes down to 0.003, and therefore, my Q will reduce from 2648 to 11 points. So, you can see the effect of having 10 shields, and the problem is how practically it is to have 10 shields between this two in this sphere in this R 1 and R 2 because that will go to increase lot of weight and that may add some conflicting problem in the manufacturing. So, this is the problem.

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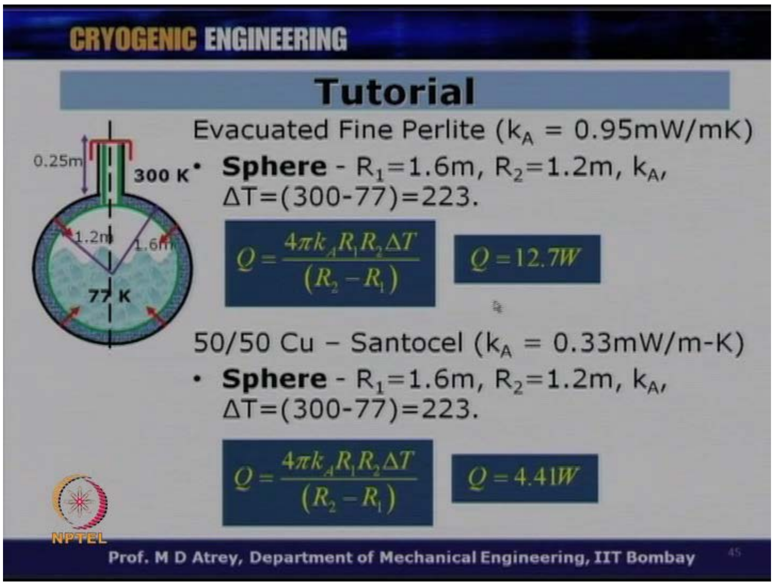

Now, let us go to evacuated fine pertile where K A is equal to 0.95, and put the formula in this again by using… I get Q is equal to only 12.7 watts in this case. So, evacuated fine pertile is much better than having vacuum alone. That is what we have said earlier and we just proven it here. And if I go for a copper santocel now, if I go for opacified powder now, my KA is going to be further reduced to 0.33, and if I apply the same formula, my Q is 4.41 watts only which shows that copper santocel or opacified powder is going to be much better on this. So, with this you get a feel of what the values of heat in leak will be for all this different insulation.

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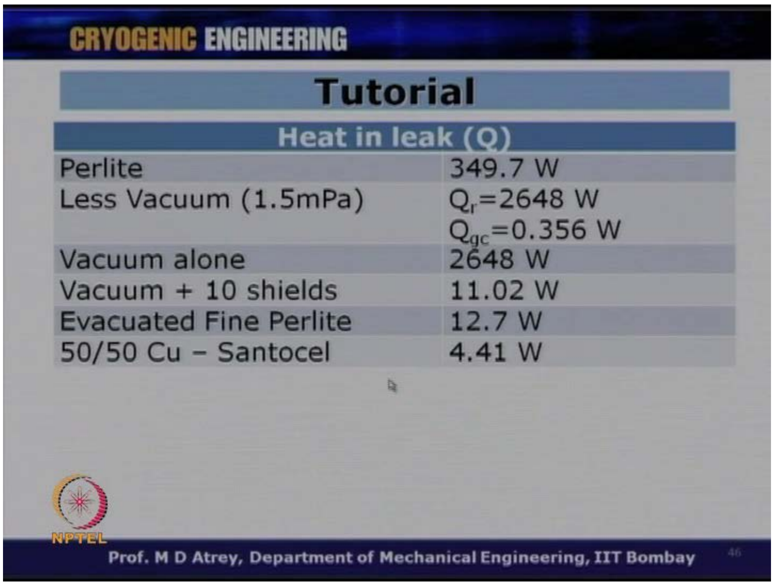

So, if I want to compare all this values, you can see it here. If I were to go for only pertile which is gas filled pertile, it is going to be 349.7 watts. If I got to be have vacuum which is going to be 2648 plus some gas conduction which is a absolutely negligible instead of this radiation heat losses, then vacuum alone is going to be same, but vacuum plus 10 shields is going to be reducing the entire thing to be only a 11 watts, but then the problem was having how to have this 10 shields over there in place. Then evacuated fine pertile powder is much better 12.7 watt and what is most preferred will be opacified powder which is copper santocel giving only 4.41 watts of heat in leak.

So, this gives an idea that evacuated fine pertile and opacified powder is going to be quite good. We cannot practically have really 10 shields in vacuum over there, going to be weight increase also the mass increase over there and going to have lot of manufacturing problems over there. So, one can get an idea of different you know heat in leaks amount for different insulations is in this tutorial. To summarize, all the insulation which we have studied, we found that in vacuum, the radiation is the dominant mode of heat transfer.

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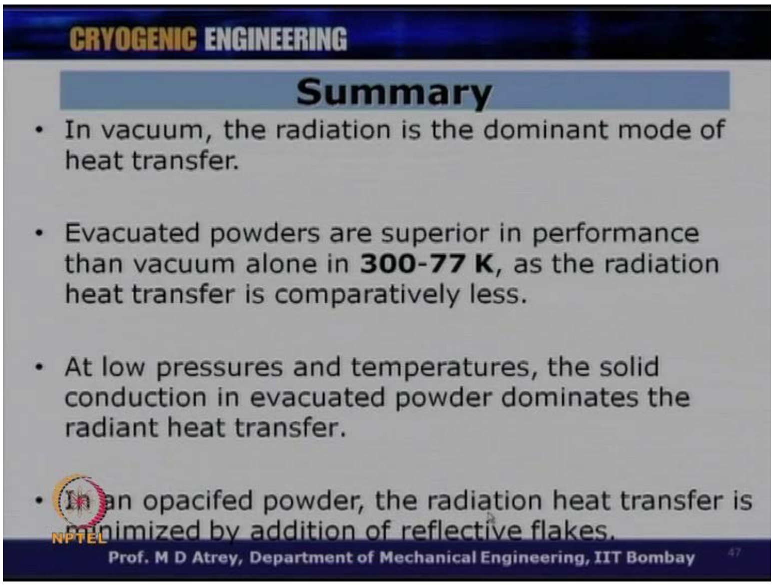

Evacuated powders are superior in performance than vacuum alone in 300 to 77 Kelvin as the radiation heat transfer is completely comparatively less which is what we have just proved with the tutorial also. At low pressures and temperatures, the solid conduction in evacuated powder dominates the radiation heat transfer and therefore, for lower and lower temperatures up to helium temperature, evacuated powder may not be used and this is what we see in the next lecture also.

Also we found that in an opacified powder, the radiation heat transfer is minimized by addition of reflective flakes and that we found that actually this serves much better actually. But understood there is a some problem associated with this opacified powder because the flakes try to come down to one point due to the vibration for this container, and therefore, they may not be preferred at many places. But what is important is evacuated powder is always preferred solution for up to liquid nitrogen temperature, and this is more kind of a practical solution to taking care of various problems.

Thank you.