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Convective Heat Transfer

Lec – 12
Thermally Developed Slug Flow in a Duct

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Hello welcome in the 12th lecture of convictive heat transfer in our last lecture we have discussed about convictive heat transfer inside a pipe from there will be continuing in this and we will be mainly seeing over here thermally developed slot flow in a duct, okay. So though will be starting from a duct flow but mainly we will be concentrating on the thermally developed slot flow inside a duct, okay. So let me show you that what are the main points we will be discussing in this lecture, we will be starting from the derivation of the energy equation.

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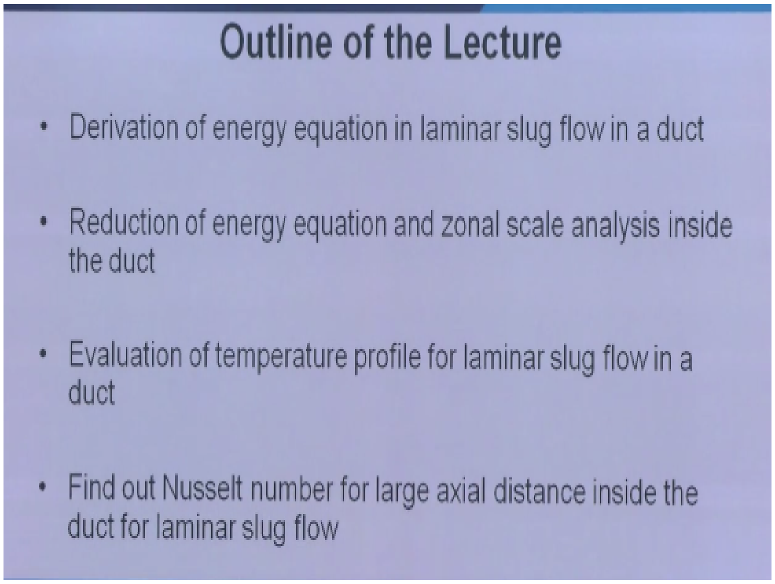

We will be stressing on laminar slug flow okay, last lecture we have discussed what is slug flow so we will be discussing from that point in case of laminar slug flow what is the derivation of energy equation, we will be also mentioning zonal scale analysis depending on the energy equation different components of the energy equation will be reducing into simplified form using scale analysis.

Then we will be going for evaluation of temperature profile okay for laminar slug flow in a duct and at the end we will be discs using about evaluation of Nusselt number for large axial distance that means away from the intrans length that means in case of fully developed thermal boundary region what is the Nusselt number that too in case of slug flow where velocity boundary layer is developed fully. So in that case we will be discussing. So let me start from the slug flow point of view, in last class we have discussed that in case of slug flow.

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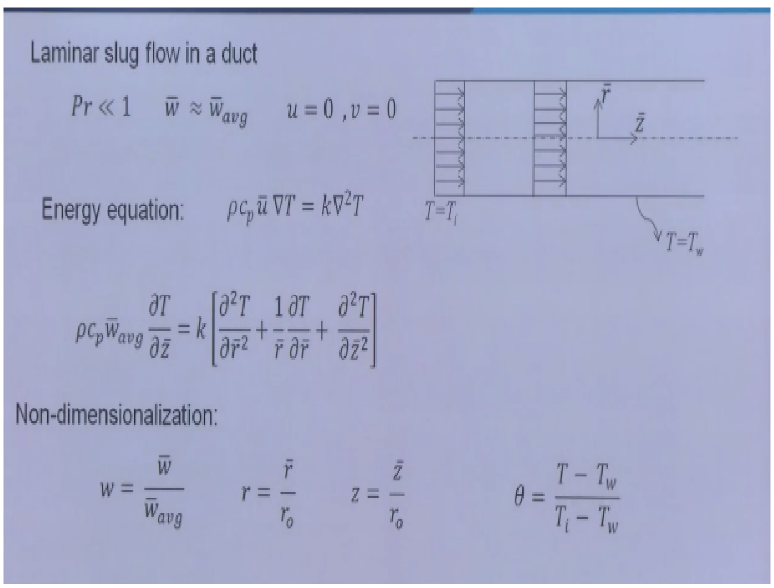

We will be having a situation where velocity will be more or less constant $W = W_{avg\ in}$ this case thermal boundary layer actually dominates over the velocity boundary layer so here you will be finding out that majority of the thermal boundary layer portion we will be getting that $W = W_{avg}$ or constant, okay. And this happens majority of the times for low Prandtl number cases okay as it is $W = W_{avg}$ we will be finding out that there is no u or v that means there is no cross directional velocity in the pipeline.

No radial velocity and on the other hand of the perpendicular direction of the radial direction we are having more velocity, so u and v those are actually 0, azimuthal velocity and radial velocity will be 0, okay. Only axial velocity will be having that two it is a constant, okay. So here I have shown schematically what situation we will be having let us say we are having this flow having constant velocity as well as constant temperature Ti and we are keeping the tube valve at some constant temperature T_w let us say, okay.

A radial coordinate and axial coordinates are shown over here as r- bar and z- bar right, so in last lecture we have mention that energy equation will be reducing to left hand side we will be having the conviction right hand side we will be having the conduction, so ρC p u –bar so this is the vector of the velocity so it will be having three components u, v as well as w so u- bar x ∇T okay and is equal to in the right hand side we are having the conduction k ∇^2 T, right?

So in case of slug flow as I have told u and v = 0 so two components of this ∇T will becoming 0 only the third component will be remaining so here you see ρC p W_{avg} and ∂T/ ∂z is actually remaining from this spatial derivative of temperature, okay. In the right hand side that kind of facility we are not having because velocity is not being multiplied over here. So all the terms we have kept over here only thing is that we have consider that it is azimuthal symmetric.

So θ component we have not involved over here, okay. So this is the radial conduction this two term and last two one is axial conduction, right okay. Here ρC p is involved in the left hand side and k thermal conductivity is involved in the right hand side, okay. So let us proceed further as we know that we are interested to non- dimensionalize this equation. So the parameters for non dimensionalization are like this, so first let us consider the non- dimensionalize velocity W is nothing but your W –bar / W_{avg} whatever the incoming velocity we are having over here so W_{avg} okay. Radial component obviously we can know non- dimensionalize by that tube radius so r = r-bar/r_0 let us do the non dimensionalize of the axial component also by r_0.

Because tube radius is always fixed and known to us okay, now this is the important part what we are doing over here for the temperature non dimensionalization is that, θ = T – T_w / T_i – T_w okay, so T_i is known over here what is the incoming fluid velocity T_w is the corresponding valve velocity, okay. So in this OA we are non dimensionalizing are of all the variables for my equation, okay.

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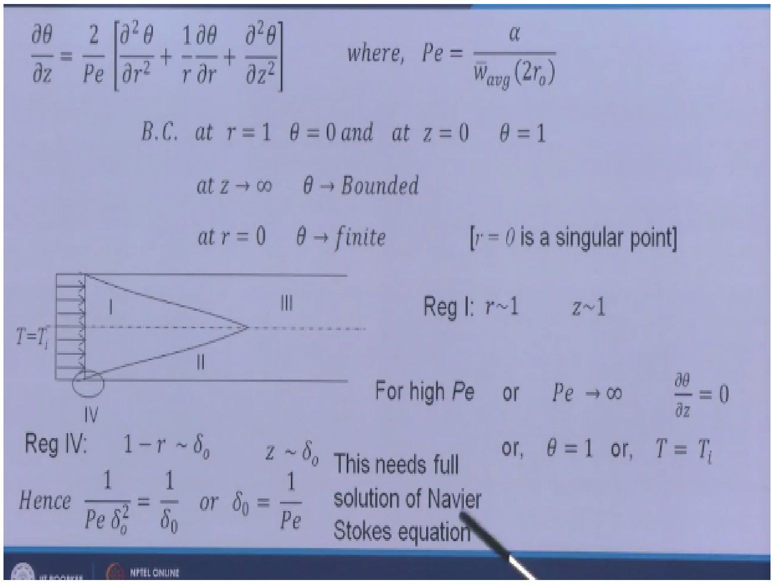

So next let us see after this non dimensionalization what equation we have obtained similar kind of equation last lecture also I have shown so in the left hand side the soul term for conviction will be turning out to be $\partial\theta/\partial z$ okay and in the right hand side we are having the conductions radial and axial conductions and all this k/ ρC_p and the corresponding radial parameter r_0 will be giving rise this 1/ peclet number, okay.

Where peclet number definition is nothing but α which is k/ ρC_p and then W_{avg} x $2r_0$ so this peclet number is defined based on the diameter of the tube, okay. Let us also see the corresponding boundary conditions, so boundary conditions here first at the valve r = 1 means r- bar = r_0 so this at valve r = 1 we will be having θ = 0 because θ we have defined in that fashion only, if at the valve if the temperature is T_w.
So $T_w - T_w/T_i - T_w$ it becomes 0 okay, so the boundary condition at r = 1 is θ = 0 and at z = 0 that means at the beginning of the tube okay at z = 0, θ will be equals to 1 that also we can get from here at the beginning T will be T_i so $T_i - T_w / T_i - T_w$ becomes 1, okay. So here we are having this two boundary conditions for r = 1 and z = 0 but here you see we require some more boundary conditions also.

Because r is having second order z is having order over here so let us find out raised boundary conditions, first let me see what is the extreme limit of z, okay. So far away from the entry of the tube okay, so z → ∝ okay at present we, so not know what will be the value that will depend on the valve temperature, okay what valve temperature you are giving but one thing we can say that obviously θ will be bounded.

There will be no infinite value of θ okay that means no infinite value of temperature, so let us consider that at z → ∝, θ will be some finite number bounded, okay. On the other hand we have considered r = 1 which is at the valve r = 0 will be at the axis of that tube okay, so at axis of the tube also θ should be finite, okay. So we do not know what will be the profile of the temperature but still θ should be finite.

It will not be infinite, so these two conditions we need to also see that these are being satisfied, okay. So we are having two boundary conditions on r and two boundary conditions on z respectively, okay for this equation. So we have non- dimensionalize the equation, now let us see that this case slug flow case how can we distribute into different zones, okay. This zones we will be using for different scaling analyses and reducing the equation into simplified form, okay.

So we are having over here a schematic, so you see this is the tube okay which is having constant valve temperature the incoming fluid scheme is having temperature $T = T_i$ and it is entering at some constant velocity W_{avg} okay, W- bar average and here let us see these are the let us say thermal boundary layers, okay. They are developing over here and upto this we are having the thermal intrans length, okay.

Now based on this figure we can clearly see that there are different regions so first region we can say this triangular region I should not say triangular this region bounded region where thermal this is just above the thermal boundary layer or below the thermal boundary layer from this side, so in this region we can find out that temperature will be more or less remaining constant which can be the inflow temperature.

So that we have to find out so this is a separate region we are calling this one as region one in the same fashion just below the boundary layer near the tube okay we are having this boundary layer developing zone, okay. So this zone we are calling here also we will having two layer here also we will be having two this zone let us call as zone two after this thermal entrance length, okay. Where thermally developed flow is occurring.

So in that case we will be saying this is your zone three okay and near the entry this is also very critical point so near the entry this side as well as this side we will be calling zone 4 okay, so this four zones we will be seeing separately over here how the equation is changing and how boundary conditions are changing. So let us start with first zone 1, so region 1 okay in this region 1 you can find out as it is starting from the beginning of the tube.

R can span upto the tube radius, okay. So what we can write down then R-bar is actually in the order r_0 so that means smaller will be obviously of the order of 1 okay because smaller is nothing but r-bar/r_0 during non dimensionalization we have been introduced, on the other hand z is also of order 1, okay. Why because z- bar we have also consider z we have also consider z-bar/r_0 okay and this zone is very small zone.

So we have kept this z also of the order of r_0 so this is z of the order off 1, okay. Now let us see if we put this two order over here as well as we consider very high peclet number okay, then how this equation is going to reduce okay so as both are of order 1 so no coefficient will be coming out in left hand side and right hand side of the equation okay so at high peclet number region so all this right hand side terms can be cancelled, okay.

Because high peclet number means 1/peclet number will be 10 to 0, okay. So we get δ θ/ δz is actually 0, so our equation turns down to δ θ/ δz = 0 this simplified form, okay. So if you integrated once definitely it will be θ = 1 or T = T_i it validates our knowledge also that we can find out whenever just above the boundary layer thermal boundary layer we will be finding out the temperature is more or less equivalent to your incoming temperature T_i okay.

So in that case T = T_i whatever solution we have obtained this is quite logical right, okay. Next let us see another region so let us see this fourth region now, region 4 over here so in case of region 4 we are having 1 – R okay, 1 – R is nothing but if this is R then 1 – R is here to there, okay. So from 1 to the center, so 1-r obviously for this region 4 will be in terms of δ_0 , δ_0 let us say is the bound layer thickness.

So 1-r is of the order of δ_0 okay. So if it is of the order of δ_0 and as this zone is very small obviously z will be also very small so z we are also keeping in the order of δ_0, okay. So this zone is very small so this is z is of the order of δ_0 very small zone around the entry, okay. So if we consider that let us see how the conduction that means right hand term and conviction in the left hand term comes out to be.

So you can see from here conduction term everywhere we are having r^2, r and r, r^2 and here z^2 so 1/ δ^2 because both are of the order of δ_0 so 1/ δ_0^2 is coming out, so the order of the conduction term becomes 1/peclet number here 1/peclet number x 1/ δ_0^2 due to this spatial coordinates, okay. Spatial coordinate square in every term so it becomes the conduction order. In the same fashion if you see the conviction side here we are having δ θ/ δz so here obviously 1/ δ_0 will come out due to this z.

So we are having this conduction and conviction scales, if we equate then we can find out the conviction scale conduction scale equals to conviction scale if we do then we can find out δ_0 comes out in the order of 1/peclet number, okay. So if you just use this one that δ_0 = 1/peclet number and try to solve this equation, this requires the full solution of the Navier stokes equation because using this we cannot neglect any term of this equation, okay. So it requires full solution of this Navier stokes equation via numerical methodology, so we are not going in that range so let us say region 4 will be very critical we are not going in that range let us concentrate in zone 2 and zone 3 respectively.

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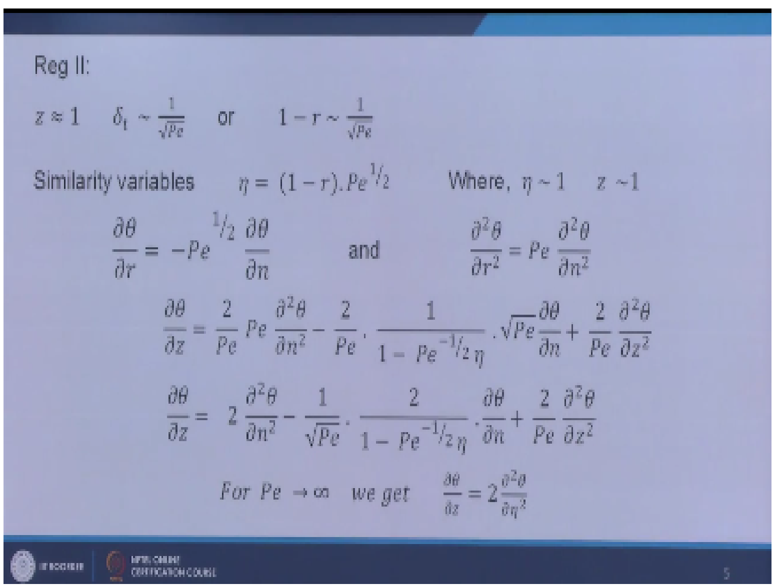

So let us first see zone 2, so in region II you can find out that in case of region II it is little bit lengthier zone so we are considering that z is of the order of 1, okay so z is of the order of 1 remember in case of region 1 also we have considered z is of the order of 1. So the axial length of section 1 and section 2 will be more or less similar, okay. So z is of the order of 1 we have considered over here.

So if we do so then we can find out from here that if z is of the order of 1 then we can find out that from both the sides if we put the scaling analysis of j over here we can find out that we are getting δ_t is of the order of $1/\sqrt{Pe}$ number okay, so why because here we will be finding out that the dominant term will be this one, the dominant term will be this one and in this side we are having 2/Pe number , so $1/\delta^2$ will be coming over here so which ultimately will be giving us δ_t is of the order of $1/\sqrt{Pe}$ number, okay.

Side by side let us also consider as δ_t is $1/\sqrt{Pe}$ number 1-r is also of the order of $1/\sqrt{Pe}$ number, because δ_t is nothing but the thermal boundary layer thickness which is nothing but 1-r okay. Next let us try to consider the similarity variable as we have obtained the thermal boundary layer thickness as $1/\sqrt{Pe}$, so let consider similarity variable is η $(1-r)Pe^{1/2}$ okay, so if we consider this then we will finding out both z as well as η in this region II becomes of the order of 1, okay.

Because 1-r is of the order of $1/\sqrt{Pe}$ so $1/\sqrt{Pe}$ and $\sqrt{Pe}$ cancels out so η becomes of the order of 1, okay, so both η and z becomes of the order of 1. So let us see the equations now before going to the equations let us first do the derivatives, so let me first find out $\partial\theta/\partial r$, so $\partial\theta/\partial r$ will be nothing but $\partial\theta/\partial\eta . \partial\eta/\partial r$ okay, so $\partial\eta/\partial r$ will be nothing but $-Pe^{1/2}$ okay, so $-Pe^{1/2}$ comes over here and $\partial\theta/\partial\eta$ is over here, okay.

We can also see the second derivative is will be giving nothing but $Pe(\partial^2\theta/\partial\eta^2)$ okay so this two terms will be required in my conduction term okay, conduction term in the energy equation. So let us now see that if we put all this terms in my energy equation then how it looks like so before going there we have to also find out what is $\partial\theta/\partial z$, so $\partial\theta/\partial z$ we will seeing over here that in case of $\partial\theta/\partial z$ both our peclet number and both θ we have to consider as the function of this one, function of r and z, okay.

So here if we put all the terms in the energy equation so you can find out 2/Pe number so this is nothing but your $\partial^2\theta/\partial r^2$ basically we are using our energy equation as I have shown over here, so 2/ Pe number $\partial^2\theta/\partial r^2$ is nothing but Pe. $\partial^2\theta/\partial\eta^2$ so that we are putting over here, then 2/Pe number multiplied by 1/r so this is 1/r this term is nothing but your η so this is here from you can get the value of r so this is becoming actually your r okay.

And then $\partial\theta/\partial r$, $\partial\theta/\partial r$ is nothing but $-Pe^{1/2}\partial\theta/\partial n$ so that we are putting over here, okay minus terms goes there okay, and then last term of get you 2/Pe $\partial^2\theta/\partial z^2$ okay. So little bit simplification if you do of this equation this turns out to be this one, this turns out to be this one, okay. Now if we take Peclet number tends to ∞ for large Peclet number cases we can write down that this two terms axial conduction term and this first second term of the radial conduction goes to 0, so only we get $\partial\theta/\partial z=2\partial^2\theta/\partial\eta^2$ so this is the equation for the region II we get for large Peclet number limits, okay. Then let us see our main component that means region III for what we have started to discuss at the beginning of this lecture thermally developed region, so in the thermally developed region obviously r will be of the order of 1 because full pipeline is coming into consideration and in case of axial length z is of the order of l_e.

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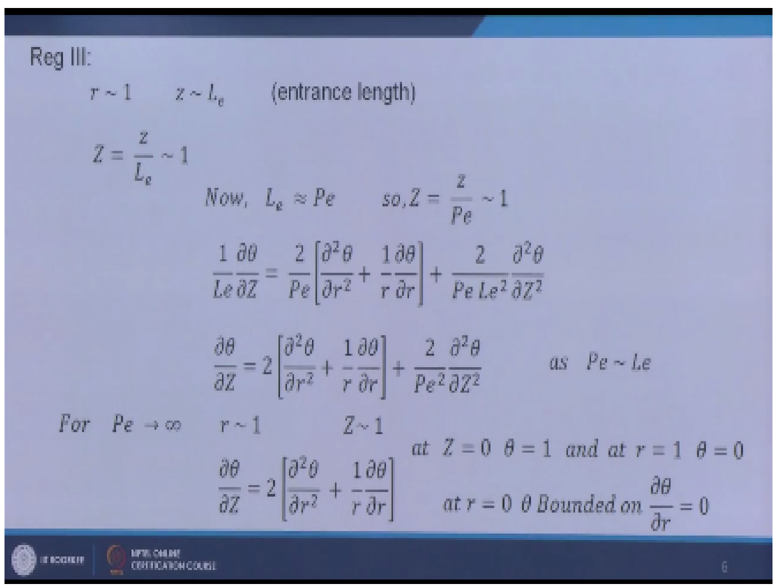

Because l_e is the thermal entrance length so after the thermal entrance length only this region III will be coming into picture, okay. So as we have already considered the r and z scales so let us do non-dimensionalization of z okay as Z so Z is nothing but z/l_e so now Z becomes of the order of 1 okay, then if you see the equation once again if you see from here you can find out that the dominant term in this side will be becoming this radial terms, okay this radial terms will be becoming the dominant term and this term axial conduction term is not that much dominant in the thermally developed zone, okay.

But here in this case we are having $1/l_e$ okay, and here we are having 2/Pe number so if you consider the orders then you will be finding out l_e is of the order of Peclet number, okay. So that we are writing over here, that if we go to the scaling analysis for this region III in the equation then we get l_e is of the order of Peclet number, okay. So what we have obtained is that if we put this l_e=Pe number in the equation then you can find out that both this left hand side convection and right hand side conductions are actually releasing Pe's, okay.

So here in the axial conduction we are having this l_e^2 and in this convection term also $\partial\theta/\partial z$ also $1/l_e$ is coming out, okay. Then if you try to simplified further then you can find out that $\partial\theta/\partial z$ becomes $2[\partial^2\theta/\partial r^2+1/r\ \partial\theta/\partial r]+2Pe^2$ so just I have multiplied this whole equation by l_e so you can find out this l_e and here l_e/Pe as both are of same order so that be cancelled so 2 into this term remains and here we are getting $2.l_e/Pel_e^2$ okay, so there also we can get $2/Pe^2$ as $Pe=l_e$ okay.

Now at large Peclet number cases for Peclet number cases Peclet number tends to ∞ what we can do this term we can neglect so our equation simplifies to this special form of this equation so that means $\partial\theta/\partial Z=2[\partial^2\theta/\partial r^2+1/r\partial\theta/\partial r]$ okay, so this is my equation and subsequently boundary condition remains as usual same so at Z=0, θ=1 that means are the entry at r=1, θ=0 that means at the wall and at r=0 it will be bounded, okay so θ will be bounded. So this is the equation and corresponding boundary conditions for region III, okay.

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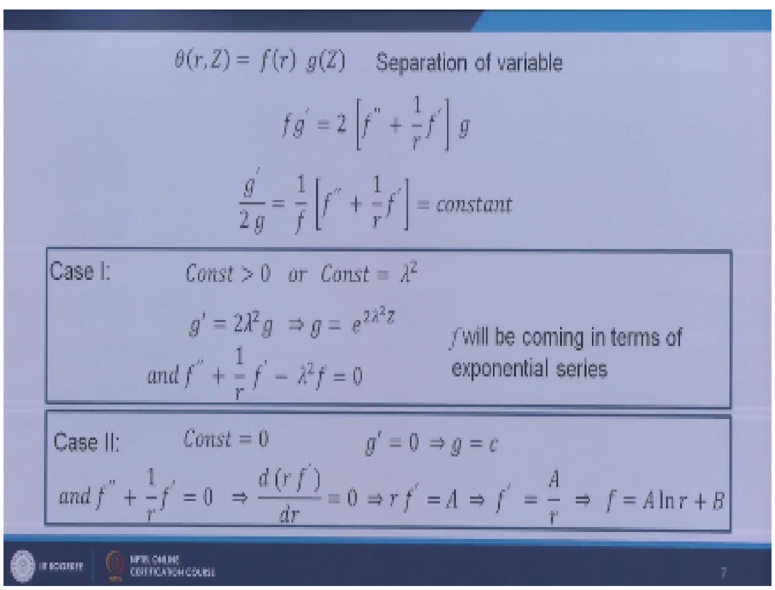

Next let us see how we can solve this okay, here you can see that we are having two variables r and z let us try separation of variable, okay. So we are trying to write down using the concept of separation of variables that θ which is a function of r and z we can write down they are separate functions of r and z, so f(r) multiplied by g(Z) okay. So this is the concept of separation of variable taken from mathematics, okay.

So if we use that then let us try to put this θ=fxg in our pervious equation as I have shown this equation okay, so if you put that one then we can find out fg′ okay, because in the left hand side we had actually $\partial\theta/\partial Z$ okay, so $\partial\theta/\partial Z$ means f will be remaining constant it is not a function of Z and g will be becoming g′ okay so fg′. Similarly in the right hand side g as it is a function of Z it will not be becoming I know if the derivative of the r directions so g we are keeping constant over here only the f we have done the derivative.

So for the second derivative $\partial^2\theta/\partial r^2$ it is f′′ and for single derivative if it is f′, okay. So little bit of sight changing if you do then we can write down $g'/2g=1/f[f''+1/r\ f']$ okay. Now you see in the left hand side we are having only functions of gs and in the right hand side we are having the functions of f okay, so in the left hand side we are having actually Z dependence in the right hand side we are having the f dependence, okay.

This is only possible whenever both of them are tending towards or both of them are equating to a constant otherwise it is not possible, okay. So we are considering that both the sides are equals to constant, okay so if we do so now there are different option this constant can be first case this constant can be greater than 0 okay, so positive constant. If it is positive constant let us write down that constant is nothing but λ^2 okay, so λ is in natural number so λ^2 is the positive one, okay.

So if we do so then what we can do for the left hand side we can write down $g'=2\ \lambda^2 g$ so it is λ^2 so $g'=2\lambda^2 g$ okay, so $2\lambda^2 g$. From here we get g is equal to nothing but $e^{2\lambda 2z}$ if we integrate this equation once, okay simple integration you can follow that one from mathematics okay. And on the right hand side so that means this f term if we equate with λ^2 we get this type of equation $f''+1/r\ f'-\ \lambda^2\ f=0$ okay, here also this is very simple equation if we try to solve this one f will come as exponential series, okay.

So the solution if λ^2 if the constant is positive the solution comes as multiplication of 2 exponentials okay. So this is the case 1 if the constant is positive, if the constant is coming out to be positive. Next let us see if the constant is equal to 0 okay, if the constant is equal to 0 like becomes very simple so here we will be finding out that g′ becomes 0 so g=c so g′ becomes 0 so it becomes c and for the f part so we are getting $f'' + 1/r\, f' = 0$ okay, constant is 0 second case.

So you can find out little bit of integration for this equation if you proceed like this then we will be finding out f=Alnr+B okay, so here also we can find out what is the value of θ so it becomes cxAln r+B okay. So these two cases are very simple.

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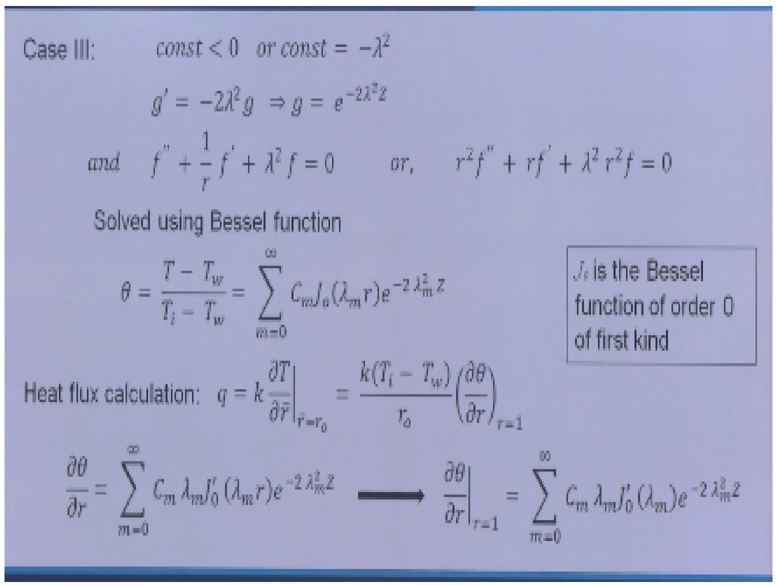

Next let us see if the constant becomes negative okay, so if the constant becomes negative means constant becomes $-\lambda^2$ so in that case g will be very simple so g′ becomes $-2\lambda^2 g$ so g becomes once again exponential so e to the power this time minus so $g = e^{-2\lambda^2 z}$ okay. But for the f the equation of f goes like this okay, $f'' + 1/r\, f' + \lambda^2 f = 0$ okay. If you do multiplication of this equation with r^2 then this type of equation comes, okay $r^2 f'' + r f' + \lambda^2 r^2 f = 0$ right.

So this equation if we try to solve then the equation the solution comes in the form of Bessel function okay, so Bessel function is once again a mathematical concept you can go back to your mathematical knowledge and from there we can write down that solution of this type of equation is nothing but θ which is nothing but $T - T_w / T_i - T_w$ as for non-dimensionalization is equals to so Bessel function, the solution of this equation is nothing but ∑m=0 to ∞ $C_m J_0(\lambda_m r)$ okay, so this much is a solution and here g is coming over here, okay.

So we can write down the overall solution of θ in this fashion whenever constant is negative okay, so here you see this J_0 is nothing but the Bessel function of order 0 of first kind okay. Now let us see that what is my heat flux so for calculation of heat flux q that is nothing but k $\partial T \partial r$ at $r=r_0$ so if we use our non-dimensionalization scheme we can write down k T_i-T_w so this comes due to non-dimensionalization of your T to θ and by r_0 this r0 comes due to non-dimensionalization of $\bar{r}$ to r okay, and the point becomes $r=r_0$ to r=1 okay. So here you see we require this $\partial\theta/\partial r$ term so as we are having this θ so let us try to calculate $\partial\theta/\partial r$.

So $\partial\theta/\partial r$ see this is not a function of r only the function of r is over here in the Bessel function, so this becomes same summation cm λ m okay here we are doing the derivation of G not with respect to r λ will come out λ m G not dash, so this is derivative of G not actually. G $_0$λ m r and rest e-2 λ m^2 z will be remaining same. Okay, now if you take r=1 in this derivative then we get this λ mr that becomes λ m. this things will be remain same okay, so we have got ∂ θ / ∂ r at r = 1 in this fashion okay.

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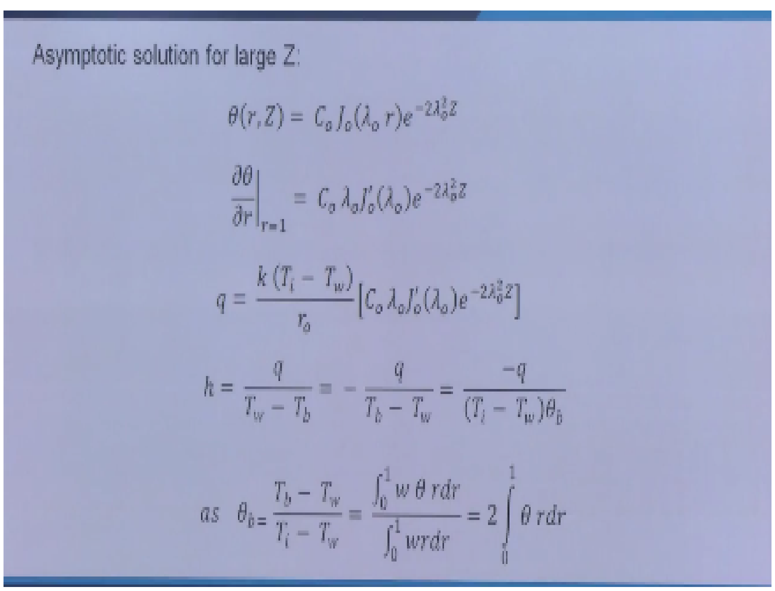

Next let us take asymptotic solution for large Z if you are going for large z. did you see in the previous one we found out ∂ θ and ∂ r the function of the series, now if z is very large then we have to only consider the that is m = 0 term. So here you see we have considered for large z only the m = 0 term. That means in place of C m we have put C 0 and in case of λ m we have put λ 0 and here also in case of λ m we have put λ 0. So this is asymptotic solution for large Z, we have found out the value of θ.

Similarly ∂ θ / ∂ r which we intersect for finding the heat flaks it will be coming in this fashion okay. Now we know we require this q so we have put this ∂ θ/ ∂ r okay, from the previous equation here ∂ θ/ ∂ r I have put so k Ti – Tw/ r_w will be remaining same okay , Ti – Tw/ r_0 will be remaining same and here and this ∂ θ / ∂ r = 1. Next our interest is to find out the heat transfer coefficient h is nothing but q/ Tw – Tb, so q/ Tb – Tw here you can see this Tw – Tb will be written as T1 – Tw into θb.

What is θ b? Temperature becomes bulk temperature and then the non dimensional of that we will be writing down θ b okay, now what is that θ b that we will try to find out θ b is nothing but Tb so in place of T you are writing Tb, so θb I is nothing but Tb – Tw/ Ti – Tw. Now in last lecture I have discussed how this bulk temperature can be found out, so that the same formulation I am writing over here 0 to 1 w θ rdr / 0 to 1 wrdr okay. Now as w is constant okay so what we can do w bar is constant whether w = 1, so what you can do the integration of this will be given you as ½ so this becomes 2 over here. So my θ b becomes 2 into 0 to 1 θ rdr right.

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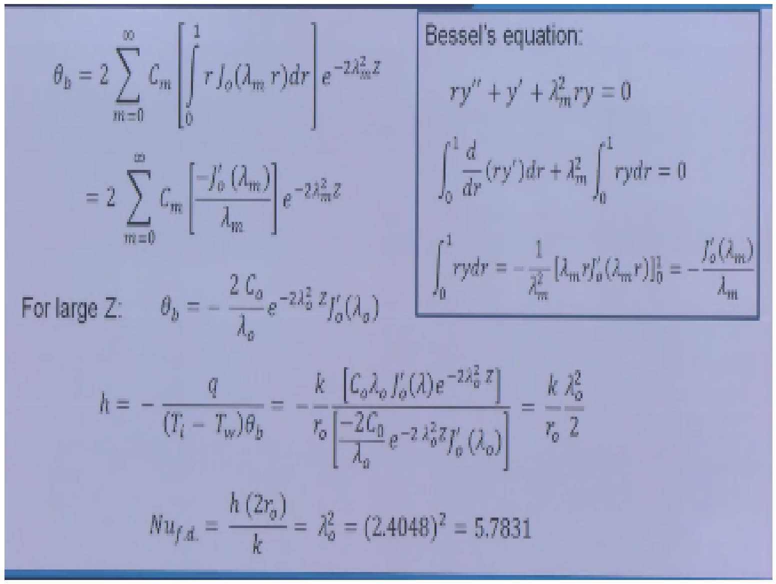

Next let us see what is that θ b once again, so if you go back to our θ equation over here, this is our θ equation and let us go back to our pervious one so the that equation was in formula was in series solution like this okay, from where if we try to find out what is θ b, soθ b once again comes like this okay, why? Because here you are having integration of θ r dr. so θ we know as a series solution as a multiplication by r and then we integrate from 0 to 1.

So same thing we are doing over here our θ was Cm G_0 DR x by this integrate quantum, but here we have multiplied by r and we try to integrate this radial function with respective to r from 0 to 1, so this is my θ b. now what is the value of this integration to understand this we have to little bit of discussion about Bessel function. So here is that one, so actual Bessel equation is this one ry + y + λ 2 ry = 0. Now here you see if we actually club this 2 term and try to make a derivative then it can be written has d/dr ry okay.

And this can be kept simply as λ2 ry. Now you try to integrate both side to the limit from 0 to 1 then you will be getting 0 to 1 d/dr + λ o to 1rydr okay and as this is actually definite integral so in right hand side we will be having = 0 okay. Now here you see what can be done this integration o to 1 rydr actually 1 / λ m 2 and then let us put this y value, y was actually Bessel function so this is the solution of Bessel function, so that will become J_0 .

So that will be becoming J_0, y this will be J_0 . So λ m J 0 dash r and due to this λ r will be coming out okay. So here you see we have kept the limit as 0 to 1 okay. If you keep the limit then the λ m from here can be cancelled and this λ m will be remaining. So you see the value of this integration is nothing but – J_0/ λ m okay. So here this we have put over here ry so this is actually y okay so rydr is nothing but J0 dash / λ m.

In this way we got the non dimensional bulk temperature θ b okay, as we have bought θ b for large z we will be taking only m = 0, so if you take that it will be becoming in this fashion okay, in place m I have put the value as 0. Now it is time calculate the heat transfer coefficient h it requires q and θ b, which we have already discussed in the previous slide. So h is nothing but q and θ b is both we have superlatively derived. Θ b we have derived over here and q we have derived over here okay.

So this two if you club and put down over here then you can see that j 0 dash can be canceled from the denominator and nominator and the simplification will be given simply k/r into λ 2 / 2 okay. Now let us try to find out nusselt number this is nothing but h $2r_0$/ k, so h we have already found out, so there from we can get if you took the value of h it becomes only λ_0^2. Now the value of λ_0 from the Bessel function concept is nothing but 2.4048, so if you put the value of λ_0 the nusselt number you obtain as 5.7831. So this very important concept in case of pi flow the thermal developed region the nusselt number becomes 5.7831 okay.

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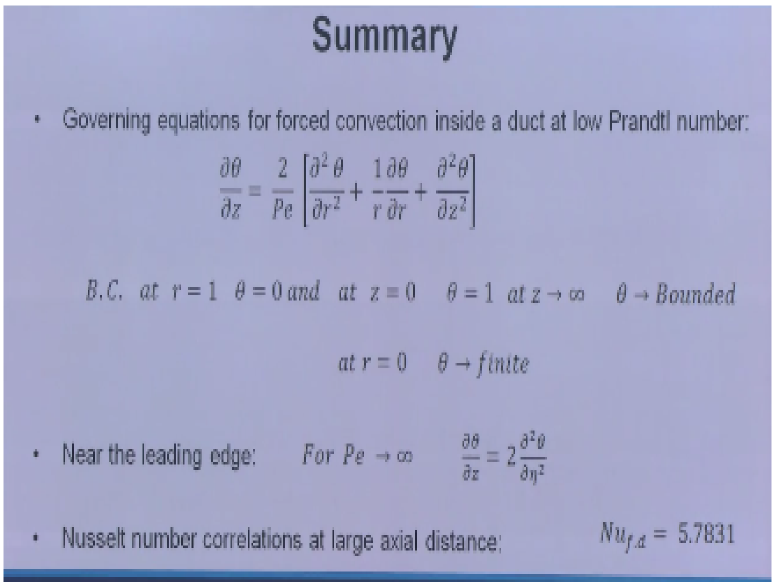

So here we will be ending our lecture let us summarize what we have done, so the summarization is like this governing equation for forced convection inside a duct at low prandti number. So this is the equation we have derived, along with the boundary condition, boundary condition for r. And two boundary condition for z okay, near the leading edge that means in the zone 2 we have found out that we require actually $\partial \theta / \partial z = 2 \partial^{2} \theta / \partial n^{2}$, and away from the leading edge developed region we have found out the nusselt number actually comes out has 5.7831.

So this requires the idea of Bessel function as I have discussed okay. Just like the other lectures let us also test your understanding what you have understood. We are having questions over here first questions goes like this that the interim of q near the central line the equation reduces to 2. So the interims of 2 near the central line.

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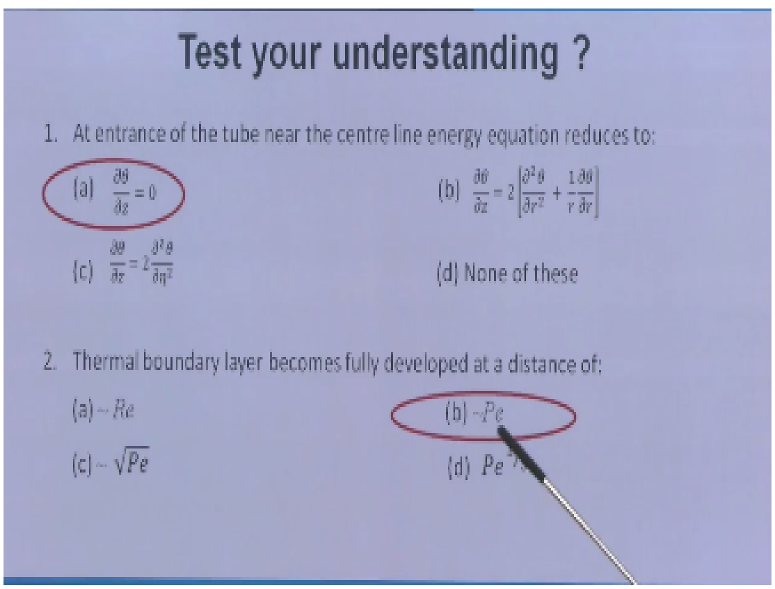

That means it is zone 1 so in case zone 1 we are having 4 options over here $\partial \theta / \partial r = 0$, $\partial \theta / \partial z = 2 \partial 2$ and none of these okay. So obviously you have understood this we already discussed in this lecture. So the answer will bee1st one and then the 2nd question goes like this, thermal boundary layer becomes fully developed at a distance of: means we have to get the value of e, so

Ae options are order of Re, order of peculiar number, order of root peculiar number, order of peculiar number of 1/3.

Okay I think all of you guessed what is the correct answer? So obviously peculiar number this we will found out from the scale analysis of q okay. So these two are the questions I think all of you guessed the correct answer. So here I end my lecture thank you please visit our next lecture which is about thermal developed flow for uniform heat flaks okay, and if you are having any query please keep on posting on our discussion forum.

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