Particle Characterization

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Module No. #9
Lecture No. # 25
Transport Properties: Illustrative Application

Welcome to the 25 th lecture in our particle characterization course. In the last few lectures, we have been dealing with particle adhesion, cohesion, removal, transport and deposition. And this will be the last lecture in that particular area, and what we want to focus on in in this lecture is what we called analogy breaking phenomena in the last lecture.

When we compute particle fluxes, the easiest way to do it as I mentioned in the last lecture is, if you can assume that a perfect analogy exist between heat transport mechanisms and mass transport mechanisms, so we can do some simple experiments primarily temperature, sometimes heat flux.

And obtain the non-dimensional heat transfer coefficients such as prandtl number, nusselt number for heat transfer, stanton number for heat transfer and then essentially from those values extract their mass transfer counter parts. So, if you know the prandtl number, and you know the schmidt number, you can estimate the nusselt number for mass transfer if you know the nusselt number for heat transfer and you can estimate the stanton number for mass transfer if you know the stanton number for heat transfer.

And once you know these non-dimensional parameters, you can always use the prevailing magnitudes of velocity and so on, to obtain the actual rates of deposition of particles on surfaces. But, the key assumptions again is that the mechanisms of heat and mass transport are identical, now when is that true? It is true in the limiting case, where, a) there are no phoretic phenomena, in other words, there are no external fields that are applied to the flow, which can affect mass transfer differently from the way of a heat transfer.

And secondly, when the particles are small enough to be considered heavy molecules, in other words, the inertial effects have not set in to a tremendous extent and the particles continue to essentially follow the stream lines of fluid flow. So, it is only under these two limiting cases that you can actually legitimately assume equivalence between heat transfer and mass transfer mechanisms and do the calculations. But, in reality, particularly in in situations that have a wide range of particle sizes, as well as a fairly broad temperature range in the system, both these violate assumptions are likely to be violated.

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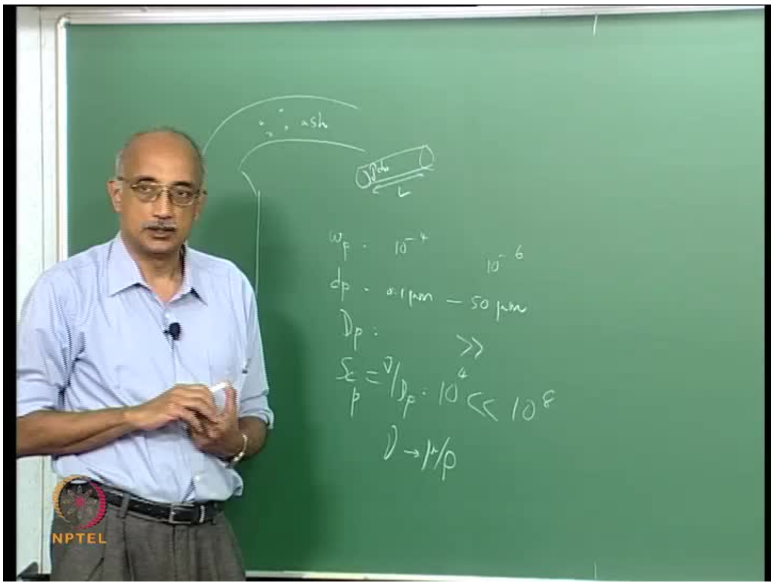

And the particular illustrative example we were looking at in the last lecture, which we will now go back to is the case of pulverized coal combustion in power plants. And in particular, we were looking at the heat transfer associated with the flow of the hot gas, which encounters a tube that is held transverse to the flow of the combustion gases, right. Again, the point here is omega p and D p, that is particle size and particle mass fraction can vary quite a bit in terms of how they are present in the gases.

The primary particle that is present in if you are burning coal, then the particles that are present are primarily ash particles, which is the incombustible, inorganic fraction of the coal matrix. And if you look at the typical size distribution of ash particles, it can range anywhere from sub-micron to 50 microns, so clearly this is a very broad distribution, within which on one end of the spectrum diffusional effects and phoretic effects are going to be important, and the other end of the spectrum where inertial effects are going to be equally important.

The mass fractions are likely to scale inversely with size, for example the 0.1 micron sized particles are likely to be present in much larger quantities compared to the 50 micron size particles. And so, in terms of the mass fraction, this may be of the order of 10 to the power minus 4, and this may of the order of 10 to the power minus 6 just roughly. And so, the relative effects of particles in different size ranges very much depends on the inventory of particles that are available in those size range, which is a function of particle size.

Now, the other parameter that is also important is the diffusivity of the particle, which scales inversely with size. So, fine particles are going to have much much greater brownian diffusivities compared to larger particles. So, if you look at the Schmidt number, which is equal to nu by D p, schmidt number for a particle is equal to nu is of course the kinematic viscosity, which is equal to dynamic viscosity divided by rho. So, if you look at the ratio of nu over D p, what is gonna happen?

This is the other way around; schmidt number for fine particles is going to be much smaller, because diffusivity is in the denominator. The kinematic viscosity is a gas characteristic, so it that remains constant. However, fine particles have much larger diffusivities and therefore, the schmidt numbers are significantly smaller for the sub-micron fraction. In fact, the schmidt number can vary all the way from 10 to the power 4 to 10 to the power 8 for various particle sizes that are encountered in a typical combustion process stream.

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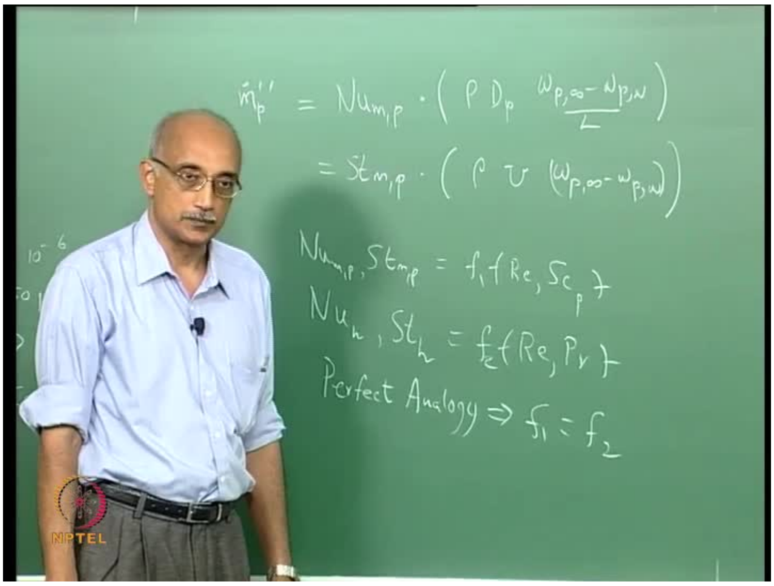

So, what this means of course is that if you now estimate the rate at which particles are depositing, and again assume that we have a tube of length l and diameter d w, you can take them mp dot double prime, which is the particle flux depositing on the wall as equal to either in nusselt number of the particles multiplied by the reference particle flux under diffusion control conditions, which is equal to rho times D p times omega p infinity minus omega p w divided by a characteristic length or you can write this as Stanton number multiplied by rho times u times omega p infinity minus omega p w. So, these are the quantity within the parenthesis, is the corresponding reference flux in the diffusion control condition and in the convection control condition.

And we have seen before, the nusselt number as well as the stanton number, or functions of reynolds number and schmidt number, just as the heat transfer nusselt number and the heat transfer stanton number or functions of reynolds number and prandtl number. In fact, as I mentioned in the last class, this f and this f are identical, the functional dependences are the same under perfect analogy conditions. So, this is f 1 and this is f 2 is under this conditions, where there is heat to mass transfer analogy, f 1 can be taken to be equal to f 2, so practically what does it mean?

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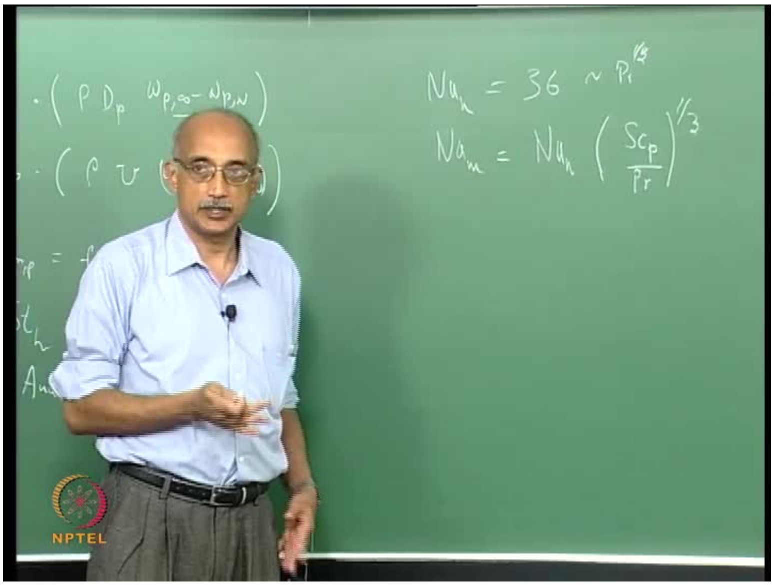

We can always estimate these values, because it is experimentally easy to measure. So, we can measure this, we can we can measure the reynolds number, prandtl number for a hot gas, is roughly point seven or so. So, you can actually establish what the nusselt number for heat transfer is, and in fact, for a typical combustion gas, that you are reaching a temperature of let us say a thousand kelvin at one atmosphere, the nusselt number for heat transfer corresponding to a circular cylinder in the cross flow is roughly 36. What does that mean for the nusselt number for mass transfer then? Is it going to be higher or smaller?

Remember that the way you estimate nusselt number for mass transfer, if you know the nusselt number for heat transfer is to multiply it by schmidt number, and divided by the prandtl number, and the function should be the same. So, let us say that the nusselt number for heat transfer is goes as the prandtl number to the power one third, which again by the way is true for most hard combustion products.

Then, the nusselt number for mass transfer will be the nusselt number for heat transfer times for the schmidt number for the particle, divided by the prandtl number to the power one third.

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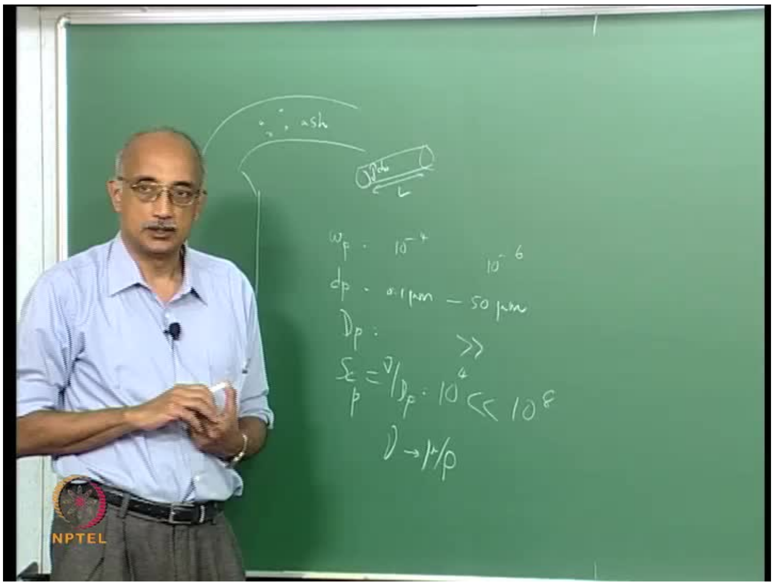

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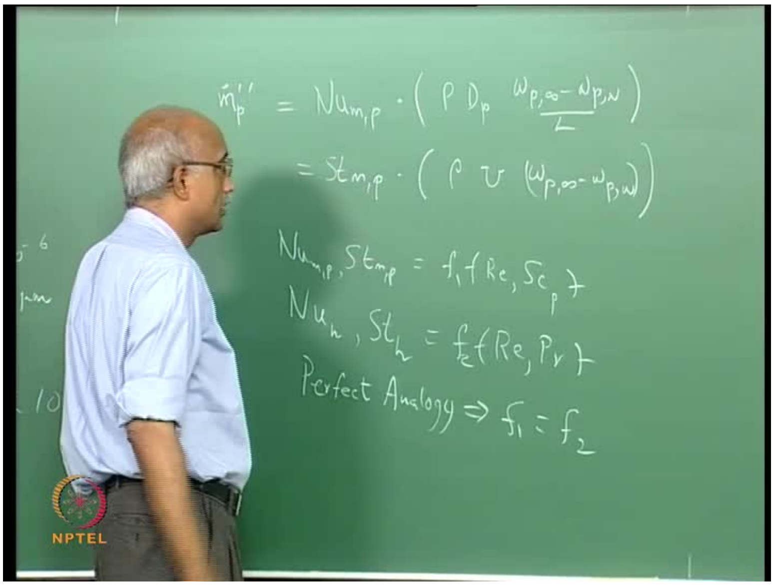

But, as we have seen earlier, because diffusivities are small values, the schmidt numbers are quite large, so the nusselt number for mass transfer is going to be roughly 10 to the power 3 to 10 to the power 4 times the nusselt number for heat transfer. So, once you know that, once you have calculated the nusselt number for heat transfer, you apply this formula, and you calculate the nusselt number for mass transfer, then you can go back to this expression and substitute values for density particle diffusivity.

For the most part, you can assume that omega p w is much smaller than omega p infinity, in other words, a particle mass fraction far away from the deposition surface is much greater than the particle mass fraction near the deposition surface.

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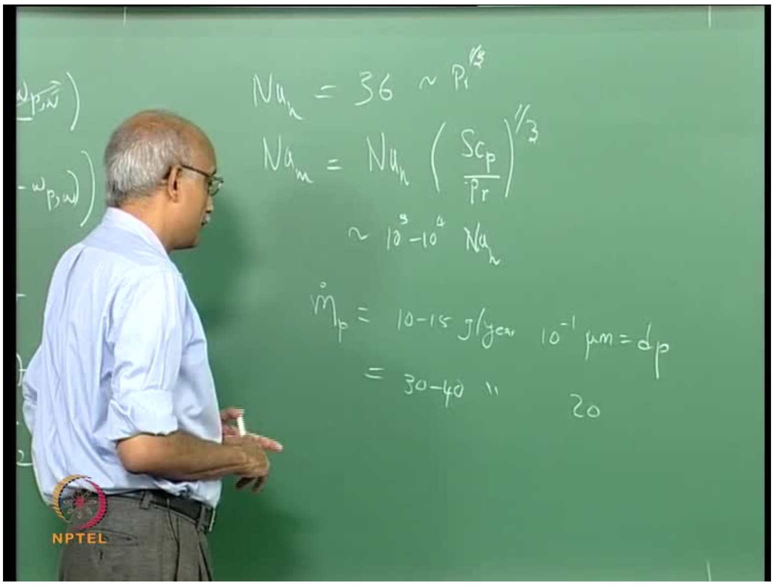

And so, you can proceed to calculate your m p dot double prime values, and divided by the area of the tube, that will give you mp dot, that is the rate at which particles are depositing on the surface, and it turns out to be under most realistic conditions, roughly about 10 to 15 grams per year for particles that are in the 10 to the power minus 1 micron size range, and it is of the order of 30 to 40 grams per year for particles that are in the 20 micron size range.

However, again this estimation does not include the contribution due to inertia, and it does not include the contribution due to phoretic forces, right. And so, it severely underestimates the deposition of ash particles on the heat exchanger surface.

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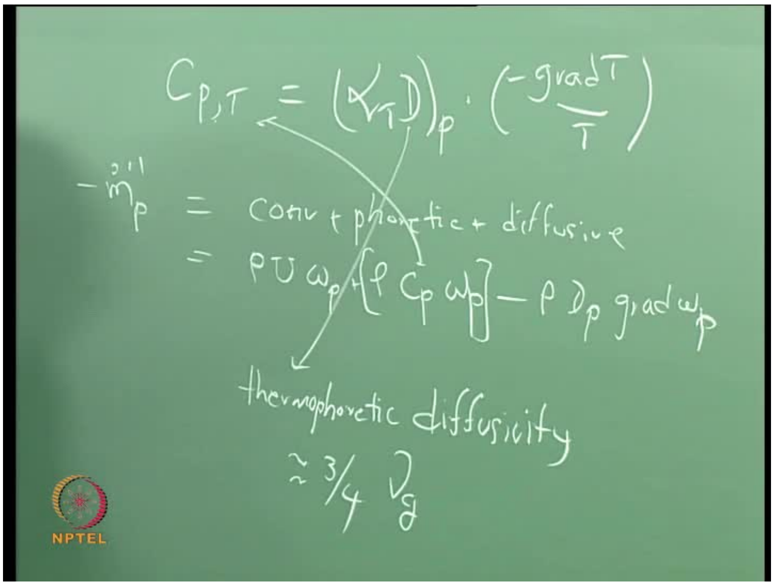

$$C_{p,T} = (\alpha_T D)_p \cdot \left(\frac{-\text{grad}\,T}{T}\right)$$

$$-\dot{m}''_p = \text{conv} + \text{phoretic} + \text{diffusive}$$

$$= \rho U \omega_p + \{\rho C_p \omega_p\} - \rho D_p \,\text{grad}\,\omega_p$$

thermophoretic diffusivity

$$\simeq 3/4 \, \nu_g$$

So, how do you address that problem? Well, you apply correction factors appropriately, so let us take termophoresis first. As i mentioned in the earlier lecture, thermophoresis is the velocity that is induced on a particle due to the presence of temperature gradient. So, a temperature gradient does not only drive heat transfer, it also drives mass transfer, because particles that are in two different temperatures have different energy levels and that the under equilibrium conditions they want to equilibrate their energy and so hot particles tend to move towards the cold regions. And of course, there is always an equal and opposing flow that is induced, and that is called stefan flow, but do not think I will get into that in in this in this course.

But, the diffusion, or the actually it is like a convective motion of particles down at temperature gradient is known as thermophoresis and the velocity c p t associated with thermophoresis. Again, if you recall the overall Flux of particles has three components to it, right, minus m p dot double prime equals a convective part plus a phoretic part plus a diffusive part. And we had written this as rho time's u time's omega p plus rho time's c p time's omega p minus rho time's D p times gradient in omega p in the last class.

So, this c p thermophoresis is essentially this component, the phoretic component, and it can be written as an alpha t d for a particle multiplied by minus gradient in temperature divided by temperature, which can also be written as minus gradient in logarithm of the temperature. Now, this parameter alpha t D p is called thermophoretic diffusivity, and interestingly enough no matter what the particle size, this parameter alpha t D p is approximately equal to three quarters of the kinematic viscosity of the gas. This relationship is prevails virtually in every practical environment that has been sampled, so it basically says that if you know the temperature distribution that present in your system, and you know the viscosity and density of the fluid in which the particles can be suspended or suspended, then you can estimate the themophoretic velocity, that is the convective velocity that is induced on the particle by the presence of a temperature gradient. So, let us say that you have estimated c p t, what do you do with that?

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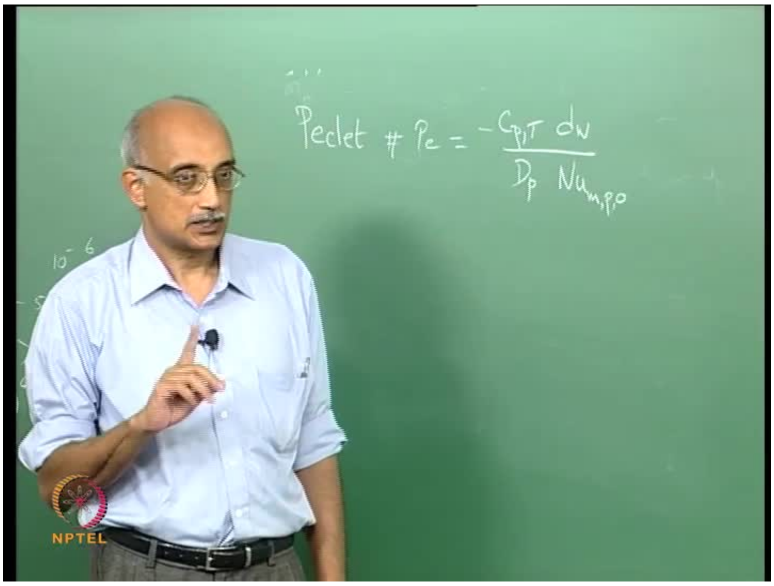

On the next thing, you do is estimate a peclet number, the peclet number in this case is written as minus c p t times d w over D p times nusselt number for mass transfer under 0 conditions.

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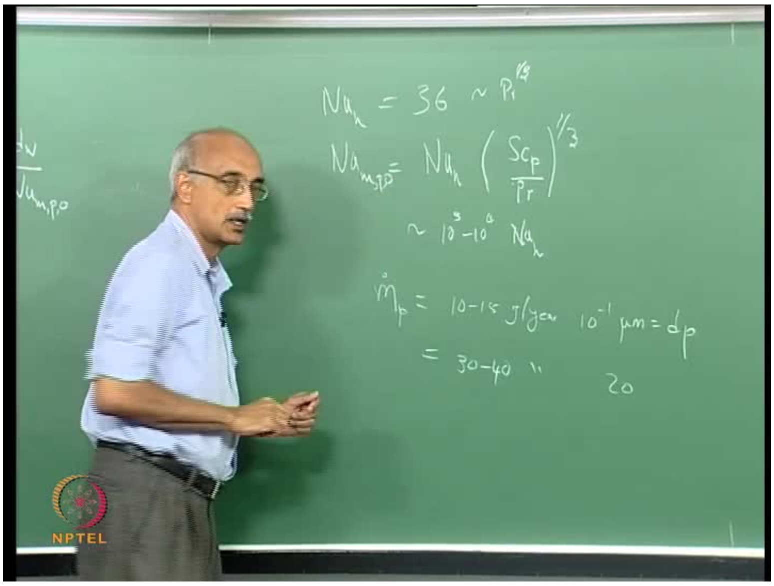

Remember, we discussed the 0 condition yesterday; this is the nusselt number that you have just estimated here. This is actually n u m p 0, again remember what we discussed in the last class, that the 0 condition here implies that we have been assuming perfect analogy between heat and mass transfer.

So, this is your base line nusselt number that would have prevailed if there would be no analogy breaking conditions. So, that is now included in this peclet number, in the denominator.

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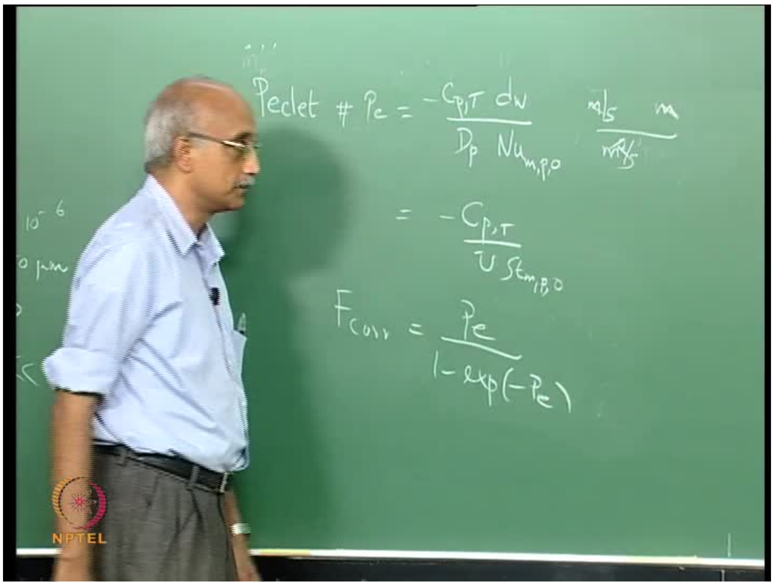

Just check the dimensionality, this is c p t is velocity times d w meters divided by meter squared per second, so this is a non-dimensional parameter which is referred to as the peclet number.

Now, the it can also be written, now this is the formulation of peclet number for a diffusion dominated case. In the case where it is convection dominated, you write it as minus c p t over the prevailing convective velocity u multiplied by Stanton number for mass transfer, again evaluated under perfect Analogy conditions assuming that themophoresis and inertia are not playing a crucial role.

So, you estimate the peclet number, because you know everything else, you know the thermophoretic velocity from that expression, you know the diameter of your tube, you know the diffusivity of the particle, and you know the velocity of the gas stream, and you know the either the nusselt number or the Stanton number under perfect Analogy conditions, because you can estimate them if you know their heat transfer counterpart.

So, peclet number can be estimated, then you develop something called a correction factor, which is based up on the peclet number, it is equal to the peclet number divided by one minus exponential of minus peclet number. And then, finally, you apply this correction factor to the base line values that you had previously estimated.

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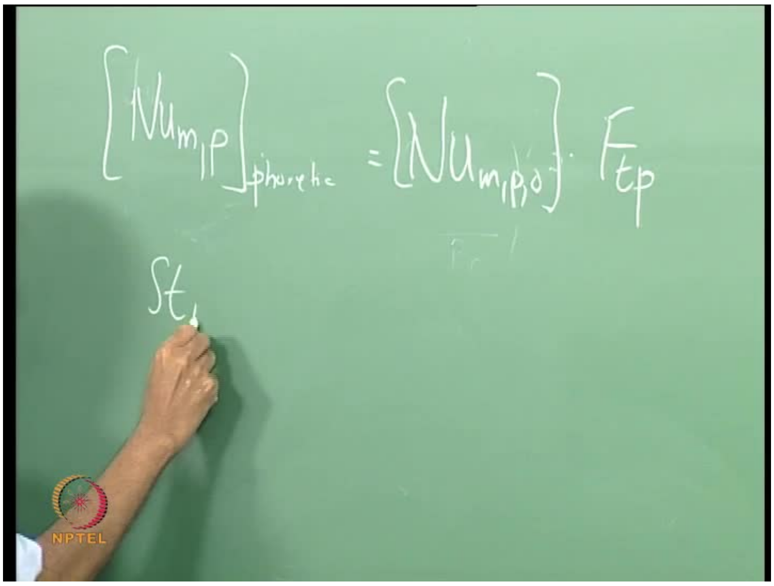

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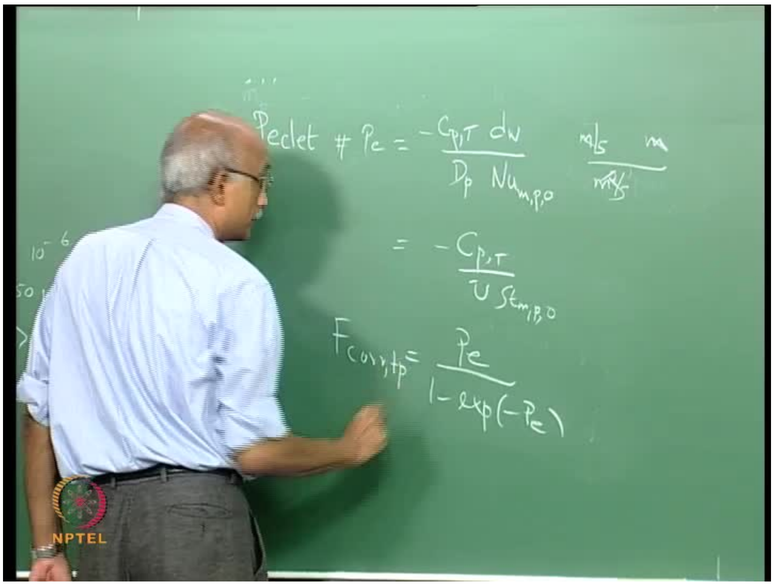

$$\text{Peclet \# } P_e = \frac{-C_{p,T}\, dw}{D_p\, Nu_{m,p,0}} \qquad \frac{m/s \;\; m}{m^2/s}$$

$$= -\frac{C_{p,T}}{U\, St_{m,p,0}}$$

$$F_{corr,tp} = \frac{P_e}{1 - \exp(-P_e)}$$

So, n u m p under phoretic conditions is equal to the n u m p 0 that you had previously evaluated times this f, let us call this f correction factor for themophoresis Ftp.

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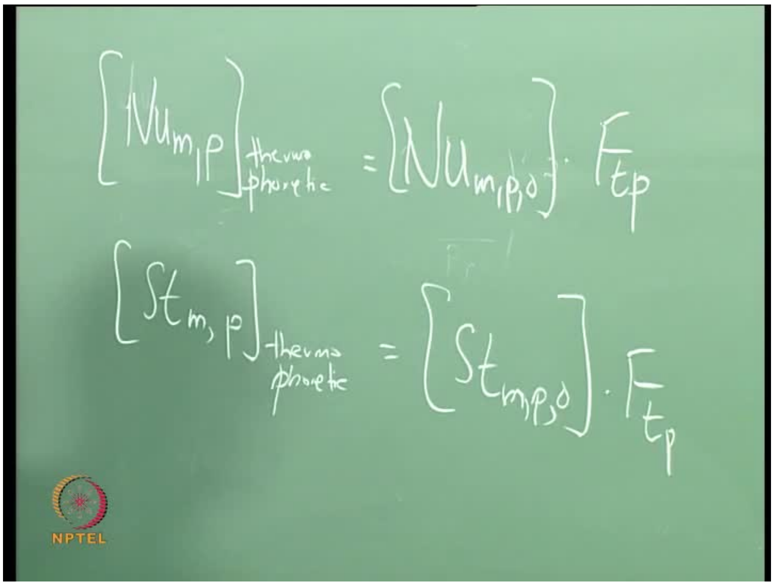

$$[Nu_{m,p}]_{\text{thermophoretic}} = [Nu_{m,p,0}] \cdot F_{tp}$$

$$[St_{m,p}]_{\text{thermophoretic}} = [St_{m,p,0}] \cdot F_{tp}$$

And similarly, the stanton number for mass transfer for a particle under thermophoretic conditions will be equal to stanton number for mass transfer for particle and under base line conditions times a correction factor frame t p, because these correction factors will be different, since these two equations are not identical, so let us say that this is some f prime of due to thermophoresis.

So, it is a step by step procedure that you have to follow, you first evaluate the stanton number or the nusselt number and assuming perfect analogy with heat transfer, and then you examine the actual flow conditions to understand is that a good assumption or that phenomena taking place that will violate this assumption.

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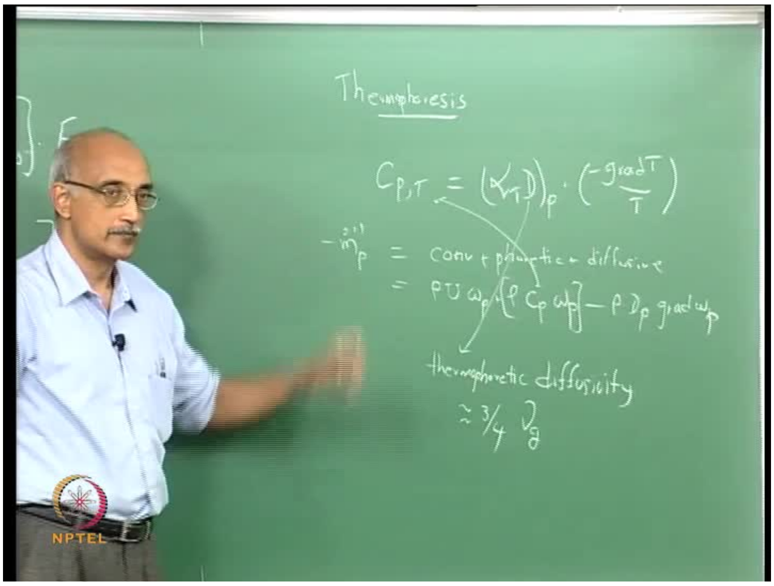

In this particular case, because it is a combustion problem, we said thermophoresis can violate this Analogy. So, we estimated the corresponding phoretic velocity, from the phoretic velocity, we estimate the peclet number, from the peclet number you estimate the correction factor, you apply the correction factor to the base line nusselt number or stanton number to obtain the actual prevailing nusselt number and stanton number. And then, again, you multiply these with a reference fluxes to obtain the actual flux that is going on.

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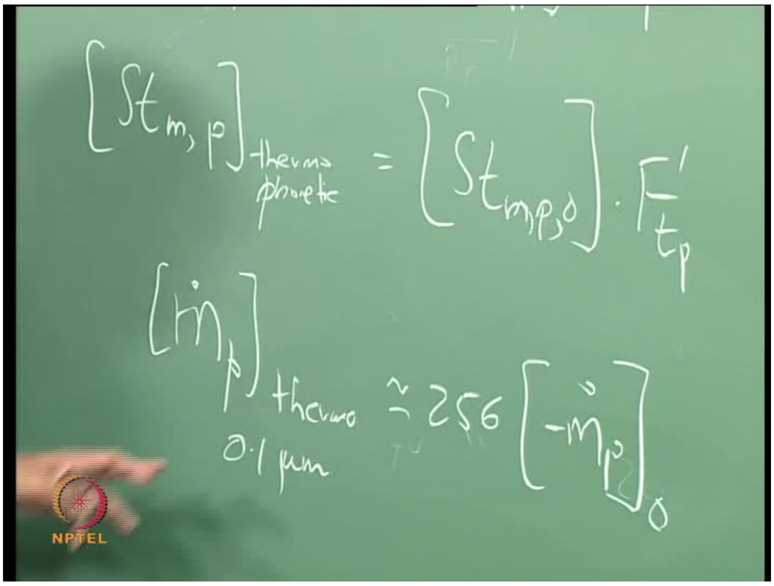

So, when you go through all that, for the same problem for which we previously got 11 to or 15 to 40 grams per year, now if you do the calculations, the m p dot value including thermophoresis, for 0.1 micron sized particles is roughly 256 times what we had previously estimated without taking into account thermophoresis, so it makes a huge difference.

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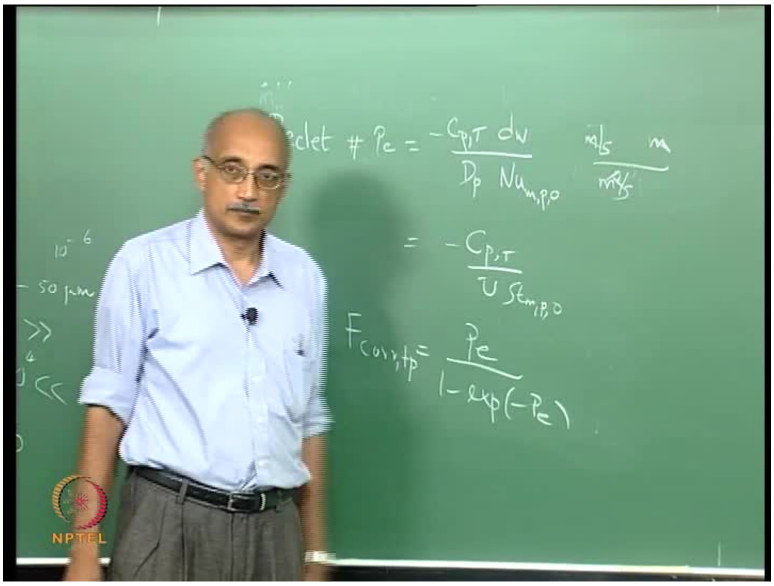

Now, why does it make a huge difference only for the 0.1 micron size particle? Why isn’t it making a similar difference for larger particles? The reason is the peclet number, again you see that the diffusivity is in the denominator and essentially larger particles will have lower diffusivity values.

And therefore the peclet numbers will be significantly higher for a bigger particle and the corresponding correction factors on the other hand will be smaller for larger particles. And in fact, that is basically what this reflects that a a large particle will have c p t values that are much smaller, the reason again is this parameter alpha t times D p has the particle diameter in the numerator.

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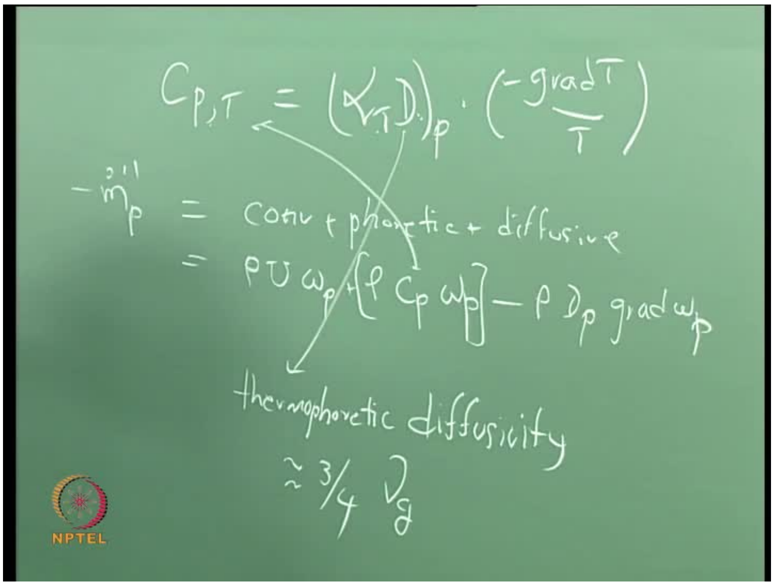

$$C_{p,T} = (\alpha_T D)_p \cdot \left(\frac{-\text{grad}\,T}{T}\right)$$

$$-\dot{m}''_p = \text{conv} + \text{phoretic} + \text{diffusive}$$

$$= \rho U \omega_p + [\rho C_p \omega_p] - \rho D_p \,\text{grad}\,\omega_p$$

thermophoretic diffusivity

$$\simeq \frac{3}{4} \nu_g$$

And that affect tends to overwhelm the effect of the particle diameter in the denominator of the peclet number, this is a essentially the D p values to some extent. If you compare this expression and that expression, the D p numbers cancel out, however, this alpha t parameter is still there and that scales with particle size. The alpha t parameter will be larger for finer particles compared to larger particles and that is why the final correction factor is much greater for finer particles.

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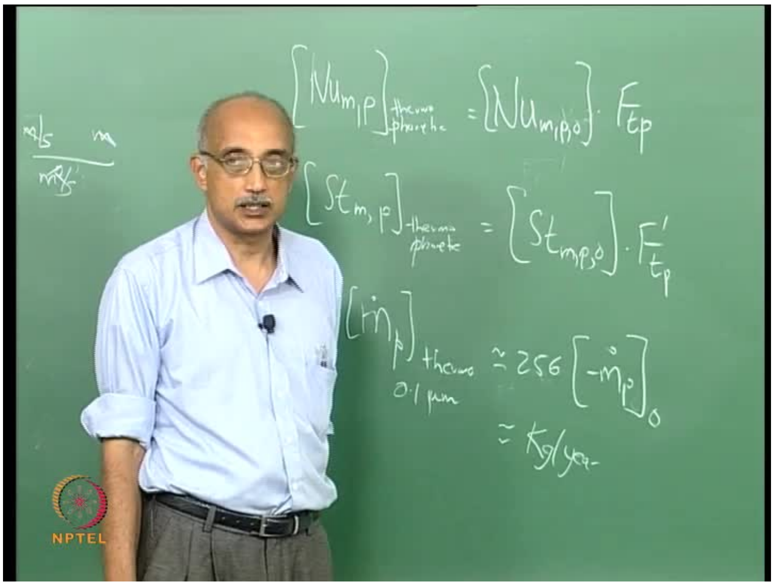

So, for particles in the sub-micron size range, thermophoresis is an important correction factor. So, essentially, now, what we will find is instead of grams per year, this leads to kilo grams per year of ash material depositing on heat exchanger surfaces, which has been practically observed. So, we know that, you know this thermophoresis is not just a theoretical concept; it is something that really affects the day to day operation of a power plant. Now, let us look at the other case of inertial transport. As we were discussing in earlier lectures, inertia is essentially quantified through the strokes number.

The higher the strokes number, the greater the associated capture efficiency and the capture efficiency will then dictate how much of the particle mass fraction that is flowing on top of a surface actually gets captured on the surface.

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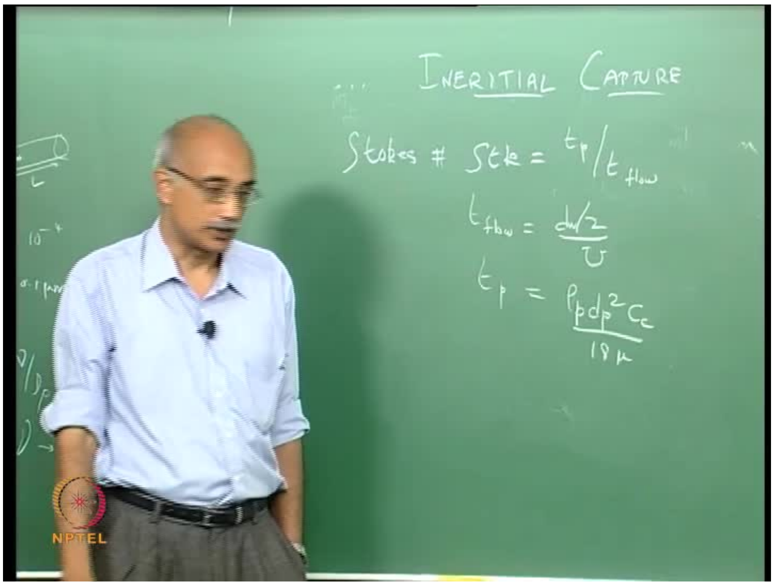

So, that again must be applied as a correction to the base line values that we have previously estimated. However, inertial Capture is not represented in terms of a correction factor f such as this mechanism is. By the way, this approach will work for any type of phoretic force, so it could be electrophoresis, if the applied gradient is due to an electric field, it could be magnetophoresis if there is a magnetic field that is applied or it could even be a body force field, if that is the field that is causing a separate velocity to be induced on the particle compared to the motion of the gas.

So, all of those essentially impart a convective velocity, on top of the convective velocity that the particle already has and that is why they can be simply in cooperated using correction factors. Over inertia introduces a total different mechanism by which particles move, so it you cannot just take the base line expression, and multiplied by aah correction factor, because nusselt number and stanton number are not even relevant any more. When inertia begins to dominate particle transport forget about nusselt number, forget about Stanton number, the only dimensionless parameter that is important is strokes number, right. So, you have to reconstitute your discussion in terms of the strokes number, again the definition of strokes number, we are actually derived the value for that couple of lecture ago, it can be represented as a time characteristic time for particle transport to a characteristic time for fluid flow. Now, this t flow, you can estimate as d w by 2 divided by u, where u is the approach velocity of the gas stream, and d w by two is the radius of the cylinder.

T p if you recall the expression that we had derived is rho p times D p squared times c c over 18 times mu, whereas the viscosity of the gas and the ratio between these two gives us the strokes number. So, for a prevailing flow situation, once you know all these parameters, you can proceed to calculate the strokes number, right. Now, the strokes number, if you actually substitute values for all these parameters and estimate strokes number for different particle sizes, what you will find is for particles that are of the order of 0.1 microns sub-micron, stokes number it is actually well below one.

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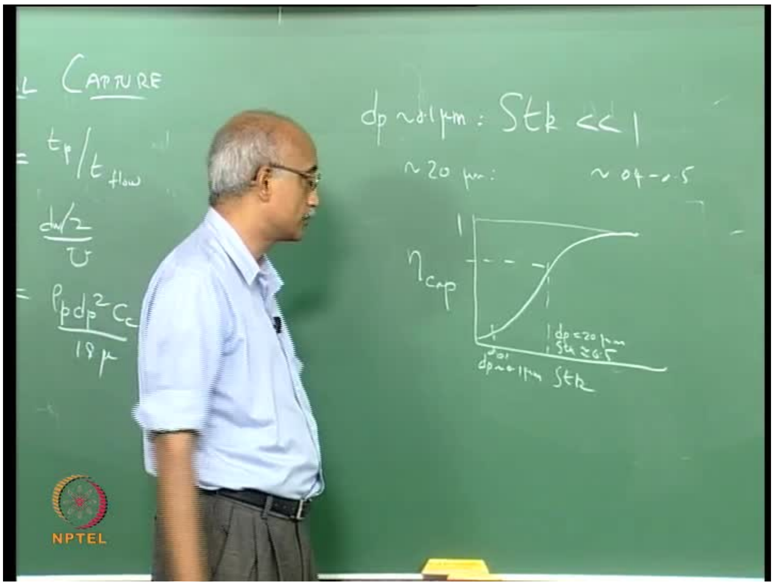

It is of the order of 0.0 something, whereas for particles that are of the order of 20 microns, strokes number is approximately 0.4 to 0.5. So, what is the practical implication of that? If you recall the graph we had sketched in the last lecture, if you plot strokes number verses capture efficiency, you have an s shaped curve. So, for a particle diameter of 0.1 microns, your strokes number is going to be roughly 0.1 and for a particle of size D p equals 20 microns, strokes number is going to be approximately 0.5. And the capture efficiency rapidly rises from being close to 0 for the sub-micron particles to to approaching one for very very large particle. So, depending on the actual shape of this curve, your capture efficiency is now going to have a finite value, that is somewhere between 0.4 and 1.

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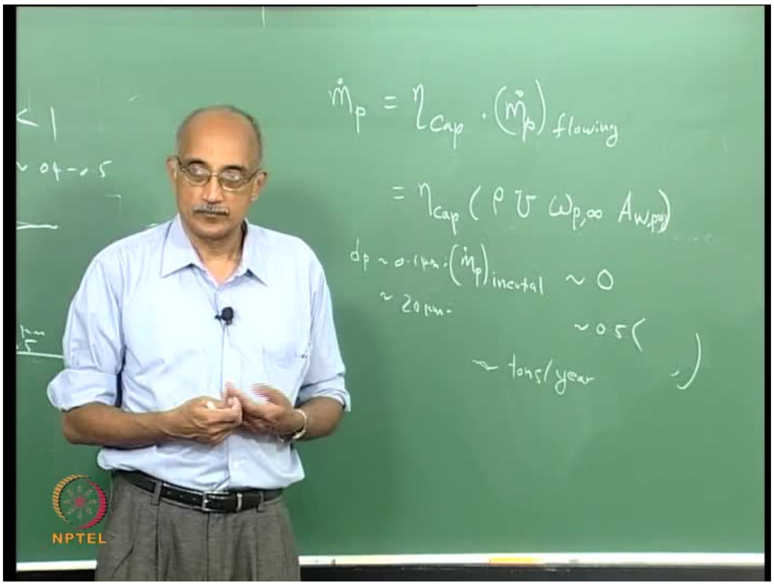

So, under conditions where inertia is dominating, the expression for particle capture m p dot is equal the to the capture efficiency eta cap times m p dot flowing. That is, it is it is a product of the rate at which particles are flowing over a surface to the capture efficiency or the capture probability. So, this is basically eta cap time's rho time's u time's omega p infinity times the area. That is the projected area of the surface that is exposed to the flow of gases, so this is the expression that you now use to calculate the rate of deposition of particle on to the surface.

And again, the key difference is, for particles that are 0.1 microns, m p dot due to inertial effects going to be virtually 0, the reason is the capture efficiency is very very low. So, no matter what the mass fraction or mass flux of particles is that is flowing over the surface, as long as the capture efficiency is very very low, it does not matter, it will be asymptotically approaching 0. Whereas, particles that are of the order of 20 microns, the same value is going to be the capture efficiency value, whether it is let us say it is 0.5 times this number in the diameter, I mean inside the parenthesis.

And again if you do the calculation for a realistic set of power plant conditions, we finally obtain values that are of the order of tons per year when you include inertial effects into your calculations. So, you know, if you recall, we have gone from grams per year of deposition, if you assumed perfect analogy between heat and mass transfer to kilo grams per year.

If you assume that thermophoresis is important to now estimating tons per year, if you assume that inertial effects are also important, so what do you do? You actually look at a power plant that is operating, and try to get some data on what is he observed rate of deposition, and what do you find, this is actually happening in power plants today.

And that is the reason why, you know, the power plant losses due to fouling is such a huge problem in the industry. When there is a literally millions of dollars of loss daily on a global scale due to the fouling problem, because of you know the shutdowns that are required, the cleaning that is required, the reduction in the heat transfer efficiency, the reduction in the momentum transfer efficiency, all of that is associated with the growth of these fouling deposits, which is directly related to this phenomenon. So, this should give us some clues about how to extend the life time of boiler tubes.

Again, if you look at this expression, if you reduce this value, if you reduce the amount of ash that is present in the combustion gases that has a direct effect on this parameter, right. So, the number one strategy is to use low ash coal. That remember, I said that, that is not always a sound strategy, because a - low ash coals are not available in India, and b - usually low ash coals have high sulphur, which can introduce other problems such as corrosion and so on.

The second trick would be to use, well try to lower the capture efficiency, now that is primarily a size dependent effect. So, you try to reduces the size of the ash particles that are present in the combustion gases.

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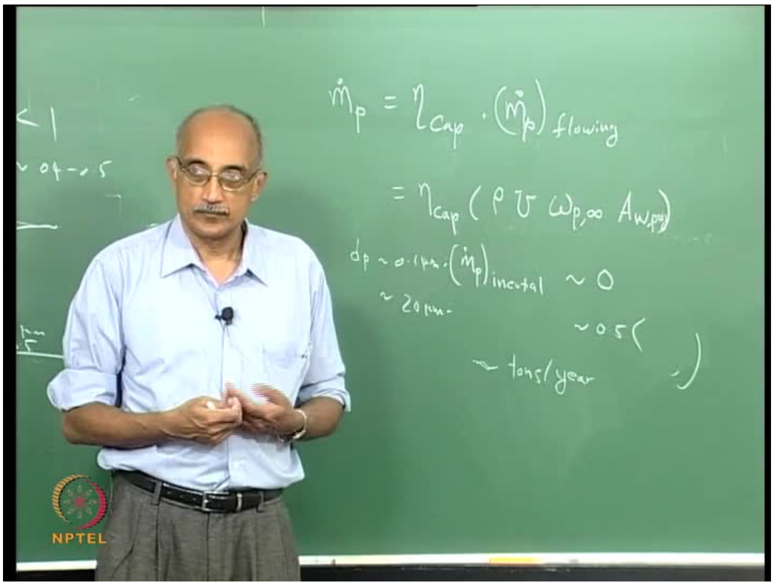

How do you do that? Well, you can clean the coal and try to remove ash, and you can also try to reduce the size of the ash coal particles that you burnt, so that the corresponding ash particles that result will also be smaller. Because the way that a coal particle gets converted to an ash particle is due to the loss of the volatile material, that is present loss of the organic carbon, so whatever is left is the inorganic phase, which is called ash.

So, if you can reduce the size of the coal particle prior to combustion that will have a direct effect on coal size after combustion. So, you know the crushing and the grinding process that is used to prepare coal for combustion needs to be optimized, so that bigger an optimum size range that will result in a minimum of capture efficiency. Because, things like velocity you cannot play with too much, because you need high velocities for high heat transfer efficiencies, so you do not want to reduce the u value, you want to keep it actually as high as possible, both for the purpose of extracting momentum in the case of gas turbines. And you can also operate a gas turbine using coal combustion, in that case, you do not care so much about extracting heat, but rather you are trying to extract momentum on to turbine blades, stator wanes and so on.

Or in the case of boiler tubes, you are trying to extract heat, for both high u values is good, because that results in a high Reynolds number. And the higher the Reynolds number, the higher are the heat transfer coefficients and momentum transfer coefficients.

But this can still give you some ideas on how to minimize the growth of fouling layers on heat transfer surfaces in power plants. Now, one of the key parameters here is, as I said this eta cap, now the view that we have shown here is that the capture efficiency only depends on the particles strokes number.

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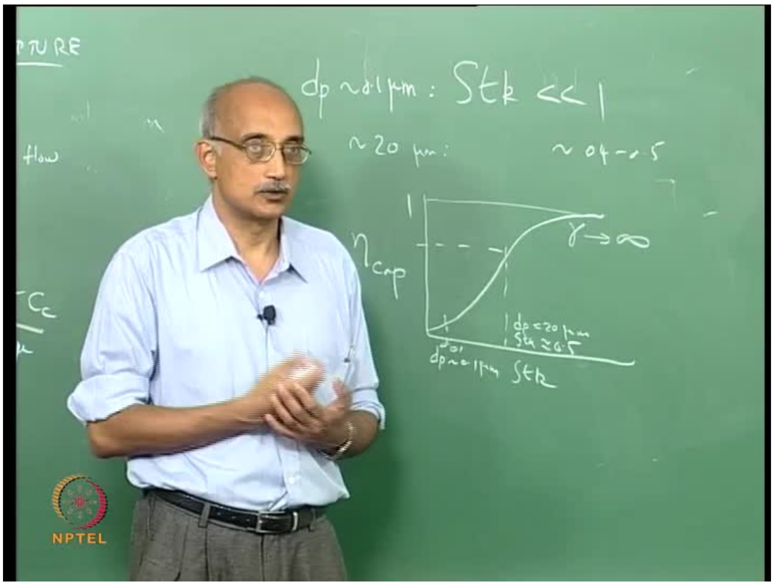

Now, is that is that true? I mean does that always work or is it too simplistic of view point? Because really a two part is here, right, the particle is moving, it has also the surface, in the surface also has to allow sticking of the particle, so this this statement or this graph makes certain assumptions. It assumes that the surface energy of the boiler tube is very very high, so, I mean, this this view actually assumes that surface energy is virtually infinity.

Now, that the in other words, assumes that if a particle can stick on the surface, it will stick on the surface, there is nothing about the surface itself that will reduce the probability of particle sticking to the surface. But, now, you recall the discussions we had regarding adhesion of particles, cohesion of particles. Really that is not true, right; the properties of the material have a huge influence on forces of adhesion.

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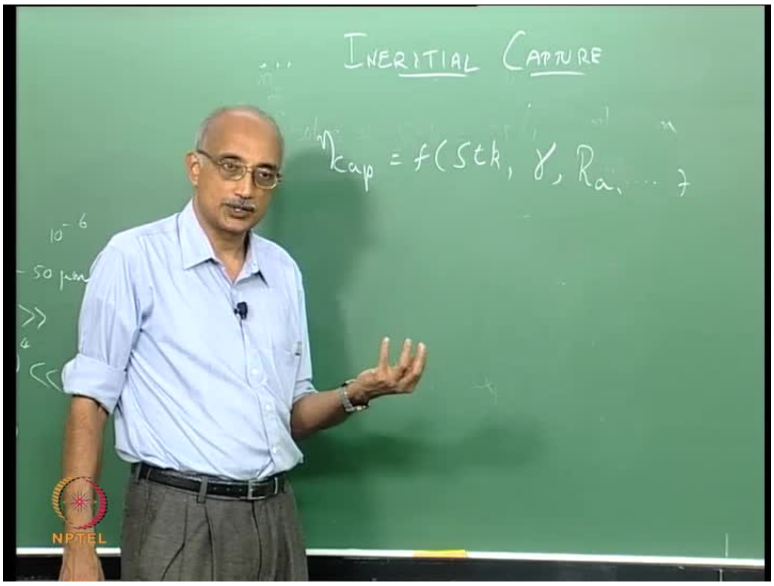

So, a more realistic representation of the capture efficiency would be that it is not only a function eta cap, is certainly a function of the strokes number, where it should also be a function of surface energy of the surface on which the particles are depositing. Anything else, it should also depends on the roughness, because we know that, again as we discussed in the module on adhesion, particles stick to a rough surface very differently from the way they stick to a smooth surface, so something like a surface asperity Ra value will also play a significant role.

And actually, you know when you think about it, there are many many more parameters that play in to this. Even things like, you know the hardness of the particle that should play a role, I mean a harder particle should be able to rebound more easily than a softer particle, because it can deform.

Again, remember the discussion we had about a deformable verses a non-deformable surface. If you have two deformable surfaces coming into contact, the adhesion force between them it is likely to be greater because the effective interfacial area will be larger. And also it will keep increasing with time, because you know, with time the two surfaces will accommodate each other, right. So, all of those factors can come into this also, this representation that we have, the capture efficiency is only a function of strokes number, is an over simplification to high highlight the fact that particle transport does play a significant role.

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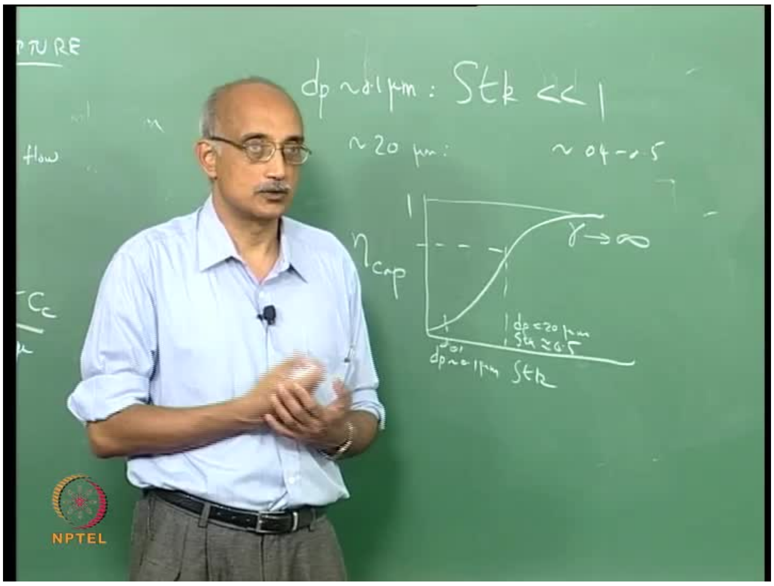

But, a material scientist or a metallurgist would argue that these aspects are just as important if not more and I would agree. So, for example, this curve that we are showing, if all we do is change the surface from a high energy surface to a low energy surface, how do you do that? There are coatings that are available, there are plating’s that have low energy, good example is Teflon.

There are also various ceramic coatings that have low energy. So, for the same particle flux approaching the surface, if you all you did was you know take the surface and just coated with a low energy material, all of us sudden this capture efficiency will drop to this, the difference is here gamma tends to 0, tremendous effect. And you could argue that from a fouling view points, this is really the first order effect, because it as such has a dramatic effect, you know no matter how much this is, as long as you can maintain a low energy surface, it will repel whatever particles comes near, so it does not care.

But, that is from a fouling viewpoint, again, remember, there are multiple mechanisms by which particles can degrade surfaces, fouling is one, but there is also something called erosion, erosion does not care about surface energy. If erosion particles strike the surface at high velocity, and cause physical damage to the substrate, you know, it is does not matters if it is a low energy or a high energy substrate, surface energy only affects fouling, which is an adhesion phenomenon, it requires that particles stick to the surface, so surface energy has a very direct effect on that.

But, if you are also worried about erosion of a material due to, for example, ash particles, then you should be much more concerned about the hardness of the surface, the hard of the surface, the less prone it is to erosion. So, again what that means is if you are trying to reduce fouling and reduce erosion, then you should use a material that is both low surface energy and also high strength or high hardness.

Good material like that is ceramic, and that is why in critical locations, in pipe lines where you have particulate material flowing, use ceramic liners. So, the entire pipe may be made of steel or stainless steel or aluminum or whatever, but in critical locations, where they know that there is high propensity for particle related damage, you always put a low energy lining material. And ceramics are very very popular, in fact there is a company called carborundum universal, which you may have heard about.

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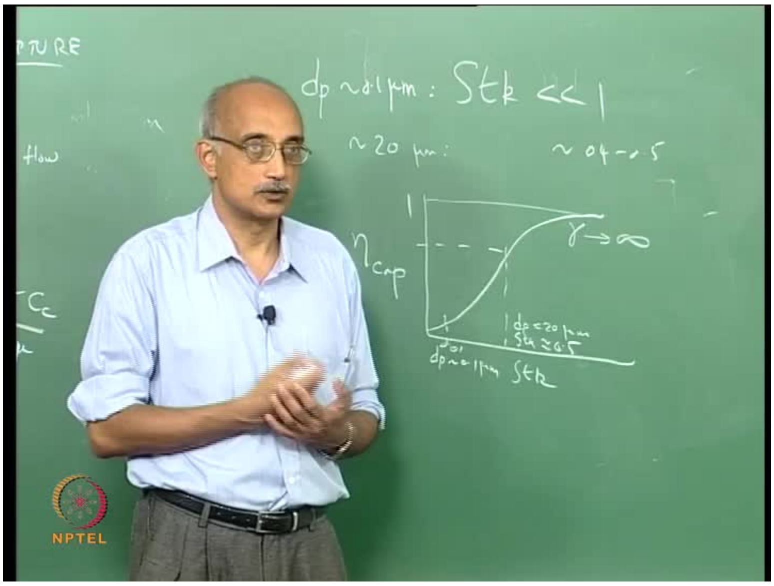

One of their main business is to make these ceramic liners that can be inserted in specific locations in pipe lines in order to minimize damage due to erosion, and due to fouling, because the third aspect is corrosion, how do you minimize corrosion? Well, if you want to minimize all three simultaneously erosion, corrosion, fouling, then what you really need is a ceramic liner on top of a stainless steel substrate, because a stainless steel will prevent corrosion from happening, and the ceramic liner which can be localized, you do not have to put it everywhere, you put it where, there is a maximum likelihood of erosion and fouling happening that can prevent those mechanisms from happening. Because, there is a forth mechanism as well, and it is called slagging. Slagging is different from fouling in the sense that in in fouling, the situation we have is solid ash particles approaching a surface and building a layer on top of it, the difference in slagging is the ash particles or any particles that are approach a surface are actually in the molten state.

And so they actually hit the surface like a droplet and spread on the surface, and then they solidified on the surface. So, it is it is a very different type of phenomenon, and again you can make the argument that this view is actually only valid for dry particle impaction. Because if you have a very fine particle, right, this says the sticking coefficient or the capture efficiency is virtually 0, but you know that, I mean if you take a very fine droplet and just put it on a surface, it is gonna stay there, right, it does not go rebound.

So, liquid droplets or molten particles behave very differently from solid or dry particles. And so in the case of slagging, where you have essentially liquefied particles approaching a surface, the primary characteristic that detects whether the particles sticks or not is a wetting characteristics. If the particle can wet the surface, then it will stick to the surface, if it cannot wet the surface, it'll stick out like a drop and it can be removed by the flow of gases. So, again, it comes back to surface energy, if you have a low surface energy surface, it can minimize fouling as well as slagging. And at the same time, if it also has high hardness, it can also reduce erosion, and if it is on top of a corrosion protective material, it can also prevent corrosion. So, as a power plant engineer, you really have to think about all four mechanisms simultaneously and how to minimize fouling, slagging, corrosion and erosion, while also minimizing cost, I mean, obviously, if you have unlimited recourses, you would put a ceramic liner everywhere or you coated with some kind of a fancy low energy, you know plastic ceramic composite material, but you typically do not have the luxury to do that.

So, essentially the stati that is used is, putting the corrosive corrosion protective material everywhere, that is stainless steel, and then do some fluid dynamic analysis c f d to really understand where particles are going to have the maximum impact velocity, those are the areas where you need erosion protection, identify the areas where particles are going to stick or a large quantity of particles are going to be arriving and sticking, those are the areas where there is propensity for fouling, and finally identify areas where particles are going to come in a molten state, that is where you have slagging, and for each you incorporate a an appropriate mitigation mechanism.

So, it is a lot of thinking that is involved in coming up with this kind of a you know systemic strategy for doing this. And also, roughness is actually a key contributor as well, it turns out that a lot of these problems, even corrosion, fouling, slagging can all be and erosion can also be controlled by using surface roughness as a key parameter.

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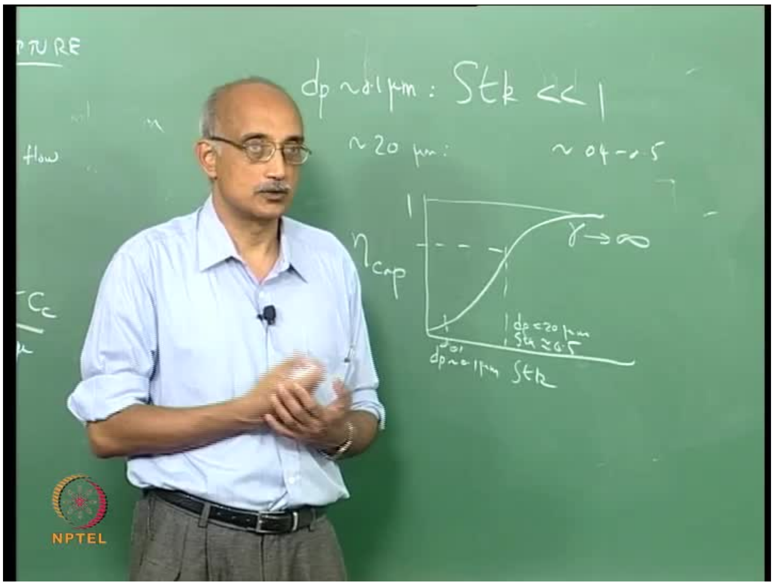

But, it has interesting effects, you know for example, erosion will be worse on a rough surface compare to a smooth surface, right, because roughness asperities can break off easily. Corrosion also is typically worse on a rough surface, because there is no essentially more area available for reaction and corrosion is a chemical reaction.

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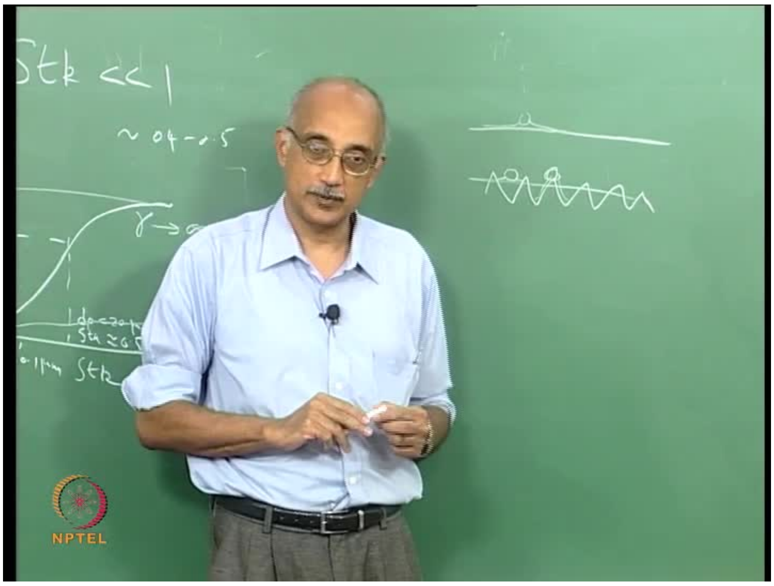

Fouling on the other hand is actually less on a rough surface, because the effective interfacial area of contact is reduced by introducing roughness on the surface. And finally, slagging, it depends, salgging the effect the surface roughness on slagging is kind of interesting in the sense that it depends on the relative sizes of the particles and the roughness asperities. So, if you have a surface, which has a certain roughness scale in in slagging, as I mentioned, the droplet has to hit the surface and spread. So, on a smooth surface, if a droplet hits and it is an evitable, surface is going to spread like that. So, the effective area of contact is going to be quite large, so the capture efficiency will be very high.

On a rough surface, if it gets here, it is only going to be able to spread so much, right. So, actually, the capture efficiency is going to be truncated, because the droplet cannot spread as far as it wants to. And also if the droplet hits somewhere here, you know near the peak of an asperity, what is gonna happen to it? It is essentially going to break up and kind of start forming layers in this direction also.

So, in that case, rough surface may actually promote slagging by making available a greater surface area for the slagging material. So, these are some interesting aspects that can be studied in a lot more detail, but the point that I want to leave you with in this lecture is that particle transport and particle deposition are very size dependent, and it is ultimately the size distribution of the particle population that will dictate all of its flow characteristics, including adhesion behavior, cohesive behavior, transport, deposition, ease of removal from a surface once it has been deposited.

So, these are aspects that we need to understand in a in a very fundamental way, in order for it is to be able to apply that knowledge in tackling practical situations in industry. So, we will stop our discussion of this module, with this lecture, staring from the next lecture, we will start addressing the next aspect of particle characterization, which is chemical and compositional characterization of particles. Any questions on what we have covered in this module? Ok, see you at the next lecture then.