Indian Institute of Technology Madras

NPTEL
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Video Lectures on
Convective Heat Transfer

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Lecture 29

Thermal entry length problem
with plug velocity profile:
Graetz problem

Good morning all of you so today we will look into some basics of Bessel functions because we you need to understand the solution for Bessel functions before we do the solution to the Eigen value problem.

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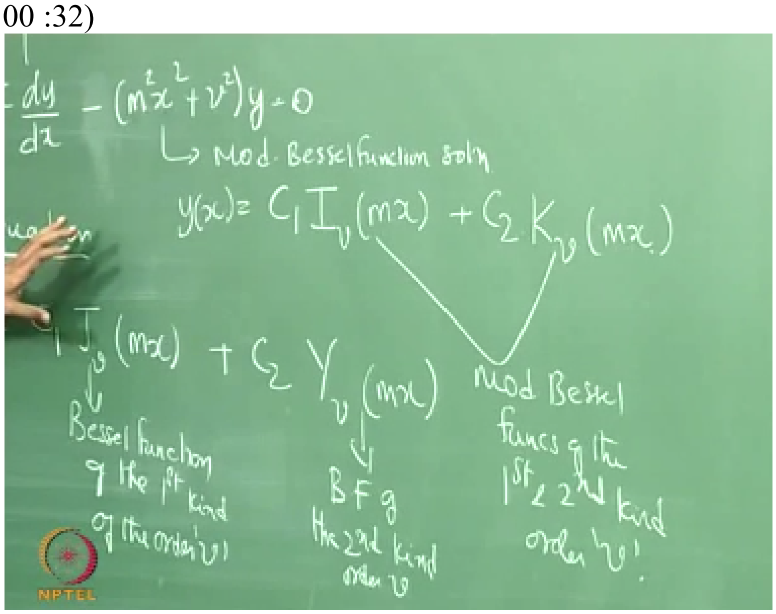

So I am not going to run a class on Bessel functions but just to prime you what should be the form of the Bessel equation and what is the solution to a given Bessel equation and some properties of Bessel function differentiation and integration okay now if you have any second order linear differential equation of this particular form okay the form that I have written here so you have x^2 d^2 y / dx^2 +x d y /d x + this coefficient now this coefficient is function of X here okay so times y =0 .

So this functional form of this equation is referred to as the Bessel equation after the German mathematician Bessel so the solution to the Bessel equation is given as y(x)= some constant c1 times Bessel function so you use the Bessel function there are two kinds one is the Bessel function of the first kind and Bessel function of the second kind okay the Bessel function of the first kind is represented by the letter J okay.

So J and the order of the Bessel function is denoted by this value of Nu here this is any real number and you use the okay nu here to denote the order of the Bessel function this is a function of (mx) where m is the value that you have got here so m (x)+ c2 now the Bessel function of the second kind is represented by the letter Y the order is represented by the subscript nu m(x) okay so this is called the Bessel function of the first kind and of the order nu this is the Bessel function of the second kind and order nu okay.

So this is so far to say for a Bessel function now you can slightly write this Bessel function in a different way suppose if you are M ^{2} here was instead of being a positive value if you have a negative value here so you can replace this with a negative sign and you can write an equation like this okay suppose your M^2 value has to be a negative value in that case then you write like this then this becomes what is called as a modified Bessel equation it is the same structure as the Bessel equation only the coefficient term here will have a negative sign and correspondingly the solution to this here this is M.

So now this will become imaginary number okay once this is negative here so this will become M I basically an imaginary number so instead of writing everything in terms of imaginary functions okay so they have introduced what is called as a modified Bessel function okay which takes into account naturally the imaginary part of the coefficient so therefore for that you have a modified Bessel function solution.

So where you represent the solution as C 1 times the modified Bessel function of the first kind is denoted by the letter capital I subscript nu for the order m(x) + the modified Bessel function of the second kind is represented by the symbol letter K subscript nu (m x) ok so these are your modified Bessel functions of the first and second kind and of the order nu okay. So as far as the solution to our Eigen value problem is concerned I think this is all sufficient to write how to represent the solution to the Eigen value problem okay .

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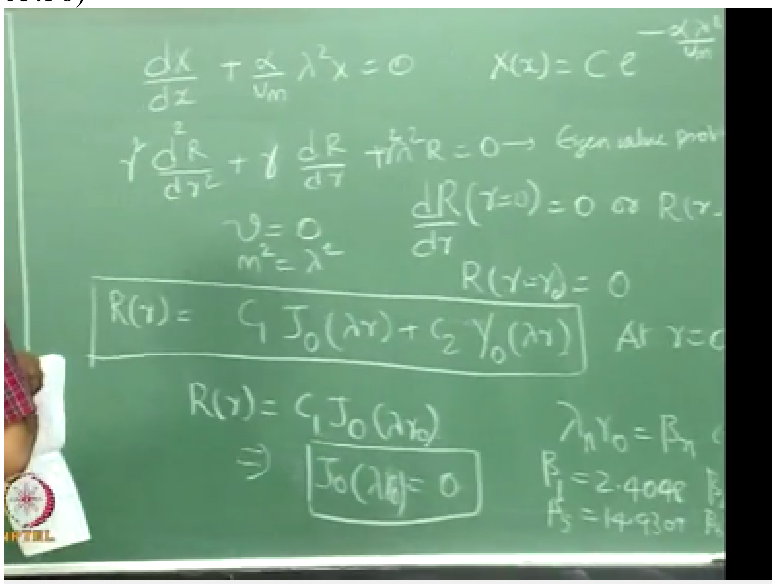

So now we will compare this Bessel equation with the Eigen value problem that we have okay so what was what were our solutions basically when we substituted when we use the separation of variables into the energy equation we found out that the PD can be reduced to two Odies one is the first-order odie with respect to X so here we have assumed that the Grates problem has originally assumed that the profile velocity profile is a slug flow profile .

So it is a uniform velocity the value is um and the solution to this along the variation along the X is given by the first order odie okay and we have also seen the solution to can be written as some constant times $e^{-\alpha \lambda 2}$ / um x X right so directly you can integrate it out and the actual eigen value problem in terms of R was this t and the boundary condition for R what were the boundary conditions to solve this second order odie in terms of our R at R = 0 you have any boundary condition at R = 0 ok finite or I would say d R/ d r should be 0 okay or R at R = 0 should be finite both are equivalent the other condition R at r = 1 should be 0 okay because the temperature there at the wall is constant wall temperature.

So θ has to be 0 therefore R at r = 1 has to be 0 so now you compare this with your Bessel equation ok so the original Bessel equation not the modified one so you multiply throughout by R^2 so you have R here you have again R^2 so now you see these and these coefficients are exactly identical instead of X you have R ok now as far as this coefficient is concerned you have m^2x^2

y okay instead of that you have λ^2 R^2 capital R and there is nothing like a nu here the nu =0 .

So therefore the order of the Bessel functions is 0^{th} order okay so that is one thing and your $m^2 = \lambda^2$ so therefore the solution to this odie will be in terms of the Bessel functions of the first kind and second kind 0^{th} order so $c1j_0(\lambda r) + c2\ Y_0(\lambda r)$ okay so this is your solution to the Eigen value problem so this is your Eigen value problem so any Eigen value problem should have two homogenous boundary conditions okay so this is the solution to the Eigen value problem so now we apply the two boundary conditions to get the two constants okay .

So now directly we come to the condition at R =0 R should be finite and capital R should be finite so I will also show you how these Bessel functions behave so if you draw the Bessel function J as a function of your X or R okay so it will start from 1 and then so this is your J 0 apart okay and J 1 will have a behavior like this and j2 will have another behavior and so similarly if you draw the Bessel function of the second kind that is your Y as a function of R .

So this is negative and this is positive here so the first the 0^{th} order Bessel function of the second kind will at R =0 will start from infinity and it will increase to + value and it will be oscillatory again okay so this is your $Y_0(x)$ and you will find that Y 1 will have another behavior like this Y_1 (r) and Y_0 so this is how your Bessel functions behave okay and your modified Bessel functions will have a different behavior .

So you are I versus R so this is 0 this will always be positive here so this will be your I_0 (r) and then this will be your $I_1(r)$ similarly your Bessel modified Bessel function of the second kind that is your K function of r so this is your K_0 (r) this is your K_1 (r) okay this is to just give you an idea how the Bessel functions you take any Bessel function chart you will find the tabulated values corresponding to different values of X or R you will find the corresponding variation in the first kind and second kind all the different orders are starting from the 0 th order first order second or second order the zeroth order Bessel function here means it is the highest order it does not mean it is the lower order it is the highest order and one two three four there are the lower order Bessel function okay.

So now coming back to this particular Eigen value problem so at R =0 if your capital R has to be finite now you can see that at R =0 my Bessel function of the second kind will be going to infinity right therefore in order to make my capital R finite c2 has to be 0 okay so at R = 0 my

Y_0 (0) goes to infinity so this gives that c2 has to be 0 for the solution to be finite so therefore my R (r) directly reduces to $c1j_0(\lambda r)$ okay so this is how my Eigen value problem reduces okay now again I can find out the constant c1 by applying the other boundary condition.

So now the thing is I should also know what is the Eigen value here because the Eigen value is also undetermined so the remaining constant whatever is left out that is at r = 1 capital R =0 that will be used to find the Eigen value okay so one of the constants is determined from the one boundary condition and the Eigen value is determined from the other boundary condition .

So this constant is not a problem because final solution for θ I can multiply and this into a single constant and I can use the remaining boundary condition that is at X =0 that is one more boundary condition which I have not utilized so totally there are three boundary conditions okay so that I can determine it later but right now I can use the second boundary condition for the Eigen value problem and determine the value of λ here.

So therefore the condition that R (r= 1) = 0 so this should give me the fact that $c1j_0(\lambda r)$ =C 1 J = 0 or in other words so the Eigen values should satisfy this particular equation so that means you look at the Bessel function so wherever it becomes 0 so these are the solution which will give you the corresponding value of λ right so okay so this should be R($r = r_0$) or not okay these are all dimensional so I should write in terms of J or not here please correct it so this is at r = r these are all dimensional radii so I should use at $r = r_0$ so therefore it should satisfy this particular equation.

So the corresponding value of λ r_0 will be the ones where J becomes 0 so you can see there are several values right there are several places where J becomes 0 so this has now multiple solutions ok so I will just give you the first few roots where I where J becomes 0 so let me call λ n r_0 as some factor β n okay so the 0 so these are the zeroes of J_0 β n = 0 okay so the first six zeroes correspond to β 1= 2. 4048 then β 2= 5.5207 then β3 = 8.6537 and β4=11.7915 and then β5 =14.9309 and the last one β6 =18.071 so these are the first six zeros so the corresponding value of λ r_0 okay .

So now I have determined my Eigen values because these Eigen values are all nothing but these values so this says this is λ λ1 r_0 λ2 r_0 λ3 r_0 and so on and so forth you can have many number of solutions but I have given the first six these are the most relevant okay the other ones will be of the lower order which you can neglect all right so I have I will give you two more properties when you differentiate and integrate the Bessel functions which are important now .

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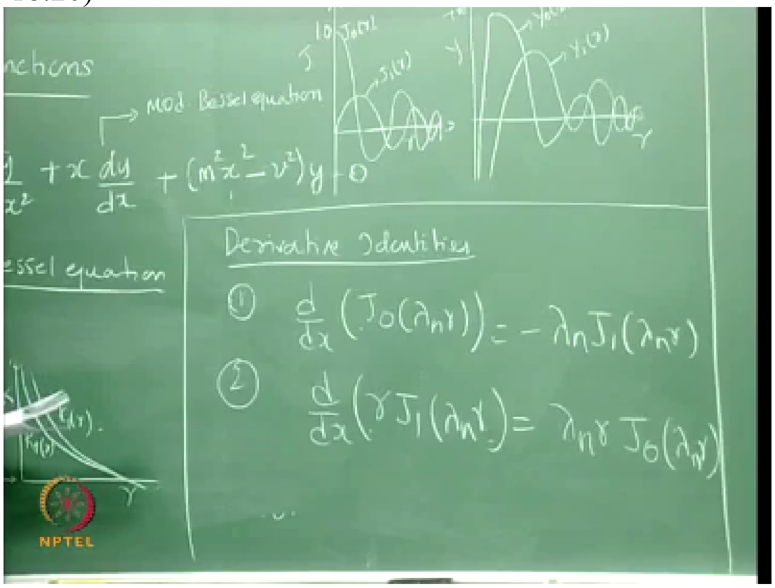

So I will give you the derivative identities of the Bessel function so I will call this as derivative identities so the identity number one if you differentiate the zeroth order Bessel function of the first kind that is your J_0 (λ n r)   so that gives you - λ n J_1 (λ n r) okay this is your first identity a second identity if you differentiate (r J 1 (λ n r) so if you multiply R with the Bessel function of the first order ok by pestle the first kind Bessel function of the first order you will be getting (λ n r) into Bessel function of the zeroth order (λ n r) this is your second identity we will use all these identities .

So number three is the fact the Bessel functions have another important property that is the principle of orthogonality ok so if you look at any Eigen function Eigen value problem and you determine any Eigen function so in this case the Eigen functions are Bessel functions of the first kind of the zeroth order these are the Eigen functions right so these are the corresponding Eigen function to the Eigen value problem okay.

So this is your Eigen value problem so the solution to R is in terms of Bessel function of the zeroth order of the first kind so these are your Eigen functions now any Eigen function any Eigen value problem where you determine your Eigen function should satisfy the principle of orthogonality okay we will see that that is very useful to determine the determine the remaining constant okay now that principle of orthogonality for this case can be written as 0 to r_0 r $J_0{}^2$ (λ n r) dr= $(r_0)^2/2$ $(J_1(\lambda \text{ n } r_0))^2$ okay so this is another important property when you integrate multiply R $J_0(\lambda$ n r) so you get this particular expression okay.

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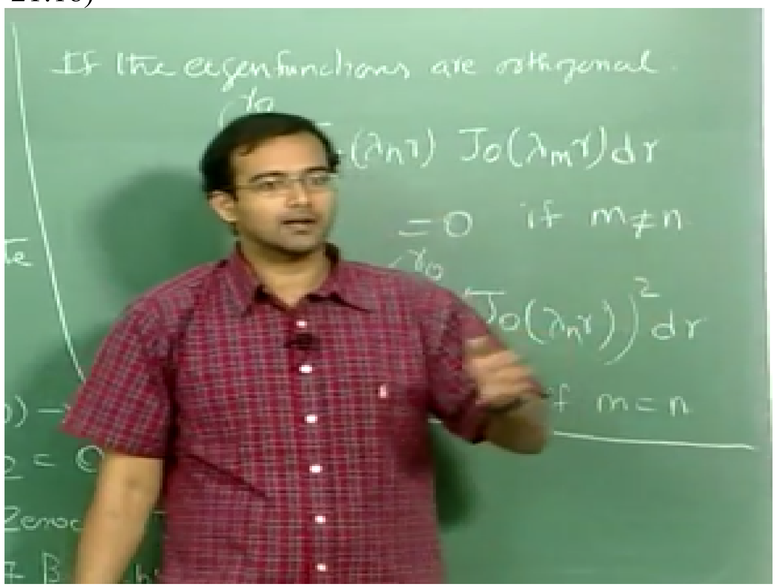

So this is another thing which you should remember now the principle of orthogonality states that if the Eigen functions are orthogonal if you integrate them if you multiply an eigen function $J_0(\lambda$ n r) with the Eigen function (λ m r) so n being different from M so these are different integers okay so your n may go from 1 2 3 and for a fixed value of m okay now if you multiply these two Eigen functions and you also multiply R okay and if you integrate it this will be = 0 if $m \neq n$ and this is the principle of orthogonality okay .

So only if m = n the Eigen value integer corresponds exactly same so then only you have some finite value non-trivial value so this will be = 0 to r_0 r($J_0(\lambda$ n r)$)^2$d r if m = n so this is the principle of orthogonality basically so that means see these Eigen values are like principle directions like your XYZ Cartesian directions so these represent and the variation of solution in those principal directions .

So if you if you multiply the solution corresponding to 1 principal direction to another so those two are mutually orthogonal directions so therefore the product will be 0 okay so whereas if you multiply in the same direction then this is where you get a non-trivial solution so this is where the principle of orthogonality plays importance and when you are integrating this 0 to r_0 $r_0(J_0)^2$ we will use this particular identity here all right .

So now we will erase this we do not require this is the principle of orthogonality clear I think if you take any course on linear algebra I think you will be taught this it is like saying you are I . I = 1 your i.J = 0 so these are mutually orthogonal direction so the Eigen values correspond to principle directions which are mutually orthogonal and the Eigen function should respect that orthogonal T all right .

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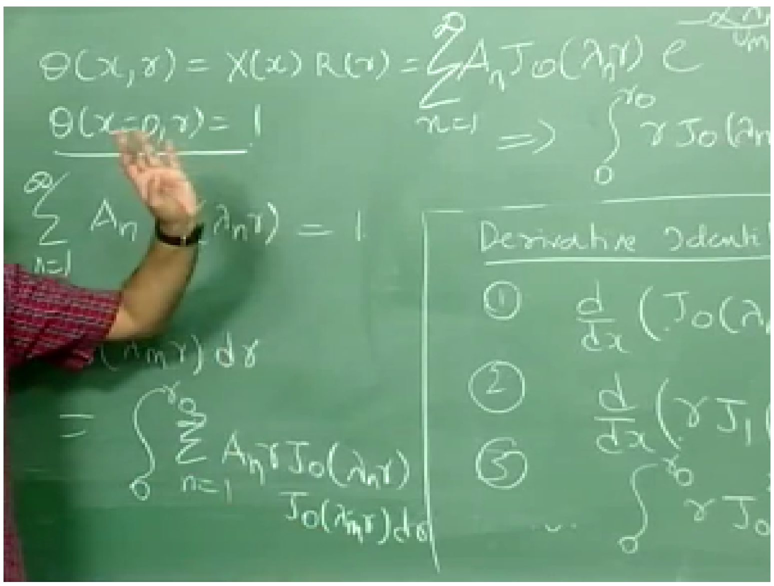

So now we have all the necessary background therefore you can write your solution for $\theta(x,r)$ so you have to now tell me what will be the solution this is nothing but according to separation of variables and now we found the solution for both X and R so how can we write it so let us multiply C 1 and C and call this is another constant C okay some constant C or maybe a or whatever you want to call it me I have used in my notes as A so I will use A and what is the remaining $J_0(\lambda\ r)$ C_1 $J_0(\lambda\ r)$ is your eigen function okay and what is the remaining part X of X will be $e^{-\alpha\lambda 2}$ / um x .

So finally your solution reduces to this so in terms of X it is exponentially decaying function your θ starts at 1 at the inlet where the temperature = Ti and then somewhere downstream your temperature should approach the wall temperature therefore the difference should become 0 T- T wall should become 0 so that is your exponentially decaying function with respect to X right now with respect to R it is a Bessel function variation now you see that when you found out the Eigen values you had multiple Eigen values right .

So you had first I had written down the first 6 Eigen values okay but there are multiple Eigen values and they are all solutions so then how do you include them so you assume that they are all linearly super post and you can denote your final solution as a summation of all those from n = 1 to infinity and you have λ n okay so this is your final solution so which is a linear superposition of all your solutions for different values of Eigen values for each value of Eigen value you have a particular Bessel function you have a particular exponential term.

So like that for each λ 1 λ 2 under three you now get all the value sum them up so that will give you the final value of θ of course the first few terms will be the significant terms the first say three or four terms after that they will be insignificant and even if you do not include them it is not going to change the solution much okay so therefore this is your final solution and now the thing is how do we calculate the remaining constant A so this A also becomes A n so corresponding to each value of λ n you have particular value of this constant A n.

So now how do you calculate this constant now we use the remaining boundary condition for θ (x =0,r) should be 1 should be one now how do we apply this boundary condition here so therefore we say that Σ n = 1 to infinity An $J_0(\lambda\, n\, r)$ and this becomes x=0 so that will be 1 so this should be =1 but still we have not determined what is A n because this is within the summation so now we make use of the orthogonality principle okay .

So what we will do is we will multiply both sides with $J_0(\lambda\, n\, r)$ where m is different from n okay and integrate them so we so for orthogonality condition in this case of Bessel function you should be having r $J_0(\lambda\, n\, r)$ so we will multiply both sides with that so we have 0 to r_0 so my right hand side I am writing on the left hand side here I multiplied with r $J_0(\lambda\, m\, r)$ dr that is my RHS right on the LHS I have this 0 to r_0 Σ n =1 to infinity A n x r $J_0(\lambda\, n\, r)$ $J_0(\lambda\, m\, r)$ dr okay .

So now of course it has to satisfy orthogonality condition here therefore for any values of m $\neq$ n this will be 0 and this will be equal to r $J_0(\lambda\, n\, r)^2$ dr for m = n so only there it will be a non-trivial solution so therefore this will become 0 to r_0 so for m = n so only then so you can imagine the summation here so now I sum from n = 1 to infinity for a given value of m if m$\neq$ n your so those values are all 0 so therefore the summation will reduce to the fact that it will be = $J_0(\lambda\, n\, r)^2$ only for m = n so that should be A n x 0 to r_0 and r $J_0(\lambda\, n\, r)^2$ dr okay.

So now you understood so this reduces to this particular expression here so the summation is now gone because for $m \neq n$ so those values are all 0 so the final whatever remains is where your m = n so your summation is now removed and from here directly you can calculate the value of An.

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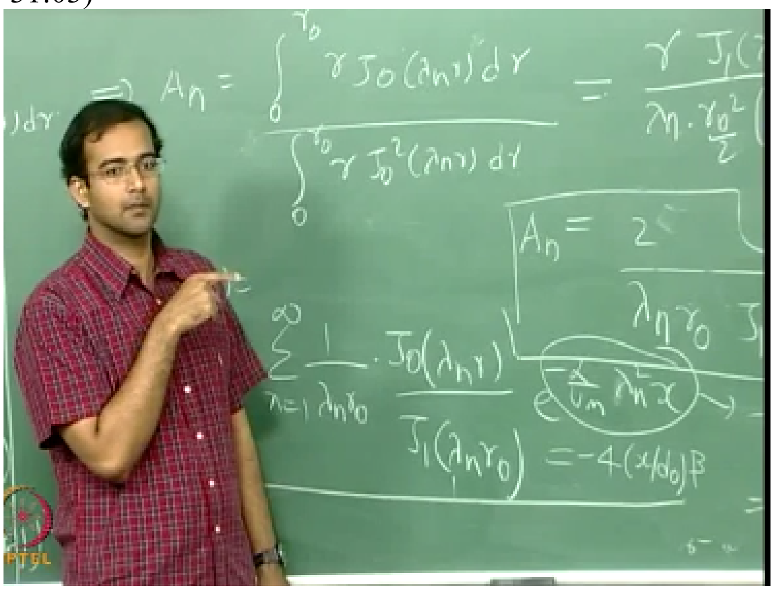

So this gives A n as 0 to r_0 r $J_0(\lambda\, n\, r)^2$ dr / 0 to r_0 r $J_0(\lambda\, n\, r)$ dr okay so now we have to simplify this further so that is where we make use of the derivative identities.

So numerator integral r $J_0(\lambda\, n\, r)$ so you integrate both sides so that should be = r $J_1(\lambda\, n\, r)/\lambda\, n$ and now you have integral r $J_0^2(\lambda\, n\, r)$ so that is you use this identity number three that should be r $J_0^2/2$ now of course when you integrate it you have to apply the limits here this is between 0 to r_0 and when you integrate this from 0 to r_0 you directly get this particular expression $r_0^2/2$ ($J_1^2\, \lambda\, n\, r_0$)okay so at 0 J_1 will be what 0 if you look at the curve .

So therefore this will be r $J_1(\lambda\, n\, r_0)$ / $r_0^2/2$ so this J_1 cancels here r_0 cancels so this can be written as 2 here r_0 and $J_1(\lambda\, n\, r_0)$ are not okay so this is your expression for a final expression so therefore you can substitute this into the let me call this as one number one for A n and you can substitute and then you can write the final expression for θ as so 2 can be taken out Σ n =1 to infinity 1 / $\lambda\, n\, r_0$ you have $J_0(\lambda\, n\, r)$ / $J_1(\lambda\, n\, r_0)$ exponential $e^{-\alpha}$ /u m $\lambda^2 n$ x so this is your final solution okay what we can do is we can cast this into a completely non dimensional representation okay .

So that you do not work in terms of X or λ but something like λ n r we can we have already used the notation β okay and even will non dimensionalized this term so how I am going to non-dimensionalized this the following way so I can write this $^{-\alpha}$ /u m λ^2n x as I can write this as $^{-\alpha}$ /u m x X r $_0^2$ so I am m multiplying and dividing by (λ n r $_{0)}$ ^{2} okay and I am also going to rewrite this a little bit as so I can write this as X /d_0 x (λ n r $_{0)}$ ^{2} / u m d_0 /α that is a factor of 4 okay.
So this r $_0^2$ I have replaced this by $(d_{0)}^2$/ 4 okay so and I am grouping x /d_0 as 1 non-dimensional term and I am left with u m d_0 /α so what is u m d_0 /α Reynolds number times prantle number okay so therefore I can replace this entire thing as a non dimensional group which is – 4(x /d_0) λ n I have used the notation β n okay because λ n has the units of what is the unit of λ 1/ r so therefore λ and r $_0$ will be a non dimensional group okay .

So that therefore i replace that with β n $^/$ Re x pr now I use another non dimensional group called peclet number.

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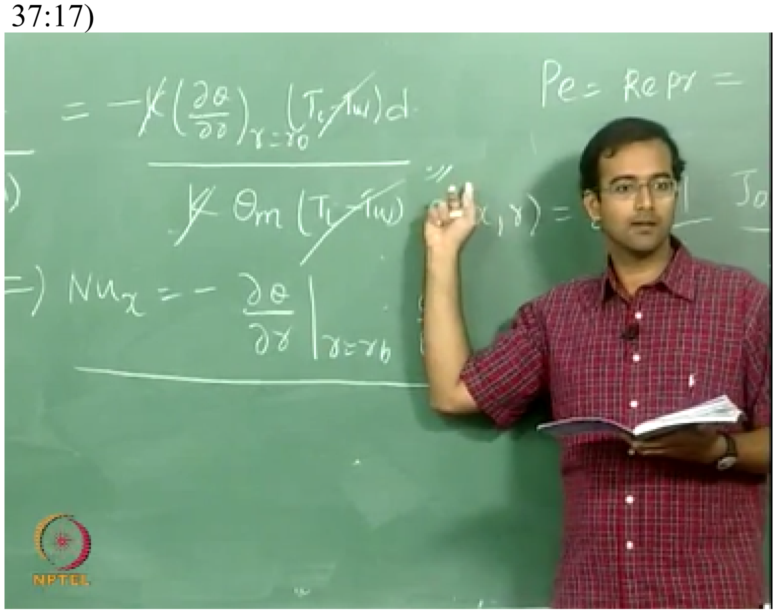

Which is the product of Reynolds number times the prantle number which is nothing but um d_0/α okay so generally rather than all that I am doing Re pr Re pr so people refer to that as a peclet number so the product of Re times p r therefore in terms of the non-dimensional form you can describe your θ as 2 n = 1 to infinity 1 / β n J $_0$ now how do you write this λ n r so you

divide and multiply by r_0 so then that will become βn times (r/r_0)okay / divided by $J_1 \beta n$ okay into e power this entire thing can be written as $-4(x/d_0)\lambda n$
r_0 is nothing but βn^2 divided by peclet number okay.

So this is completely non dimensional so once you know the particular value of peclet number that you are solving so that directly has both the Reynolds number and prandtl number for different values of non-dimensional r/r_0 and different values of non-dimensional x/d_0 you can directly get the solution for θ so everything is now non-dimensional okay so you can plot the solution for θ as a variation with respect to r/r_0 and x/d_0 for a given value of peclet number okay .

So once we got the solution now still we are not done so ultimately we need to find what is the Nusselt number expression for Nusselt number right so therefore for Nusselt number we need to do a little bit further work whether quantities are required okay the first quantities now when you define a Nusselt number here so your Nusselt number is basically hd/K now you should be careful here that in the case of thermally developing flow your h is not a constant h is a function of the axial location so this should be strictly speaking h subscript X okay .

So now that you define this as K (dT/dr) at $r=r_0$ d/ K (T wall - T means) this is how you express your heat transfer coefficient wall flux divided by temperature difference so now I can substitute in terms of non-dimensional θ so θ is defined as T- T wall /Ti- Twall okay so I can write this numerator as now - K (dθ)/dr $r=r_0$ times (Ti- Twall)d / K times now (T wall - T means) so I can define θ mean as T mean - T wall / Ti- Twall so I can write T mean - T wall as Ti- Twall θ so into θ M so K θ m (Ti- Twall) so already I put a – sign because this is Ti- Twall I am putting - TM - t1 okay.

So this cancels right here and of course your K cancels .So this will be so left with nu x = - d θ / dr at $r=r_0$ (d/ θ m) so therefore now to calculate your Nusselt number what are the quantities that you need one is your mean temperature θ m the other is your derivative of the wall so you have your temperature profile now we can calculate these two quantities so first we will calculate your mean temperature so very quickly .

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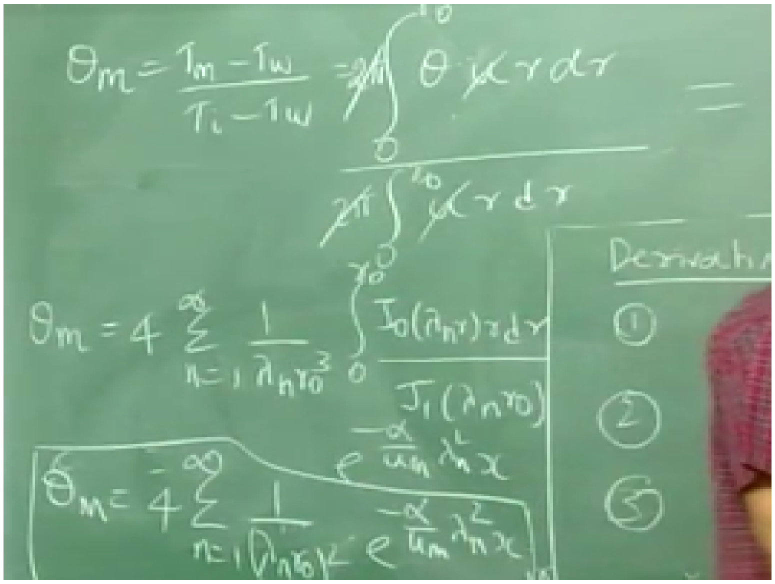

We will do that so your θ m is nothing but your Tm- Twall/ Ti- Twall that will be what so you integrate you take the mass weighted average of θ both θ x r x u so this will be θ x u r dr of course you have 2 Π / integral 0 to r_0 you have 2 Π u of r d r right.

So this is your this is how you define your bulk temperature or mean temperature mass weighted average okay now in your present case your u is a constant this is a slut plug flow case so therefore the u can be taken out of the integral and cancelled off straight away so integral 0 to r_0 r d r will be r_0^2 / 2 okay so this ^{can} be written as 2 /r_0^2 integral 0 to r_0 θ r dr okay now if you substitute for θ from the final expression that we have you can write your θ mean as 4 times n = 1 to infinity 1/λ n $r_0{}^3$ 0 to r_0 $J_0(\lambda$ n r) rd r / J_1 λ n r_0 into $e^{-\alpha}$ /u m λ^2n x so I am just substituting for θ and multiplying with r here okay.

So you can just verify it you know I am going a little bit fast but it is straightforward there is no difficulty here so integral 0 to r_0 $J_0(\lambda$ n) r so already we have that identity so that will be r J_1 λ r_0/λ n so if you put that and you manipulate it finally you get your expression for θ m as 4 x times you please check this 1/$(\lambda$ n $r_0)^2$ $e^{-\alpha}$ /u m λ^2n x so this is the final expression for θ m that you will be getting okay .

So if you if you just use this identity and then you substitute it here you will cancel off $J_0(\lambda$ n $r_0)$ this $J_0(\lambda$ n $r_0)$ will be nothing but J_1 λ n r so that and this will get cancelled off okay so it is just a very simple manipulation and from your θ you can also calculate your d θ / d r at r=r_0 .

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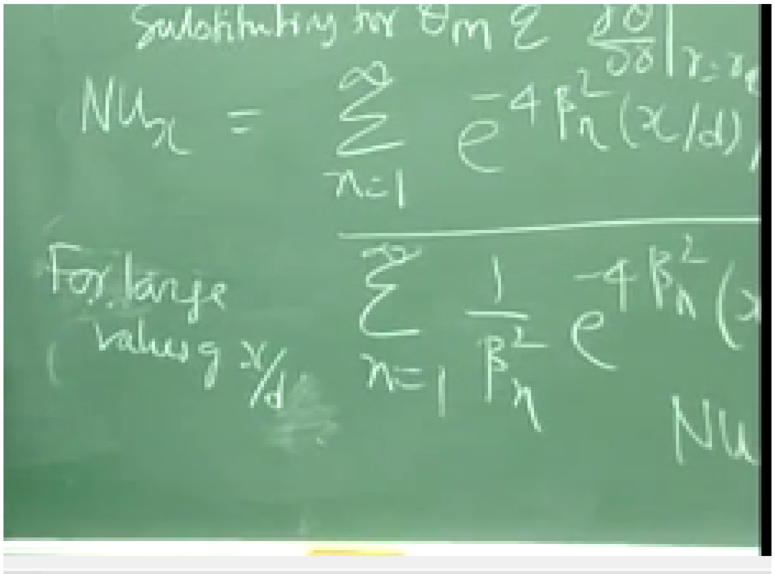

Which comes to 2 summation n = 1 to infinity 1 / β n so now when you differentiate you have to differentiate $J_0(\lambda)r$ right .So $J_0(\lambda)r$ as I said that is nothing but - l-λ n J 1 lambda n R okay so that will put a minus sign here so this will be l λ n J_1 λ n r and at $r=r_0$ this will be at r_0/ you already have J_1 λ r_0 into e^{-4} β n^2 X by d by peclet number so once again these two will cancel off and if you substitute your derivative as well as your mean temperature into this expression let me call this as expression number 2.

So this will give me Nusselt number substituting for θ M + d θ/ d R at $r=r_0$ into 2 the final expression I think if you cancel off some common terms which is straightforward you can do that you will get $^{-}4$ β n^2 (x/d)/ peclet number divided by summation n = 1 to infinity β n^2 power minus 4 β n^2 into X by D by peclet number okay this is the final expression for nusselt number as a function of X okay.

So all you are doing you have this θ M you have taken the derivative of θ with respect to R at $r= r_0$ just you substitute into this it is a very simple manipulation just one step and then you finally get the expression for a N u x so as you can see it is a function of only X therefore all the functions of r have canceled off you have only variation with respect to X and these summations are separate in the numerator and denominator you cannot simply cancel this term here okay .

So this is a separate summation this is a period summation okay now this is a general expression further completely for fully developed hydro dynamically and thermally developing flow okay now we should asymptotically retrieve the case for thermally fully developed flows from this expression what is the asymptotic case what is the limit at which we can retrieve the fully developed case when your x/d goes to infinity for large values okay .

So for large value or you can say for large values of x by d by peclet number or you can just simply say for large values of x / d you go asymptotically because you now are in the thermal entry length region so if you keep going down further and further and further okay so somewhere so you have your thermal boundary layers will be meeting somewhere here so now you are X is somewhere here so if you go to large values of X okay.

So that will give you a asymptotically it will reach the limit of thermally fully developed flows so in that limit what happens is see these values of β n will be smaller and smaller as you go for larger values of x so therefore we retain only the first value of β that will be the most dominating term okay so only the first term is will be significant when you look at large values of x/d.

So that will reduce this to nu going to x/d going to infinity this will reduce to just $\beta 1^{2}$ okay for large values this anyway will cancel off no you have this going to 0 this going to 0 you have only in the denominator 1 / βn^{2} and only the first term will be the most significant term okay so that if you substitute the value of $\beta 1^{2}$ as $(2 .4048)^2$ that comes out as 5 .783 okay so this is the limiting solution for thermally fully developed flows with this is your limiting solution for thermally fully developed with plug flow whatever .

We have derived earlier was with a parabolic flow with a parabolic flow constant wall temperature boundary condition what was the Nusselt number 3.6 so now this is much higher than that value because now instead of parabolic profile you have a uniform profile everywhere you see wherever you take the profile so now what is the significance of a uniform profile earlier when you had a parabolic profile near the wall the velocity is very small .

So due to that the heat transfer coefficient is smaller now when you replace that with the parabolic prefer with the uniform plug flow profile the velocities are very high near the wall and this will improve the convective heat transfer so therefore you see the Nusselt number has gone up like anything okay the same thing if you had if I had asked you to do instead of a parabolic profile with a plug flow for the thermally fully developed case you would have reached the same value .

So that you are reaching as an asymptotic limit to the thermally developing flow okay rather than doing the thermally fully developed flow we could do this and then we can go for large values of x/d and directly get the limiting solution so tomorrow so this is the classical greates problem that he did that he assumed a plug flow and then he did it so tomorrow what we will do is we will do an extension of Wright's problem .

So we will do the extension first to parabolic velocity profile so then you should reach the value a layer what you got 3.6 okay and the next we will look at the extension of greatest problem to other boundary conditions like constant wall flux as well as linear variation so I have already posted a particular solution manual in the website that is a basically an extension of Wright's problem by Sellers the three people who did this extension work and its original classical work in 1954 and we look at some of that solution as well okay you .

Thermal entry length problem with plug velocity profile:
Graetz problem

End of Lecture 29
Next: Extended Graetz problem for parabolic velocity profile
Online Video Editing / Post Production

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