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Lecture 17
Thermal boundary layer in high speed flows

Good morning all of you so now we will look into the one of the last solutions that we can do in this course on similarity methods that is on thermal boundary layer with high speed flows so far in the earlier similarity solutions we had looked at either momentum equations without any pressure gradient term.

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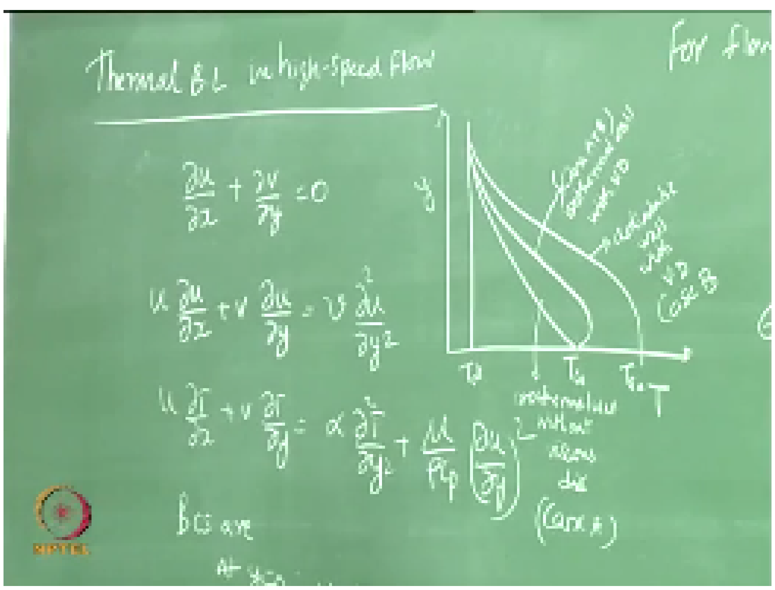

That is the simplest flat plate case and the energy equation without the viscous dissipation term also we had looked at some of the similarity solutions for flows with pressure gradient okay but still the energy equation was the same throughout in all of these configurations you know so now we want to consider a case where you can for example apply either Falkner Skan flows for wedge or you can take a simple flat plate boundary layer and you can see the effect of adding a viscous dissipation term so when is this term is going to be important primarily if you are looking at the non-dimensional variables it turns out.

To be the ratio of hat number by Reynolds number so for high values of this so the viscous dissipation term is going to be relatively important so we are looking at typically what are called as high speed flows it could be incompressible and somewhat compressible but not supersonic so it is relatively high speed subsonic flows basically that's why we have this what we are interested in we are also making an important assumption that the properties are constant even though they are high speed flows.

Where relatively the temperature fluctuations could be strong and the properties also could be compressible like density could be compressible we are ignoring that we are assuming that density is constant and also all the other properties are constant and therefore we are taking all this out of the derivatives okay so that is another constant property assumption is another assumption that we are making okay so these are the boundary conditions so we are writing this for the flat plate right now we can also do the same thing for Falkner Skan solution okay so the only the similarity solution for the momentum will change right.

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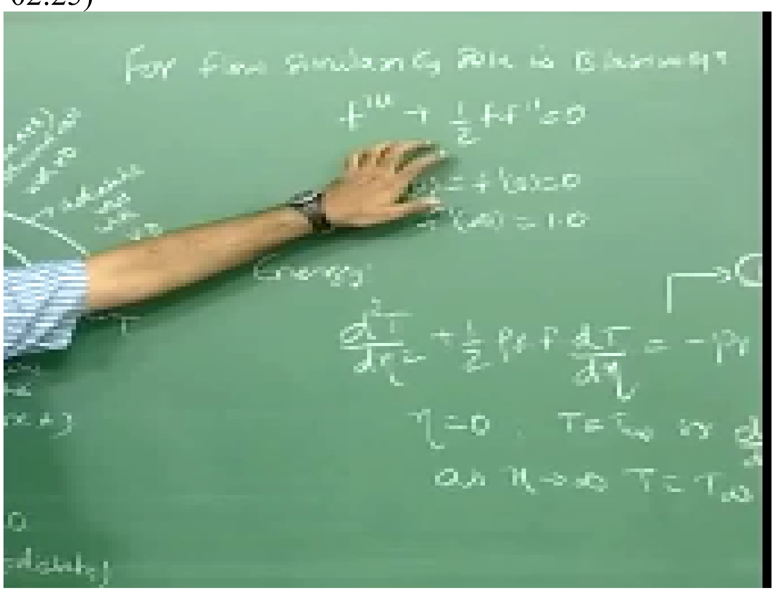

Now the similarity solution for momentum is still the Blasius solution okay so if you are doing this for which flows then you have to rewrite that with the similarity solution for Falkner Skan problem okay so now the modification will be in terms of the energy equation so now you have included the viscous dissipation therefore the energy is coupled to the velocity gradients earlier in the Falkner Skan are brushes the energy was completely decoupled okay in the sense only the one once you solve this you substitute the velocities and that is it here you also need the velocity gradients okay so a little bit more coupling coming out and these are the corresponding boundary conditions.

For the flow it is very straight forward as far as the temperature is concerned you can either have two conditions one you can have an isothermal wall okay and in fact this is what we are going to see in this particular case we are going to consider flat plate where the temperature at the wall is isothermal its constant and you have a very high speed flow you have your boundary layer development Δ and Δ T now you are interested in this case when you include the viscous dissipation and with a is thermal wall what will be the effect of including the viscous dissipation okay so you can consider.

This problem into two sub problems since the energy equation is quasi linear you can actually split this into two sub problems with two different boundary conditions one problem is where you know do not take the viscous dissipation term into account and then you assume purely isothermal wall in the other you take the viscous dissipation into account and you maintain an adiabatic wall okay so in the case even with an adiabatic boundary condition you have heat transfer possible because of the viscous dissipation okay so if you do that of course the similarity solution for the flow is still the Blasius solution.

Now if you substitute for similarity variables for U and V and D u / dy x the energy equation and you do not write a non-dimensional form of temperature you just θ in the dimensional form so this is the similarity ordinary differential equation for energy so you now see compared to the other case the Falkner Skan are the flat plate case you have now this additional term coming from the viscous dissipation okay if this term was not there it will reduce to your earlier more simpler form and now this can be subjected to either of these boundary conditions depending on the case.

So what I am saying is rather than solving this directly so that is one more way of doing it you can directly solve it I mean you can define a the θ which is t - T wall by T ∞ - T wall okay plug it in you can divide throughout by T ∞ - T wall and you can define this as your Eckert number even free T^2 / CP T wall - T ∞ is your record number so in that case you can you will find a non-dimensional form of this okay so this will become your non-dimensional form in terms of the θ defined this way of course you can solve this by shooting technique just like any other OD that you had seen before and you can get the solution for the θ.

But we are not simply interested only in getting the temperature profile or the slope of the temperature in this case at the wall but we are more interested also in knowing what if what happens if you put an adiabatic boundary condition at the wall and what will be the value of this adiabatic temperature okay so this gives us an opportunity to analyze the case where you are DT by dy is 0 and you have viscous dissipation and what will be the value of this adiabatic temperature okay so in order to do that we want to separate the problems into two sub problems as I said do them separately also know get information about the adiabatic wall temperature and combine these two and get the final solution for the global problem.

You know which involves viscous dissipation with an isothermal boundary condition okay so this is what we are going to see today so the first the sub problem we can write as the isothermal flat plate with stout viscous dissipation that is your case a that I have drawn on the figure okay so if you have a simple profile like this now that means you do not include the viscous dissipation this is nothing but the pole how since similarity solution okay so there you define you are the θ the same way that.

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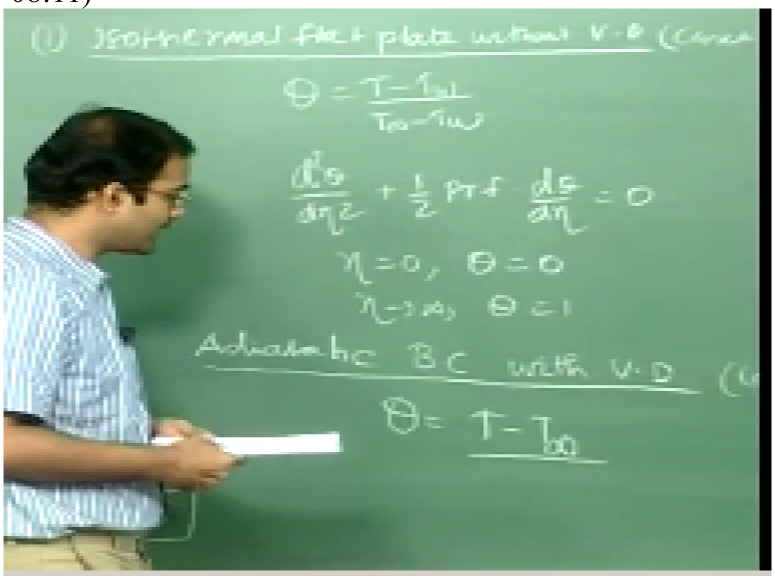

I have defined here t - T wall by T ∞ - T wall and you substitute in your energy equation without the viscous dissipation you give you write the Palau sense equation. Which is nothing but the left hand side term of this so this is d^2 the θ by D Θ^2 + half PRF into D the θ by D Θ equal to 0 subject to boundary condition that Θ equal to 0 but the θ = 0 and Θ R going to ∞ the θ = 1 okay so this is your solution which I have already done you have solved by shooting technique or whatever and now the second part of the solution so this is one problem which you have considered what will be the second problem.

So one we have split this into two solutions one so this is now without viscous dissipation with isothermal wall the other should be including viscous dissipation but adiabatic boundary condition okay so this is adiabatic so this is what I call as case B and if you look at the temperature profile typically this is how it looks you know so this has to satisfy the zero flux at the wall therefore it becomes normal okay.

At the wall you are okay so what we are trying to say I you can solve this equation as it is okay so this is for the case where you have a high so thermal boundary condition with the viscous dissipation okay this is what we need the solution but we are also interested to know the solution for the adiabatic wall case we want to actually measure what is the adiabatic wall temperature so in order to do that I want to stake a case where I have an adiabatic boundary condition with the viscous dissipation and also the fact that for this particular problem you can linearly superpose two solutions it works out and mean I mean that is what we are going to check you can have one problem.

Where it is isothermal the other where you do where you include this and you make it adiabatic and the entire solution to this problem is a is a linear combination of those two solutions okay so we are going by that method now okay although we could have directly solve this and got the temperature profile which is nothing but this which I have drawn here we are also interested in calculating the adiabatic boundary they are the adiabatic temperature okay so in order to do that we have to solve case B now it is also possible that you can solve case a case B separately and keep it and you can linearly combine and get the solution for this generic problem so this is what this is what why I am doing this way okay.

So assume that you have two solutions one for isothermal case the other for adiabatic case okay you can combine them directly we will see how we are going to combine it and that will give your case which is your generic case isothermal wall with viscous dissipation okay otherwise you could out directly solve this equation by shooting method alright so coming to the second problem how are we going to define the θ here because we don't have anything like fixed wall temperature okay so now the first question is how do so I can say this as something like $t - T_{\infty}$ I can define but the denominator is a problem I do not have any T wall so what I would like to do generally in high speed flows that is a difference between the static temperature and the stagnation temperature okay.

So if you are looking at compressible flows in fact what is the relationship between the stagnation and static temperature okay.

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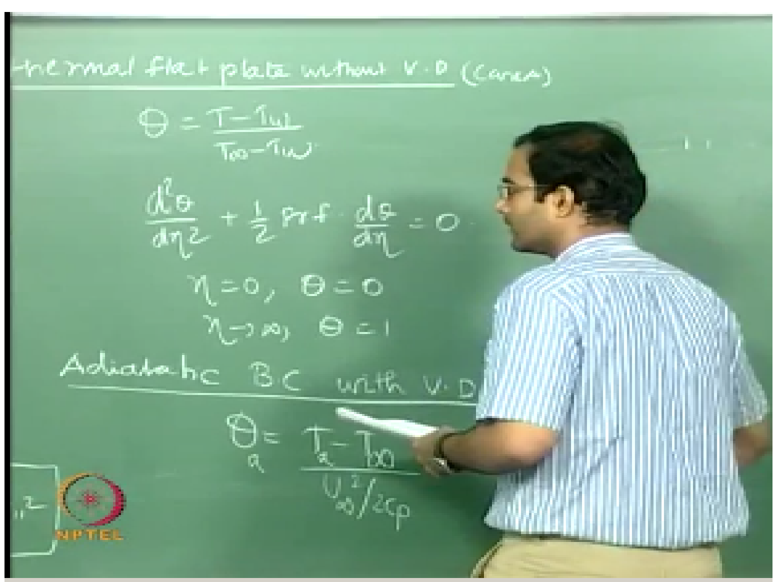

So of course that low-speed flows the velocities are so small that you know you can neglect this and therefore you can approximately say your static and stagnation temperature is the same but high speed flows you cannot do that okay so I am going to call something like my δ T which is your say T 0 - T and you can say dimensionless quantity will be something like u ∞ square by 2 CP so this is the δ T that I am going to use to scale this okay so this is what I am going to how I am going to scale my the θ and of course what I am going to do is I am going to define the θ which is different from this the θ because this is the isothermal the θ.

So I am going to define the notation a for adiabatic boundary condition okay so I am going to substitute now for TA into this and write in terms of the θ.

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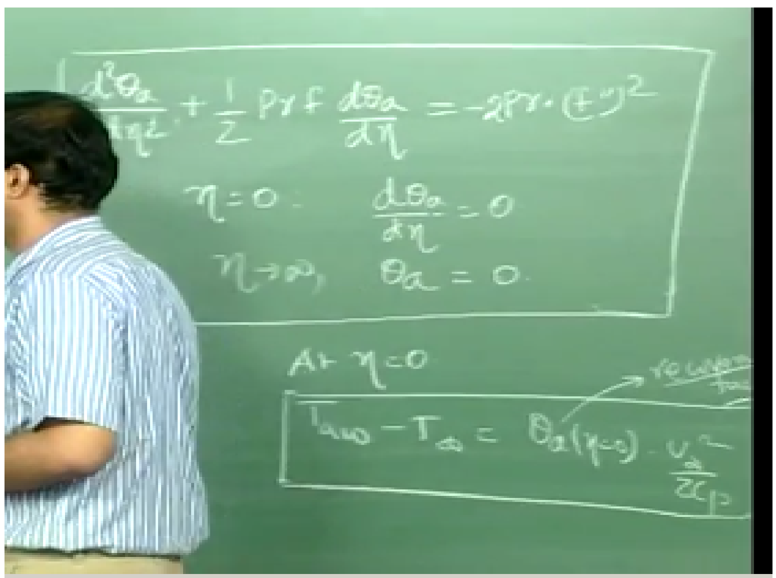

So that will give me d ^{2} θ a so you have u ∞ ^{2} CP and when you substitute there is u ∞ ^{2} / 2 CP so finally you will be ending up with what - 2 times prantle number into f $''^{(2)}$ okay, so the boundary condition now at $\Theta = 0$ what will be the boundary condition θ equal to 0 why it should be 0 your gradient of so d θ a / d Θ should be equal to 0 and your Θ R going to $\infty = 0$ okay, so now you have two definitions of θ one for the isothermal boundary condition the other for adiabatic boundary condition and finally we have to mix these two solutions ok so now this again can be solved by shooting method right so this is another OD which you can write into two first order Rody's you have boundary condition for of course.

You do not have the boundary condition here for θ at $\Theta = 0$ so you can guess that you have boundary condition for θ $''$ at $\Theta = 0$ so you can guess the value of θ at $\Theta = 0$ such that the data at some $\Theta = 10$ becomes 0 okay so this is the other way of doing the guess work so that you match this condition so you keep guessing the value of $\theta =$ 0 here okay so anyway so you can solve this problem by shooting method this problem already you have the solution by shooting method right so once you have these now I have two solutions one for the adiabatic case ones one for the isothermal case I want to now find how do I combine this how do I propose a solution.

Which is a linear superposition of these two solutions okay θ is still the same it is silly because the Θ here is coming from the flow part okay the flow similarity variable is still the same Y by Δ which is y $\sqrt{}$ of u ∞ /nu X only because in that case we consider the viscous distribution to be momentum that has nothing to do with viscous dissipation viscous dissipation is affecting only the energy okay as I said the momentum part is still your Blasius equation ok so the same thing applies the same similarity variable is put into the energy yes so no okay only possibly viscous dissipation is neglected no then you would not have been able to derive a similarity variable cinema similarity solution here.

This see the fact that you are able to reach a similarity equation shows that this is the right similarity variable okay I what I meant by when that was that was the way when Pole house and guessed that he could derive a similarity equation for energy okay because he found for prantle number one u by u ∞ is exactly equal to θ and they both the equations are similar but does not matter that does not mean that prantle number greater than one okay the form of Θ will be different no you use the same meter only and he found that it still gives a similarity equation so here also when you put all your Θ finally it comes to this which is still a similarity equation okay so therefore the energy equation does not care much about the Θ.

So the same Θ what you use for the momentum is still rained here this is your boundary layer similarity variable that is it okay once again if you go for the some kinds of flows like say free shear flows there will be a different similarity variable okay so there you will be defining something like Y by Y M by 2 in the case of jets okay so that is that is your jet half-width so this is your maximum velocity somewhere you get half of the maximum velocity and corresponding to that is your Y M / 2 so you use that to non-dimensionalize your Y okay so in different kinds of flows as far as boundary layer flow is concerned this is the similarity variable that is it okay.

So now I am going to just give you a general solution and before that let us try to understand what how this definition of θ what it means at $\Theta =$ 0 so at $\Theta = 0$ okay so I can calculate the value of TA at the wall okay that is nothing but what the adiabatic wall temperature right so that is my TA wall - T $\infty = \theta$ a at $\Theta = 0$ times u ∞^{2} / 2 CP okay so this is how I can calculate my dimensional value of Fadia by attic wall temperature once I know the value of θ a at Θ equal to 0 and how this value come by guesswork okay so you keep bitrates of Li guessing the value of θ and still it matches this and that final value is your θ at Θ equal to 0 so this factor is also called as a recovery factor although this is a non-dimensional temperature okay this relates basically your dynamic head to the adiabatic wall temperature so this is also called as the recovery factor okay so what you have defined as a stagnation temperature is what something like say $T\infty + u\infty^2/2$ CP.

Now T adiabatic wall as $T \infty$ + some factor times this okay so it is not equal to one okay but less than one so that factor is called recovery factor okay so therefore you can you can imagine that this is something similar to your stagnation temperature that you have defined but may be of a different factor okay so that factor comes through this recovery factor here okay now I am going to propose a general solution which is a combination of the two cases.

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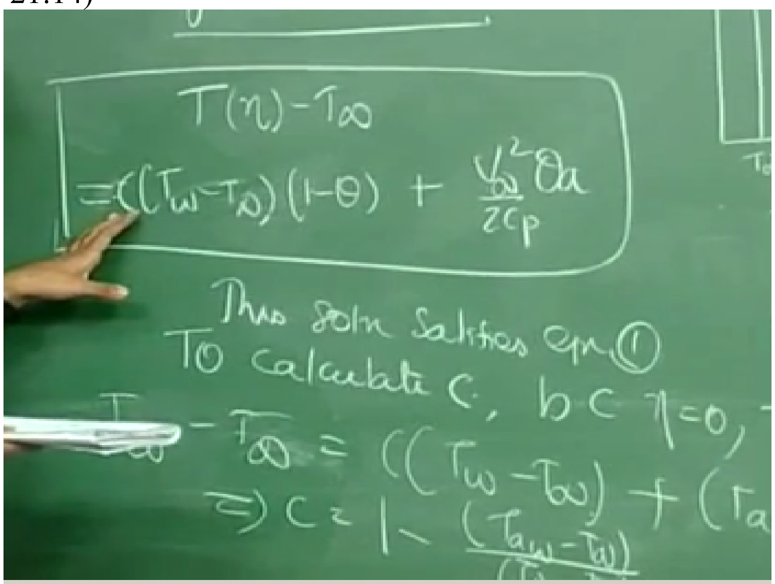

So I am going to define T as a function of Θ - $T\infty$ okay so t - $T \infty$ now already for the case be - $T\infty$ is defined as θ a into $u\infty^2$ by two CP that is one part of the solution okay now I want to blend these two solutions there is a linear combination. I want to propose so this is one solution now here I have defined θ as t - T wall by $T \infty$ - T one so if I want to get to the form of t - $T\infty$ and then I will say this is 1 - θ ok 1 - θ into $T\infty$ - T wall or so if I say 1 - θ it becomes t-- teen one - θ will be what t - $T\infty$ by T wall - $T\infty$ is that right the science will flip okay so therefore I can just write this T - $T\infty$ as 1 - θ x T 1 - $T\infty$ okay so this can be written as T wall - $T\infty$ into 1 - θ okay still this is not a linear combination because I will just simply added it okay so I have to propose some factor some constant which gives a weight edge for this part of the solution and this part of the solution.

So this is a relative weight age I am giving a weight age of 1 for this corresponding to that what is the weight age to this okay it can be > 1 < 1 so this is your final form of the general solution ok so what you are saying is your general solution is a linear combination of these two solutions and how do you know that this is the correct one so you can simply substitute this back into this equation number 1 and you will check that it satisfies that equation that means this is the right combination okay so I am not going to do that you can do that yourself and check simply substitute this and you will get you can group into two forms okay.

So one form will be of this which is already satisfied by itself okay, the other form will be this which is also satisfied okay so those two will be perfectly satisfying the OD so this solution satisfies equation 1 okay, I want you to just check that so therefore this is the right solution now one more thing already when we propose the solution we have satisfied the boundary condition that it Θ are going to ∞ t = t ∞ okay because the way that we have defined my θ so at large values T will become T ∞ and this will become one here and here the value of θ becomes 0 so this naturally satisfies the boundary condition that this is this ok but still I have not come clearly specified the wall boundary condition here okay, so this constant can be determined by satisfying the boundary condition at the wall okay so to calculate C so the BC should be at Θ = 0 for the solution.

Which involves θ T wall should be T ∞ and the solution which inverse θ a so there B DT / D Θ = 0 okay so if you can you substitute this boundary condition and tell me what will be the expression for C so T at Θ = 0 - T ∞ okay, so this is nothing but what T at Θ = 0 is what T wall ok that is a fixed boundary condition so T wall - T ∞ will be =C x T 1 - T ∞ x what will be θ at y equal to 0 0 right therefore this will be just 1 + u ∞ square by 2 CP x θ DT = 0 okay now from this definition θ a at Θ = 0 x this is nothing but P a Val - T ∞ okay so this will give me C equal to what 1 - so I can just take this common so this will be 1 - C + is equal to this so C will be 1 - PA 1 - T ∞ divided by T 1 - T ∞ okay or I can rewrite this as C = t1 - T adiabatic wall by t1 - T ∞ okay so now that I have written mind C now the solution is now complete okay.

So once I finds two separate solutions one for θ one for θ a I found out the constant factor which combines this linearly okay so therefore I can write my final solution.

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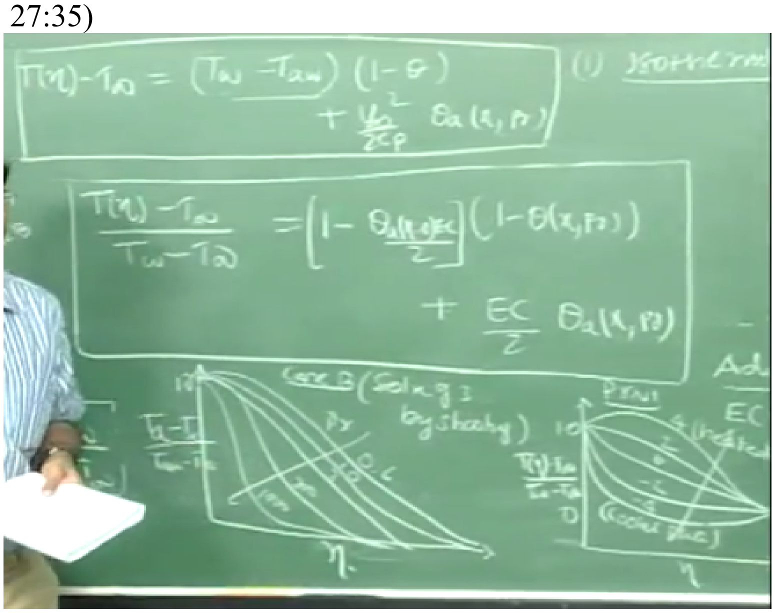

Term - T ∞ = D w- so - T wall - T ∞ cancels when I substitute this so it will be T 1 - T adiabatic wall into 1 - θ + okay so I can still θ in this as u ∞ ^{2}/ 2 CP x θ as a function of V time so this is my final solution okay, I can also go one more step I can non-dimensionalize this with t - T ∞ by T wall - T ∞ okay so I can divide throughout by T 1 - T ∞ so that I get a final expression for non-dimensional temperature and this will be still one – θ.

This is a function of Θ on frontal number now this will be I can write this as if I divide it by T one - T ∞ this will be u ∞ ^{2} / CP T one - T ∞ is a card number so Eckhart number by 2 into θ a now this part coming to Tw T adiabatic wall by T wall - T ∞ okay so that can be written as you can just check 1 - θ a at Θ = 0 into a cot number by 2 okay because θ a into Eckert number that is that is basically this term Eckhart number is u ∞ square CP δ T into this okay so that will be T adiabatic wall - T ∞ so you can you can say 1 - this divided by T 1 - T ∞ will give you this final you can just check that okay so this is your final non dimensional solution okay so all that requires is your solution for θ okay.

Which is coming from K safe and for θ a coming from case B and you combine this like this and you get your final solution also this is nothing but your θ right so this was this could have been directly obtained by solving the similarity solution that I had written before okay directly okay the same thing can also be done by linear combination of these two fundamental solutions so let us see how if you plot the solution for temperature how this profiles look like okay any doubts on this so far so if you plot the temperature profile first let us look at case B solution because case a we already know how the temperature profile looks case B if you plot it as non dimensionalize the adiabatic temperature has ta - T ∞ by P a w - T ∞ such that it scales between 0 and 1 okay.

So at y = 0 this becomes T adiabatic wall it becomes 1 at Y going to ∞ this becomes 0 okay so on the x-axis you have Θ so for large values of Θ so this becomes 0 okay small values at were Θ = 0 this becomes 1 okay it starts from 1 and you will see the solution this is with increasing parental number your slope at the wall keeps increasing this prantle number 0.6 1/3 this is like 300 and this is like thousand okay.

So this is your case B solution that is only for the case with adiabatic boundary condition at the wall this is how the non-dimensional temperature profile behaves once use once you solve this if you want to call this as number two and number three so if you solve three by shooting method this is what you get finally okay so this is coming from solution of three by now for the general solution for this the combination of these two solutions if you can plot for a given value of prantle number that is my (t) Θ - /T w - T ∞ okay as a function of Θ this will also be between 0 and 1 and this will show behavior something like this okay my 0 actually somewhere here this is for different values of Eckert number into θ = 0 this corresponds to a heated plate okay.

So in the case of heated plate your wall temperature is greater than your T ∞ in the case of cool plate wall temperature is less than T ∞ so you can get negative values of this when you plot it and these are for different values of Heckert number into θ a Θ = 0 so you can write this as something like a cut number into θ = 0 so you if you look at the solution for this problem 3 and if you look at the generic solution here this depends on θ θ a and a cut number so you have to plot this for a particular value of prantle number for a particular value of θ a Θ = 0 a cut number okay so this is could be for say Prandtl number around 1 okay, so you have to fix the Prandtl number here.

Because everything there are too many parameters you have prantle number we have the Eckert number here so you fix the ax-cut number to some value fix the Prandtl number and then plot the variation of this non-dimensional temperature as a function of b θ and this is how it looks now there could be different values of Eckert number x θ a for a heated plate you have profiles which are like this where the cool plate you have profiles which are like this okay, so all this can be verified once you solve this equation by shooting technique okay so for a particular value of a cut number you can combine these two solutions and you can get this kind of a temperature profile okay.

So finally we are interested in the calculation of heat transfer coefficients we will see how that can be obtained so if you are confused about the definition of this your Eckert number into θ a at Θ = 0 is nothing but your T adiabatic wall - T ∞ / T 1 - T ∞ okay so because this is the TA w - T ∞ so this should be a cot number is again u ∞^2 / CP x T w - T ∞ so this should lead to some non-dimensional form of temperature like this okay so for different values of this you are plotting this if you are not clear about how the account number comes into picture okay so that is how the adiabatic wall temperature enters here through the occurred number times this.

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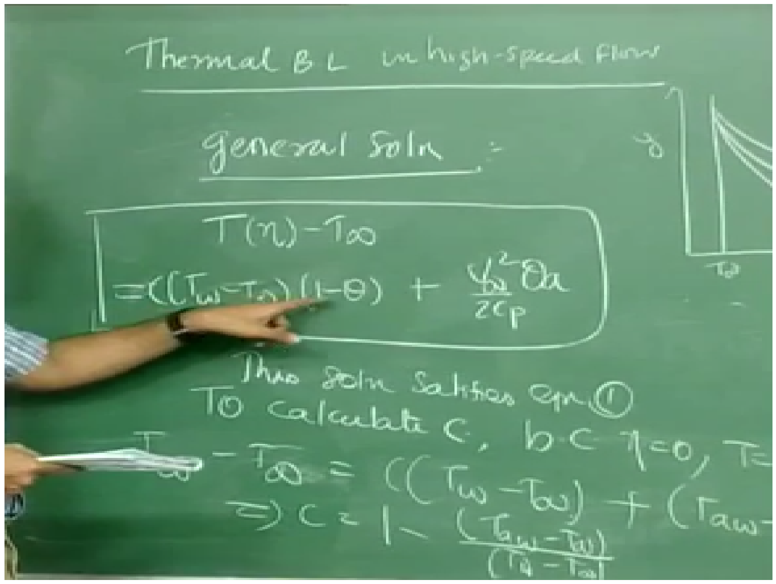

Now let me also write down the form of heat flux okay. So now when we write down the heat flux we look at the temperature profile which is their general profile here so therefore I have to differentiate it with respect to the general profile so this will be a - K first you can write this as D θ - D θ / D Θ so - and - - will get cancelled here so this will be K x T wall - T adiabatic wall x D θ by D Θx D Θ / D Y this is at θ =0 okay + you have u ∞^2 + K x will be a - here u ∞^2 / 2 CP x D θ a / D Θ at Θ = 0x D Θ by D 1 right.

So this is coming from the general solution now what is the value of D θ a by D Θ D Θ Θ = 0 0 so this entire term and we knocked off and this can be written as q wall into DT / dy √ u ∞ / μX okay into θ ′ by DT = 0 okay now once you determine the value of θ ′ at Θ equal to 0 that is for the pole how since condition this is coming from the pole houses case so when you solve this you naturally determine θ ′ at Θ = 0 so once you do that you substitute it and this will give you the wall heat flux all right so we have already done that okay, if you can perhaps recollect if you can recollect for prantle number range.

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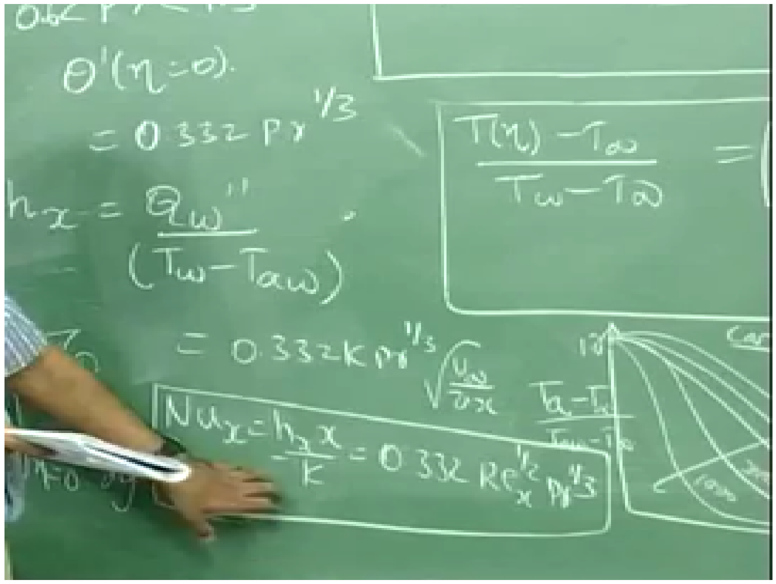

In fact pole house and did this for small Prandtl numbers for me intermediate parameter Prandtl numbers for large potential numbers okay the correlation for small pattern do you remember what it was - half not for small point for intermediate prantle number mask okay so that was .3 2 prantle number raised to the or 1/3 okay, so this can be substituted to calculate q all double ′ and from there you can calculate heat transfer coefficient you can now define heat transfer coefficient how do you now define it now this can be p wall- whether you want to use t ∞ here or T adiabatic one T ∞.

Why because if you look at this form right here if you had defined based on T w - T adiabatic wall this will get cancelled straight away okay so therefore we would like to define my heat transfer coefficient based on T 1 - T adiabatic wall so in that case and therefore my so this will come out to be 0.33 2k Prandtl number 1 / 3 $\sqrt{}$ of μ u ∞ nu X it will exactly cancel the temperature differences and therefore my nope local nusselt number I can define as HX by K will be 0.33 2 into Reynolds number power 1/2 prantle number 1 / 3 okay so now you see the nusselt number relation is exactly identical to the flat plate case which is isothermal there is no difference okay but the definition of heat transfer coefficient is different okay.

Now you are defining this as T wall - T adiabatic wall t w- T ∞ okay now this is the difference between the high speed flows and if you neglect the viscous dissipation okay apart from this the final expression for nusselt number is still the same all right so the important conclusion here is that for non dimensionalizing okay your there are many temperatures. You have now T ∞ now you have T wall you have T adiabatic wall so all the three has to be considered some way okay and to define heat transfer coefficient you have defined based on t w - T ∞ okay so everything is fine so therefore since you are arriving at the same correlation Jordan all Sinology is still valid okay.

So the Reynolds analogy which says that Stanton number = CF by two for prantle number of one okay four otherwise there Stanton number 2/3 = CF /2 so this is still valid for high speed flows also because for prantle number equal to one you will still θ in the same expression for between Stanton number and CF so therefore the nonce analogy is still valid now one thing is for calculation of properties so far for low speed flows how did we define the property how did we calculate the properties we calculated them at some mean temperature which we also call as film temperature okay so this is called the film temperature which is the average between the wall temperature and the free stream temperature okay so if .

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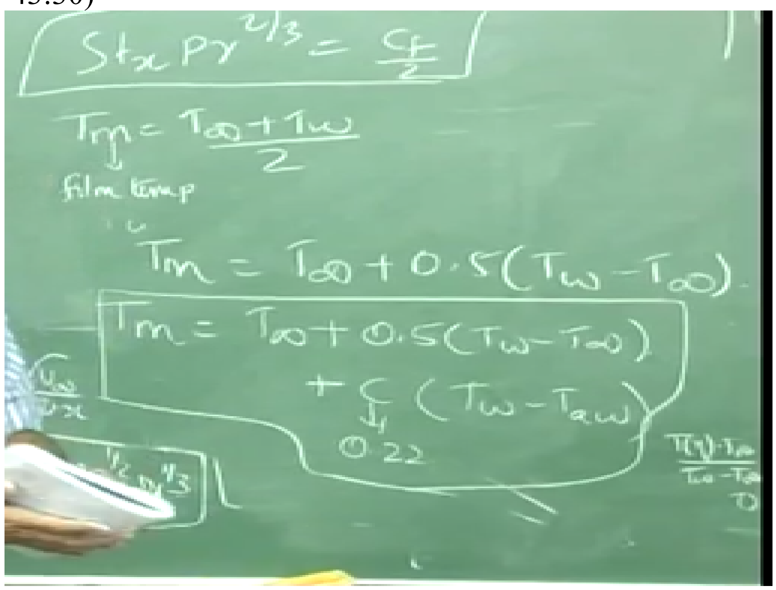

You if you can also extend this and write like T ∞ + okay so you can write this in this form okay now the same way in the case of high speed flows we have to define some mean temperature to calculate the properties okay so now we have as I said three different temperatures to non-dimensionalize okay. Now so already you have 0.5x T 1 - T ∞ now you also want to account the adiabatic wall temperature somehow so therefore we define + another constant into Tw - T adiabatic wall okay so this constant generally is empirical it is taken somewhat something like 0.2 - okay so we calculate mean temperature or film temperature this way in the case of heights high speed flows and then we calculate all the properties based on.

At this value of property at this temperature okay now for the limiting case where you do not have viscous dissipation the T w will become equal to exactly T adiabatic wall okay so it will reduce to the form of your earlier case that is your film temperature okay so you have to be careful that the definition of heat transfer coefficient is different but finally the form of muscle camber is exactly the same and the properties where you calculate the property corresponding to the temperature the temperature has to be calculated in this particular fashion okay so this is a very important thing that so with this we have completed all the similarity solutions for external boundary layer flows if you want I can just quickly summer summarize.

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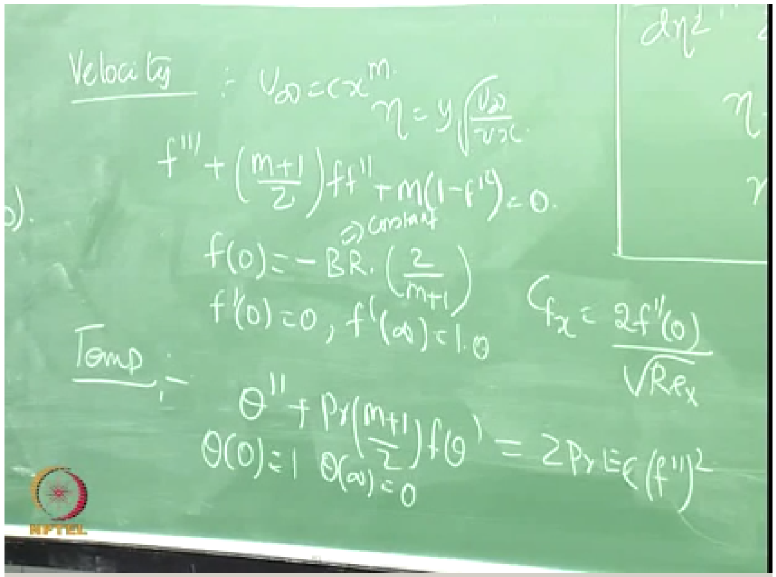

The similarity solutions that that we did before we stop okay so summary of similar solution just two more minutes so for velocity I am just writing the global similarity solution which is nothing but the Falkner Skan from there all the other special cases can be derived so for the Falkner Skan you have F triple ′ okay the boundary conditions are for the similarity problem you are F of 0 F ′ of 0 should be 0 F ′ at ∞ should be equal to 1 now what is the condition most general condition for F of 0 do you remember from our transpiration problem.

This is - glowing ratio times 2 by M + 1 okay the blowing ratio is a constant value okay then when you blow blowing - equal to 0 that becomes the case without transpiration where F of 0 equal to 0 ok now we in all these cases we are we have made the assumption that your u ∞ is of the form CX power M okay and your blowing ratio is essentially a constant and the similarity variable is right so these are some of the assumptions under which you get a similarity solution once you get it you can calculate your skin friction coefficient as two times f double ′ of zero divided by √ of local Reynolds number so same way for temperature the most general similarity solution is θ this is your most general form okay including high speed flows okay if your account number is small you can neglect the right hand side terms and it reduces.

To your follow sins equation okay the boundary conditions θ 0 equal to 1 θ at ∞ equal to how did we define θ in the earlier case it was we remember was at t - T ∞ by T 1 - T ∞ can you just check how we defined it then you may have to flip the for the general problem t - T ∞ by T one - T ∞ that is how I think I defined it so in that case the boundary conditions flip okay so θ at the wall now will become equal to one okay θ free stream will become zero if I define as t - T wall by T ∞ - T 1 it will be 0 and 1 okay so here my definition of θ = t - T ∞ by T 1 - T ∞ so only then I can write in terms of a cut number here that is why I did like this okay so for this the nusselt number relation finally will be my - θ ′ at 0 into re X √ of rx or RX / 1/2 okay.

So these are the most general similarity solutions of course for particular cases we have derived and also we have derived for the general case from which we can get those specific cases so we will stop here today and in the next class we will look at the integral method solution you.

Thermal boundary layer in high speed flows

End of Leture 17

Next: Approximate(Integral)
methods for laminar external flow and heat transfer

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