Convective Heat and Mass Transfer

Prof. A. W. Date

Department of Mechanical Engineering

Indian Institute of Technology, Bombay

Module No. # 01

Lecture No. # 09

Similarity Solution to Temp BL - II

In this lecture, we will now look at Solutions to the Similarity Temperature Boundary Layer equation. By way of reminder the equation is theta double prime equal to Prandtl number into m plus 1 by 2 f theta dash minus gamma f dash theta plus 2 Ec f double prime equals 0 square equal to 0.

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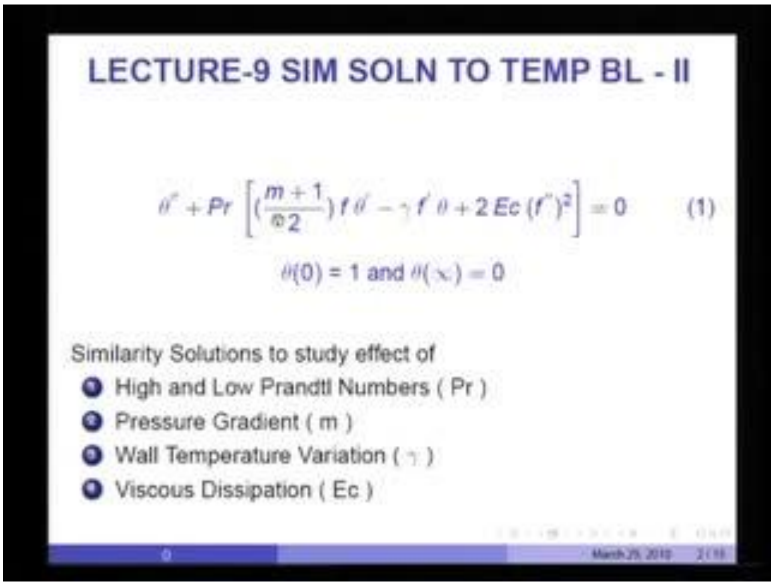

With the boundary condition that at the wall, theta 0 will be 1; and in the infinity state, theta infinity will be 0. We are interested in the developing solution, so that we will look at effect of Prandtl number, we look at effect of pressure gradient and of course, also on the suction of blowing parameter which is embedded in the solutions for f f dash and f double prime. We look at effect of wall temperature variation gamma and we look at effect of viscous dissipation on the nature of the solutions sometimes.

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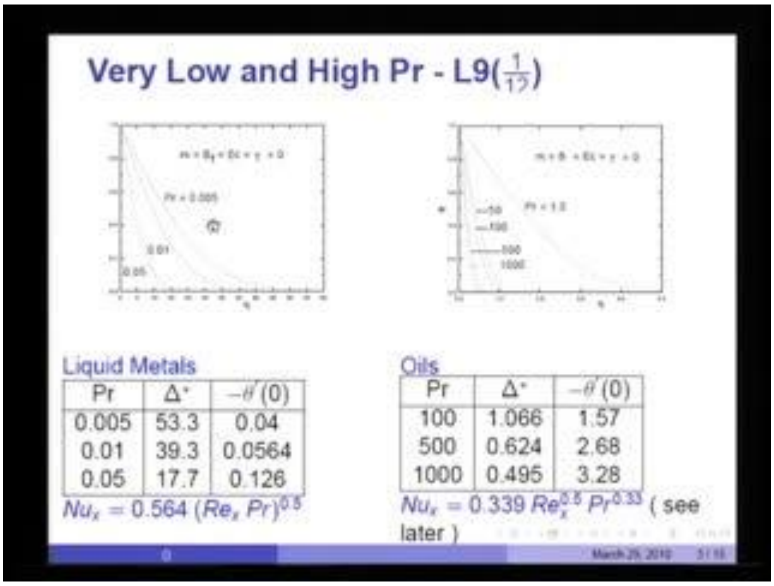

Remember, I obtained already solution for Prandtl equal to 1; m equal to 0; gamma equal to 0; and Ec equal to 0; that is the solution I presented in the last lecture. Now I want to look at effect of very high and very low Prandtl numbers and this is what you see for liquid metals, the value of eta, remember, at the 0.005 which is a very low Prandtl number. The value of theta max or the value of delta star is nearly 53.3, whereas for Prandtl number equal to 1 it is 4.92 as you remember. So, as the Prandtl number is reduced, the thermal boundary layer thickness goes on lower and lower temperature gradient.

If I were to correlate this theta prime 0, it would be correlated reasonably well by this correlation Nu x is equal to 0.564 in all x Prandtl to the half. On the other hand, on the oil side, you will see Prandtl equal to 1 gives you this which is the reference solution about 4.92 as the Temperature Boundary Layer thickness, but for 50, 100, 500 and 1000 you see the Temperature Boundary Layer thickness goes on reducing and I have given some values here for 1000; it is as low as 0.495, which is 10 times smaller than the Velocity Boundary Layer thickness which was about 5 and this is 0.624. At Prandtl number of 100, it is just one-fifth of the boundary layer thickness for Prandtl equal 1.

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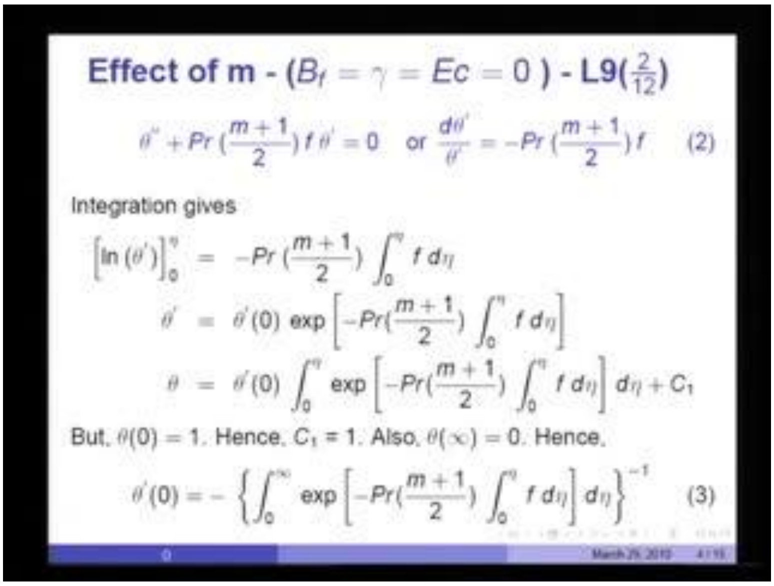

Minus theta P of 0 goes on increasing with Prandtl number and a good curve fit is 0.339 Reynolds x to the power of 5 Prandtl to the third, but we will discuss both these solutions a little later. We want to study effect of m first of all and for which, we will assume that there is no suction or blowing; we will assume that the wall temperature is constant; we will assume that there is no viscous dissipation included.

We are only including the effect of m along with that of the Prandtl number. So, the governing equation as you will see for gamma equal to 0 and Ec equal to 0, would simply be that theta double prime Prandtl m plus 1 by 2 f theta dash equal to 0; which I can write as d theta dash over d theta dash because theta double prime is simply d theta dash.

That would equal minus Prandtl m plus 1 by 2 f. If I integrate this equation once, I will get ln theta prime from 0 to eta equal to minus Prandtl m plus 1 by 2, which is a constant into 0 to eta f d eta. Another way of saying, it is theta prime at any eta would be equal to theta prime at 0 exponential of minus Prandtl by into m plus 1 by 2 0 to eta f d eta.

If I integrate this equation once again, then I get theta equal to minus theta prime 0 0 to eta exponential of this quantity into d eta plus a constant of integration C 1, which I discover firstly from the boundary condition - theta 0 is equal to 1. So, if I said theta 0 which means 0 to 0. Therefore, this contributes nothing and theta 0 being 1, I get C 1 equal to 1.

Now, I impose the boundary condition at infinity. So, theta infinity 0 - this integration will become 0 to infinity, and therefore, I will get theta prime 0 which is of interest to me equal to - because that represents the Nusselt number - equal to 0 to infinity, exponential of all this raised to minus 1.

Now you will see some special cases of f. Since, velocity solution f d eta is known, we can evaluate this integral.

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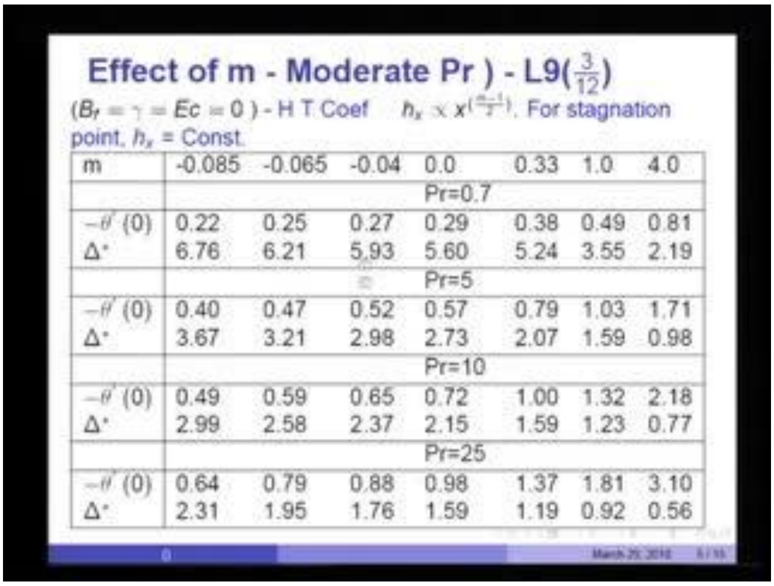
Effect of m - Moderate Pr) - L9($\frac{3}{12}$)

($B_r = \gamma = Ec = 0$) - H T Coef $h_x \propto x^{(\frac{m-1}{2})}$. For stagnation point, h_x = Const.

m	-0.085	-0.065	-0.04	0.0	0.33	1.0	4.0
				Pr=0.7			
$-\theta'(0)$	0.22	0.25	0.27	0.29	0.38	0.49	0.81
Δ^*	6.76	6.21	5.93	5.60	5.24	3.55	2.19
				Pr=5			
$-\theta'(0)$	0.40	0.47	0.52	0.57	0.79	1.03	1.71
Δ^*	3.67	3.21	2.98	2.73	2.07	1.59	0.98
				Pr=10			
$-\theta'(0)$	0.49	0.59	0.65	0.72	1.00	1.32	2.18
Δ^*	2.99	2.58	2.37	2.15	1.59	1.23	0.77
				Pr=25			
$-\theta'(0)$	0.64	0.79	0.88	0.98	1.37	1.81	3.10
Δ^*	2.31	1.95	1.76	1.59	1.19	0.92	0.56

The solutions that I show here have been evaluated for moderate Prandtl numbers 0.7, 5, 10, and 25 aligned for m negative. Remember, I cannot go for below m equal to minus 0.091 because that is where the separation occurs. So, I begin with m equal to minus 0.085, minus 065, minus 0.04, 0.0, 0.33, 1, and 4; these are excel rating flows.

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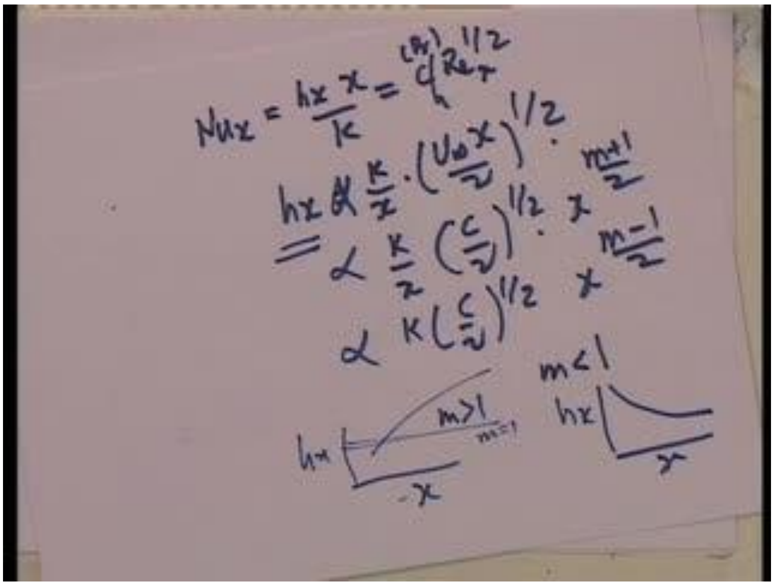

Now, remember h x will be function of x m minus 1 by 2, the heat transfer coefficient. Remember, Nu x is h x into x by k is equal to some constant into Reynolds x to the power half. This constant is a function of Prandtl number. So, what do we get? h x will be equal to k by x into U infinity x by nu raised to half into or proportional to that. What is U infinity? It is equal to C x. So, I get this as C nu by half into x into m plus 1 by 2, which is proportional to k C by nu raised to half into x raised to m minus 1 by 2.

So, remember heat transfer coefficient - the pressure gradient has this effect on heat transfer coefficient. If m is equal to 0, h x will simply decrease with the x. So, for m less than 1, h x will decrease with x, but for m greater than 1, you could also get h x relatively increasing with x. This is something very important. This is for m greater than 1 h x versus x, and for m equal to 1 h x will be constant - m equal to 1,

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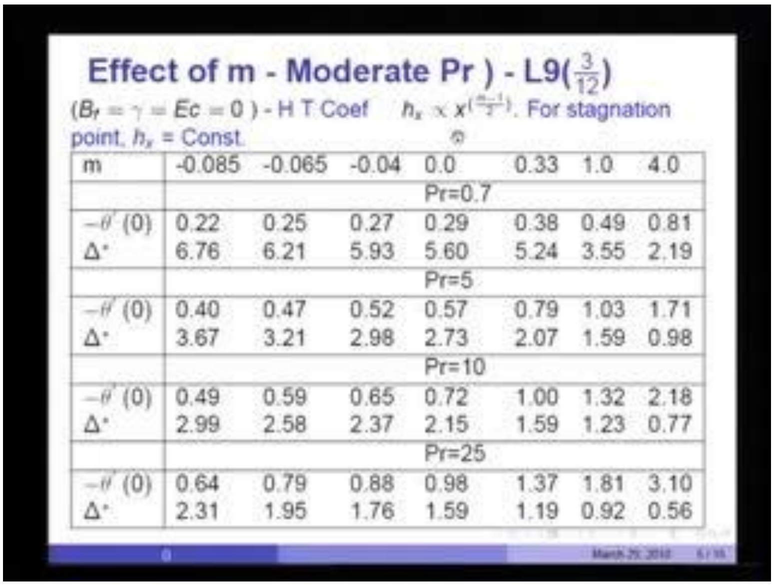

m	-0.085	-0.065	-0.04	0.0	0.33	1.0	4.0
				Pr=0.7			
$-\theta'(0)$	0.22	0.25	0.27	0.29	0.38	0.49	0.81
Δ^*	6.76	6.21	5.93	5.60	5.24	3.55	2.19
				Pr=5			
$-\theta'(0)$	0.40	0.47	0.52	0.57	0.79	1.03	1.71
Δ^*	3.67	3.21	2.98	2.73	2.07	1.59	0.98
				Pr=10			
$-\theta'(0)$	0.49	0.59	0.65	0.72	1.00	1.32	2.18
Δ^*	2.99	2.58	2.37	2.15	1.59	1.23	0.77
				Pr=25			
$-\theta'(0)$	0.64	0.79	0.88	0.98	1.37	1.81	3.10
Δ^*	2.31	1.95	1.76	1.59	1.19	0.92	0.56

Now, this is a very important point to remember that for stagnation point flow, Heat Transfer Co-efficient is essentially constant. You will recall that we had also seen that delta 2 star and delta 1 star, etcetera all the thicknesses are also constant for a stagnation point flow. So, let us look at this and the solutions for showing the effect of f at any 1 Prandtl number. Let us check Prandtl number 0.7 and then you will see that when m is equal to 0 for flat plate, the thickness is 5.6, but when you have decelerating flow the thickness goes on increasing like the Velocity Boundary Layer thickness. When you have accelerating flow, the Temperature Boundary Layer thickness also decreases as shown here. This state of affairs prevails at all Prandtl numbers that I have listed here.

Now, let us look at the effect of Prandtl number at any pressure gradients. So, let us look at stagnation itself. So, you will see that for Prandtl number 0.7 minus theta prime 0 is 0.49, it increases to 1.03 at Prandtl 5; 1.32 and 1.81. So, what have you seen, as the value of m increases, the heat transfer coefficient increases; as the Prandtl number increases, the heat transfer coefficient increases. We have captured both these effects in the solution; of course, it would be possible to develop a correlation of the form.

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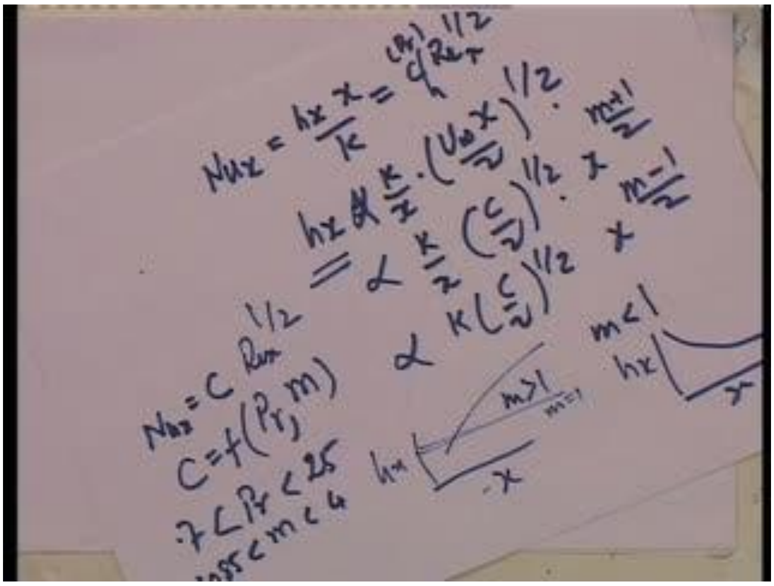

Nu x is equal to C times Re x to the half, where C is now a function of Prandtl number and m for Prandtl number between 0.7 and 25 and minus 0.085 m 4. You will see this will take the form of an experimental correlation which can be used for further design work any time we wish and one need not generate new solutions every time by means of a computer.

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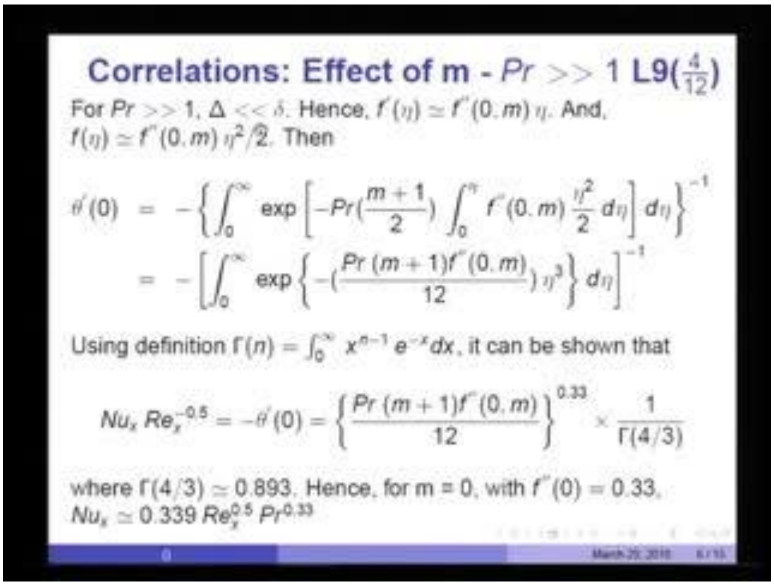

I now want to look at the effect of very high and very low Prandtl numbers in the presence of pressure gradient. So, remember for Prandtl number very much greater than 1, delta would be much less than 0.

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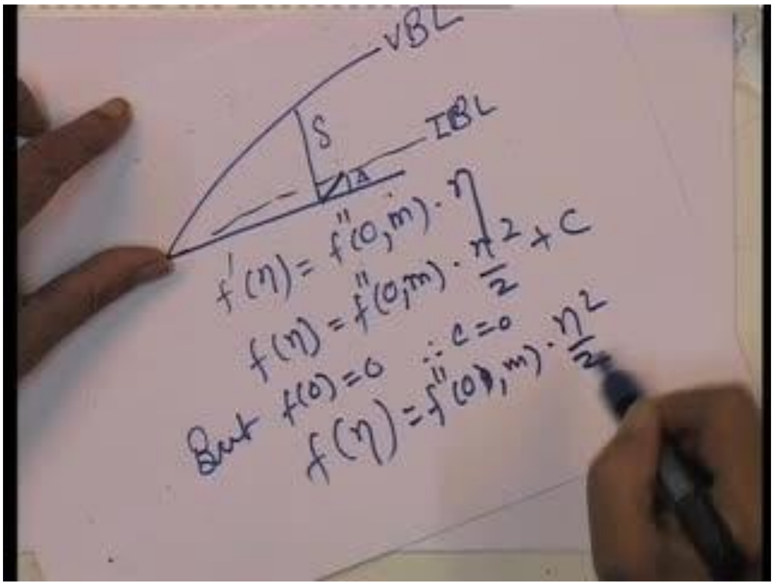

Therefore, you will have a situation of a Velocity Boundary Layer like that and a Temperature Boundary Layer just like that. So, in other words delta is much smaller than delta. So, for all practical purposes I can say that the velocity profile is really linear in the Temperature Boundary Layer equation and that we have seen many times in our earlier solution.

So, in other words f dash eta within the Temperature Boundary Layer will simply be equal to f dash 0 for that value of m into eta. Integration will give me f eta is equal to f double prime 0 m which is a constant eta square by 2 plus a constant.

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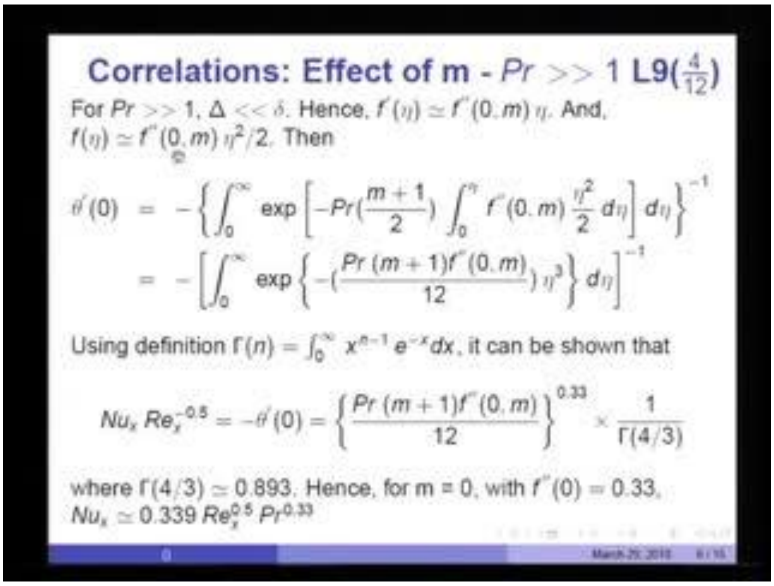

But f 0 is equal to 0 and therefore, C is equal to 0. So, essentially I get f eta equal to f double prime 0, this into eta square by 2.

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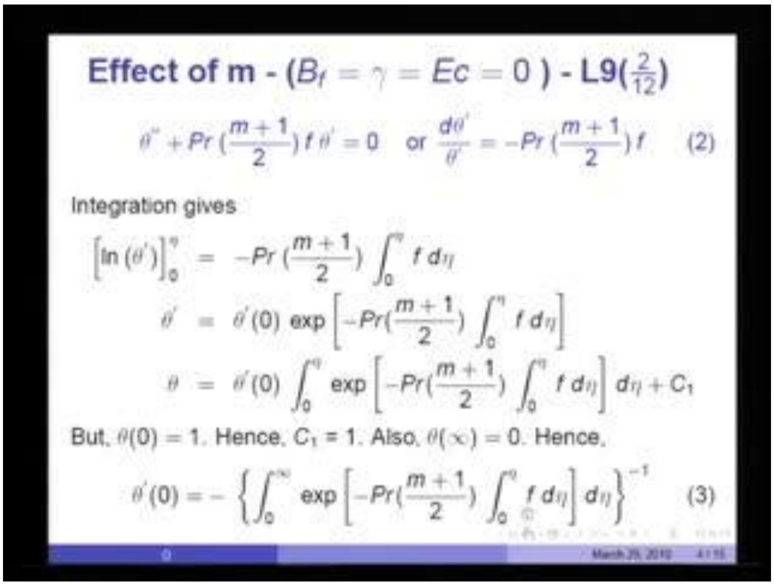

That is what I have shown here: f eta would be approximately equal to f double prime 0 m eta square by 2. So, if I now include this solution in this, here, which is an approximate solution to the velocity, in this I can readily evaluate minus theta prime 0 and that is what I have done.

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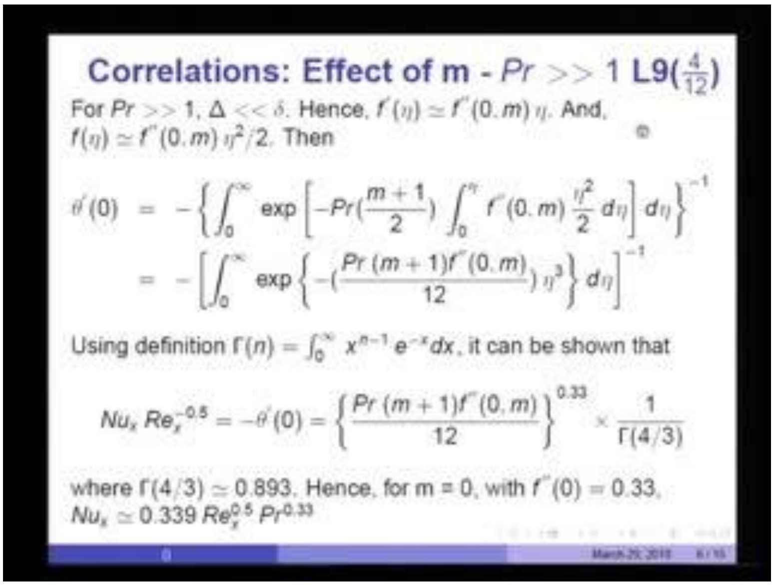

So, if I substitute f double prime 0 m eta square by 2 for f, then I get that. This would simply transformed to minus Prandtl m plus 1 f double prime 0 m divided by 12 into eta cube because this is equal to eta square is eta cube by 3 2 into 2 is 4 into 3 is 12 into d eta minus 1.

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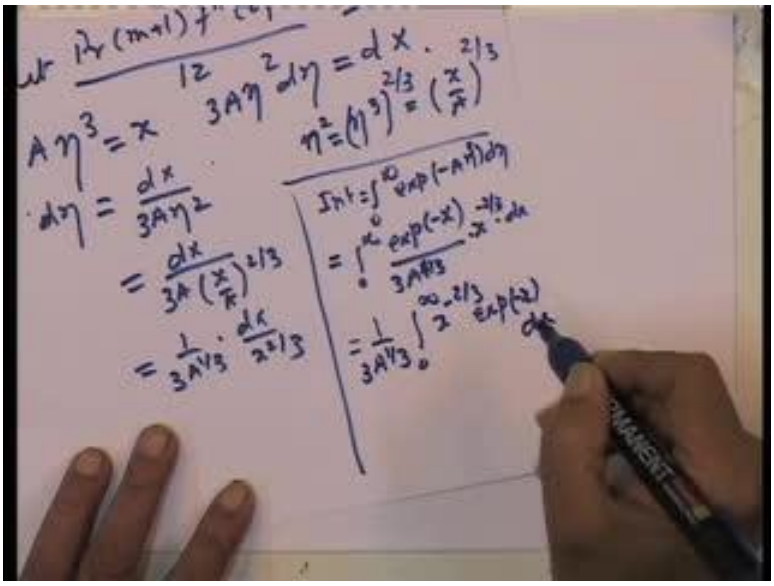

Now, if I use the definition of this and that is what I will show you how to evaluate that integral, it is not a very difficult thing to do, but we will none the less do that. So, for the moment let us say, let Prandtl m plus 1 f double prime 0 m divided by 12, let us say it is equal to A and define A eta cube equal to x. Then 3Aeta square d eta will equal d x and therefore, d eta will equal d x divided by 3A eta square and eta square will be equal to eta cube raised to 2 by 3 and that will equal x by a raised to 2 by 3. I get d x divided by 3A into x by A raised to 2 by 3 into 1 over 3A by into 1 by 3 into d x over x raised to 2 by 3.

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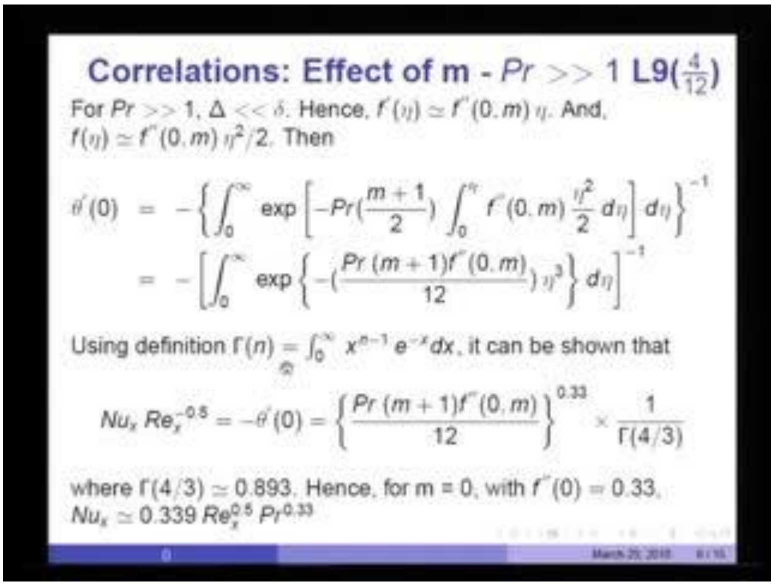

Therefore, our integral is simply 0 to infinity exponential of minus A eta cube d eta. Can be written as 0 to infinity exponential of minus x into 3A raised to 1 by 3 into x raised to minus 2 by 3 into d x or this is equal to 1 raised to 3A raised to 1 by 3 integral 0 2 infinity x raised to minus 2 by 3 exponential of minus x d x.

Now, if you recall the definition of gamma function that is given as 0 to infinity x raise to n minus 1 e raised to minus x d x. So, in our case n is nothing but n minus 1 is equal to minus 2 by 3, and therefore, n will be equal 1 minus 2 by 3 equal to 1 by 3.

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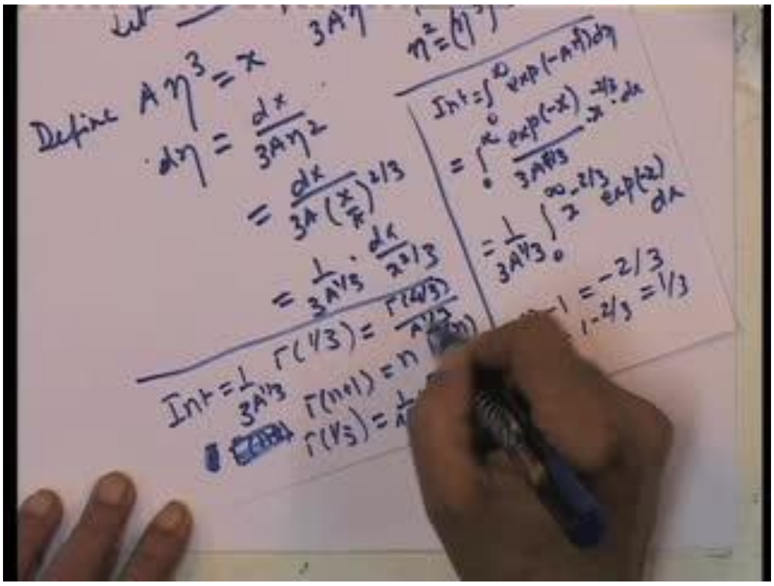

So, essentially we have integration - integral itself is equal to 1 over 3A raised to 1 by 3 into gamma times 1 by 3. But, usually gamma functions are plotted for values of gamma greater than or equal to 1, and therefore, we make use of the relationship that gamma n plus 1 is also equal to n times gamma n. So, in other words gamma 1 by 3 can be written as 1 over 1 by 3 into gamma 4 by 3 or that is equal to 3 times gamma 4 by 3.

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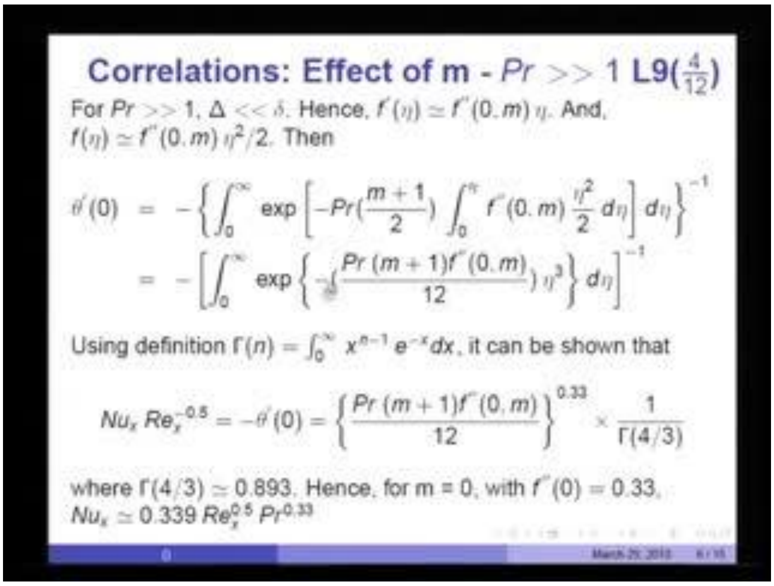

This is gamma 4 by 3, and therefore, you will see our integral can be written as gamma 4 by 3 divided by A raised to 1 by 3. The integral itself will become minus theta prime 0 A raised to 1 by 3 divided by gamma 4 by 3 because this is raise to minus 1. So, this goes into the denominator and the A goes into the numerator and this is the solution. (Refer Slide Time: 16:32) The value of gamma 4 by 3 you can look up the tables of course this is about 0.893. So, if you look at m equal to 0, if I put m equal to 0 and recall that for m equal to 0, f double prime 0 is 0.33 and use this equal to 0.893. Then you will see a correlation is possible for very high Prandtl numbers Nu x 0.339 Re x to the 0.5 Prandtl third.

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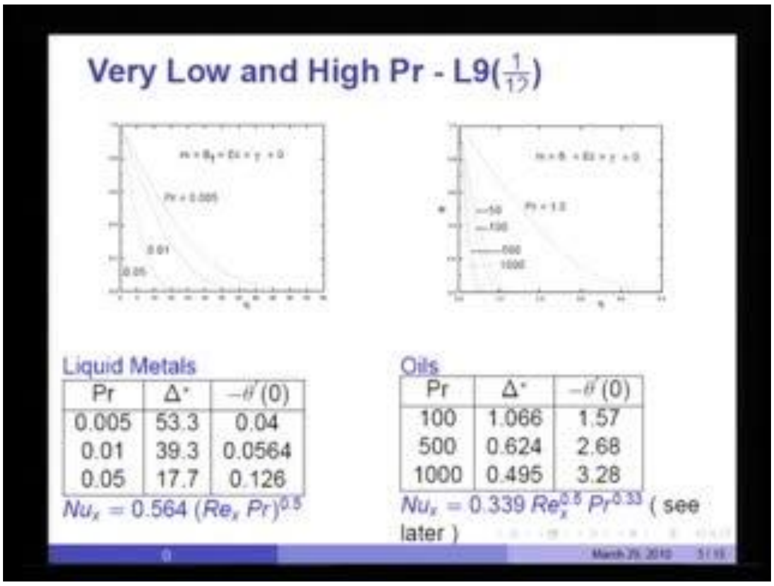

Now, I had curve fitted the solutions exactly in the same manner, here, for oils as you will see here 0.339 Re x to Prandtl third. These are numerical solutions and this is obtained from our assumption that the velocity profile is linear. So, this kind of an assumption helps you to evaluate close form solutions which we can call as correlations, but you can do this for any value of m for which f double prime 0 m has been calculated from the Velocity Boundary Layer solution.

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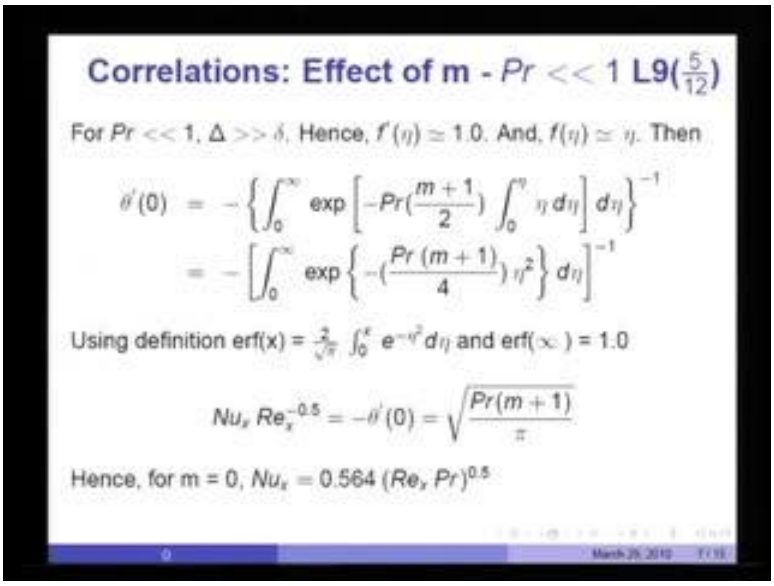

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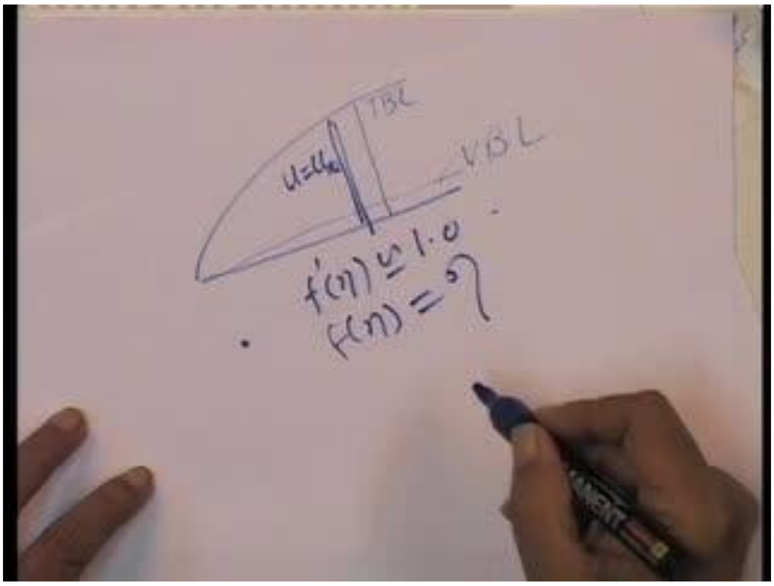

Likewise, let us look at the case of very low Prandtl number in which case as I said the Velocity Boundary Layer thickness will be solved and the Temperature Boundary Layer thickness will be solved TBL and this will be the VBL.

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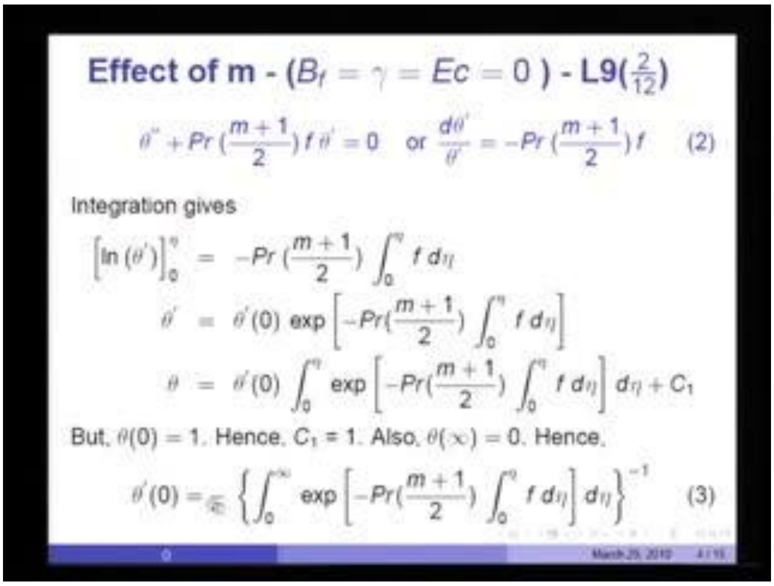

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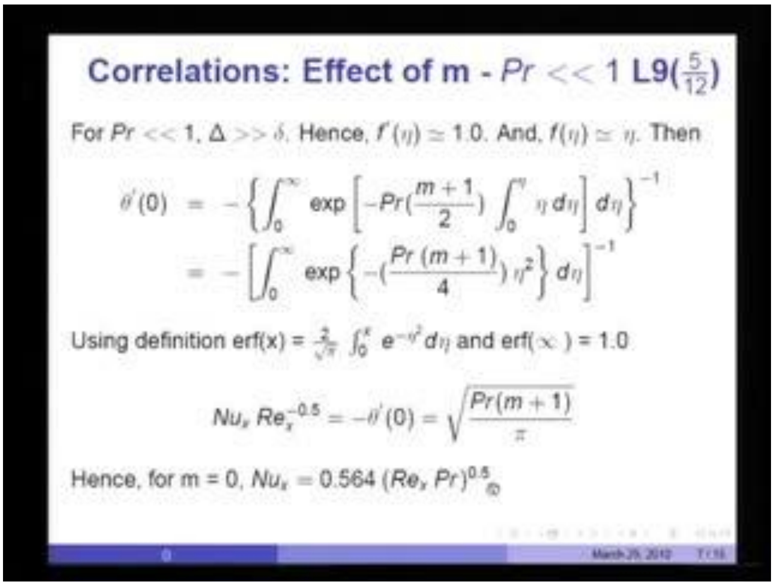

So, you will see for greater part of the thickness of the boundary layer u is, in fact equal to u infinity, and therefore, f dash eta is about 1 throughout the boundary layer which gives me f eta equal to eta itself. In this equation for theta prime 0 if I substitute f equal to eta, then I will get the relationship, and that, this will simply become eta square by 2. So, this becomes Prandtl m plus 1 by 4 eta square whole thing raise integrated raised to minus 1.

If you put this as some y or something like that you can do this, carry out this integration part easily and use the error function definition e erf x is equal to 2 by root pi 0 to x e raised to minus eta square d eta. Then you will see and note that erf infinity is equal to 1. So, then it is very easy to show that Nu x Re x to the minus 5 which is minus theta prime 0 will simply be equal to Prandtl m plus 1 by pi and that is what you see again for m equal to 0. You will see this becomes simply Prandtl divided by pi and as a result 0.564 Re x Prandtl.

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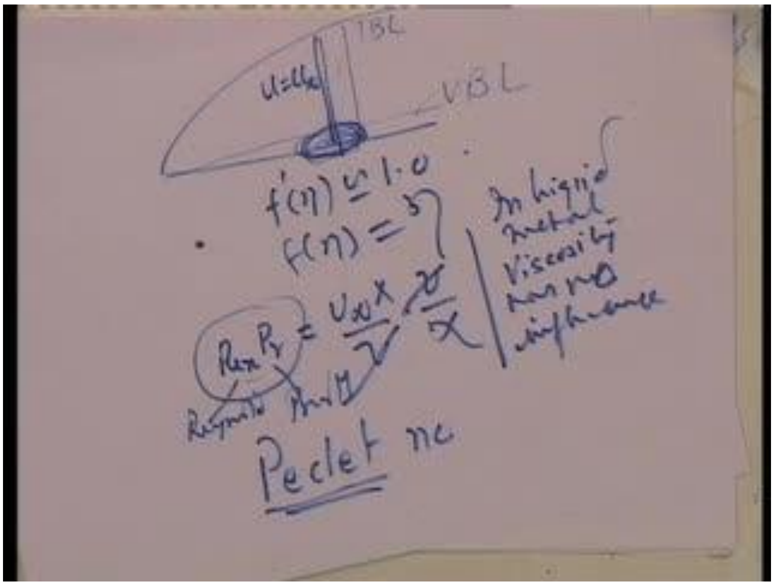

The great thing about this solution is the following at liquid metals - for liquid metals you see both the exponent of Reynolds number and Prandtl number is identical. Now what does that mean Re x and Prandtl that is U infinity x by nu into nu by Prandtl nu by alpha, the thermal. So nu and nu gets canceled, that means in liquid metals viscosity has no influence and that matches with the idea that viscosity is really if its effect is confined to such a narrow region of the thermal boundary layer thickness, that viscosity simply has no effect on the rate of heat. This resolve is very typical of liquid metal heat transfer. Whereas, for all the other higher Prandtl numbers, you will always get a separate effect of Reynolds and Prandtl number.

But here incidentally this product - this is Reynolds numbers, this is Prandtl number, but the product Reynolds, Prandtl is called Peclet number. Peclet was the French scientist and Peclet number is of importance in liquid metal heat transfer. Liquid metals, as you know are used in very high heat flux heat transfer cooling such as breeder reactors, and others.

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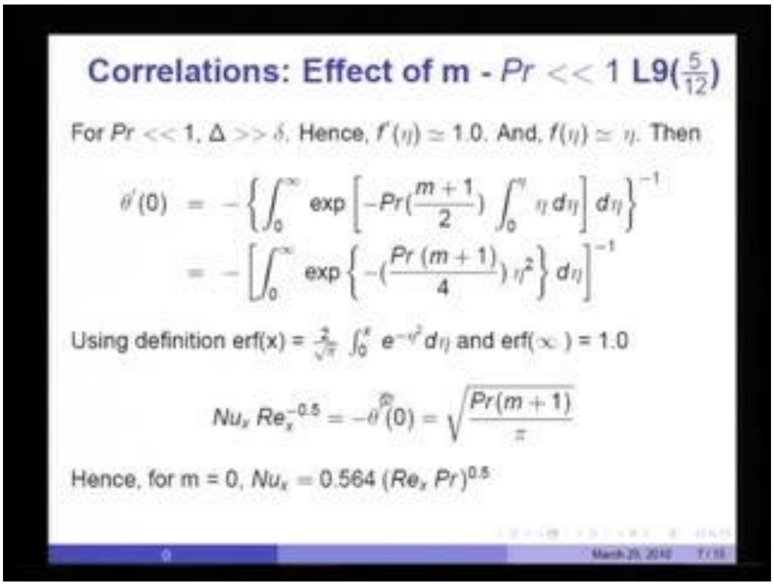

So, these kinds of solutions are great value and the constant is 0.564. If you recall, I will go back to the numerical solution that we had obtained.

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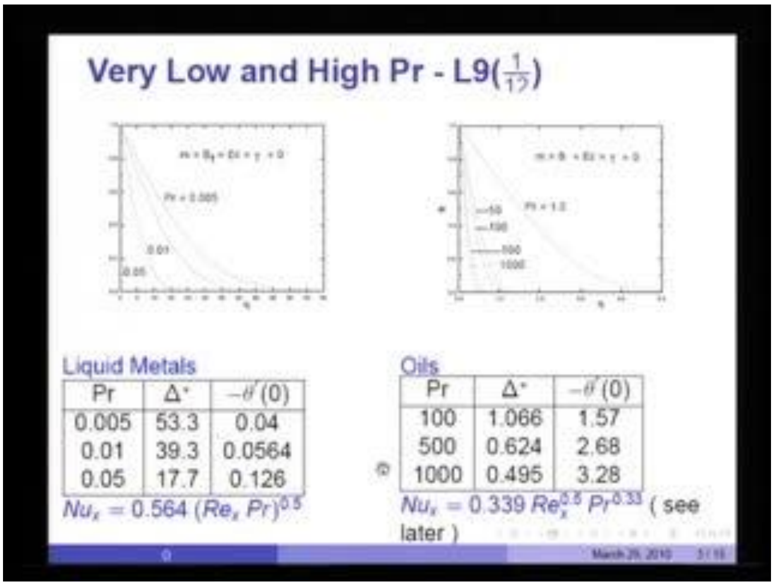

Indeed, the solutions at very low Prandtl numbers do match this correlation here and that is precisely where it comes from.

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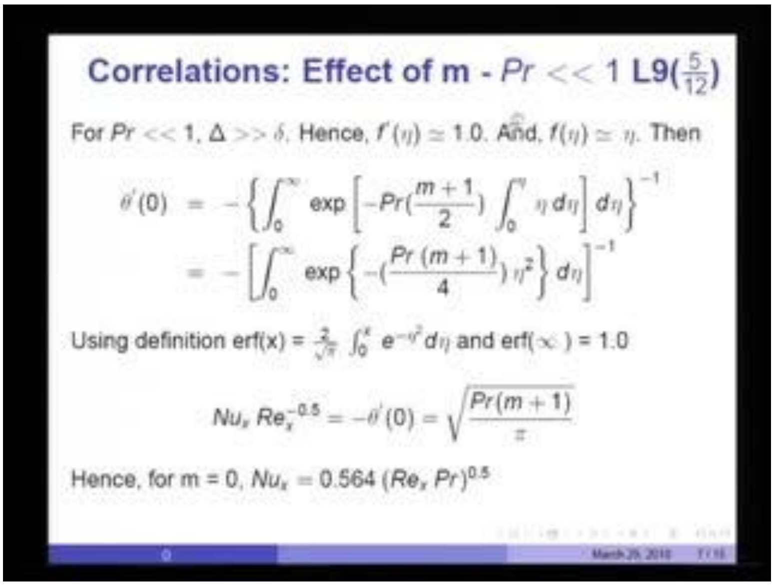

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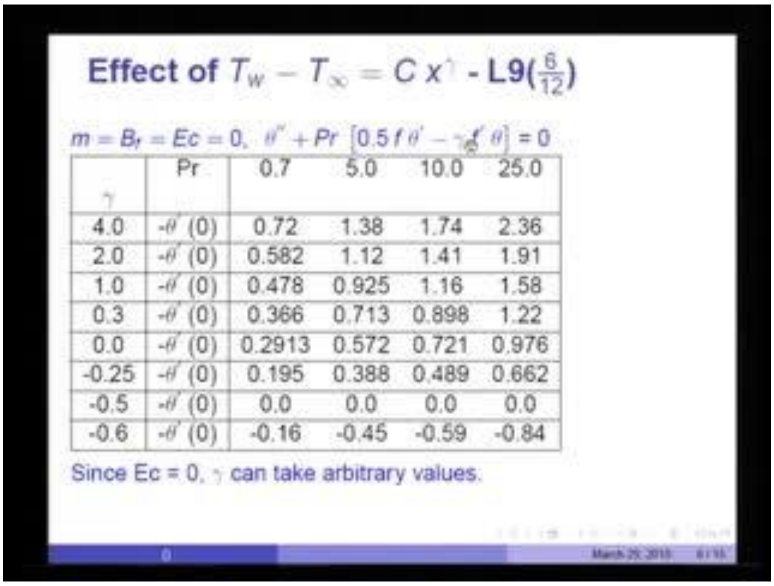

It comes from this assumption that f dash eta is about 1. So, having studied the effect of m, the pressure gradient and Prandtl number **are** high and low Prandtl number; under essentially constant wall temperatures, no suction, blowing and no viscous dissipation. We now move to the case of looking at effect of wall temperature variation. Again I am going to considered the flat plate boundary layer, no suction or blowing, and viscous dissipation is neglected.

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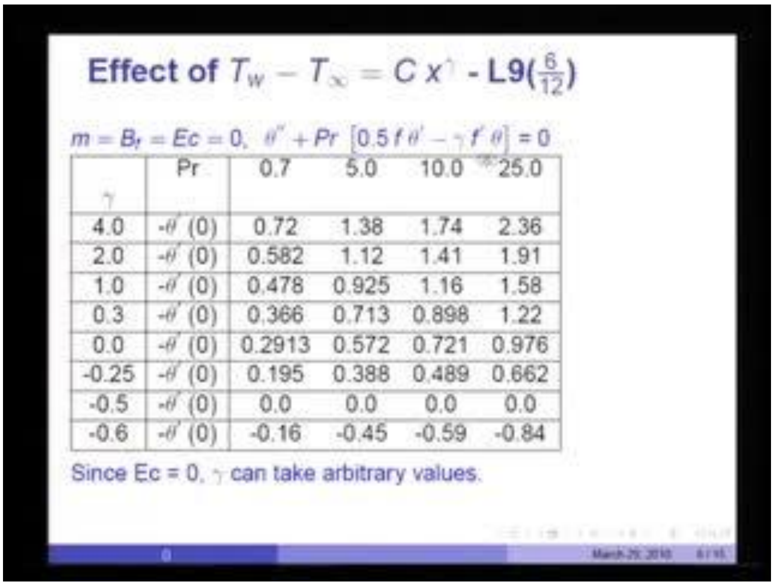

Then the governing equation, read something like this. Now, there is no close form solution possible for this because of this additional extra term and I need to now look at the numerical solution which I have presented here from very moderate Prandtl numbers wall temperature variation. Gamma positive indicates that the temperature of the wall is increasing with x; whereas, this indicates that the temperature is decreasing with x; negative value of gamma indicates the temperature is decreasing with x.

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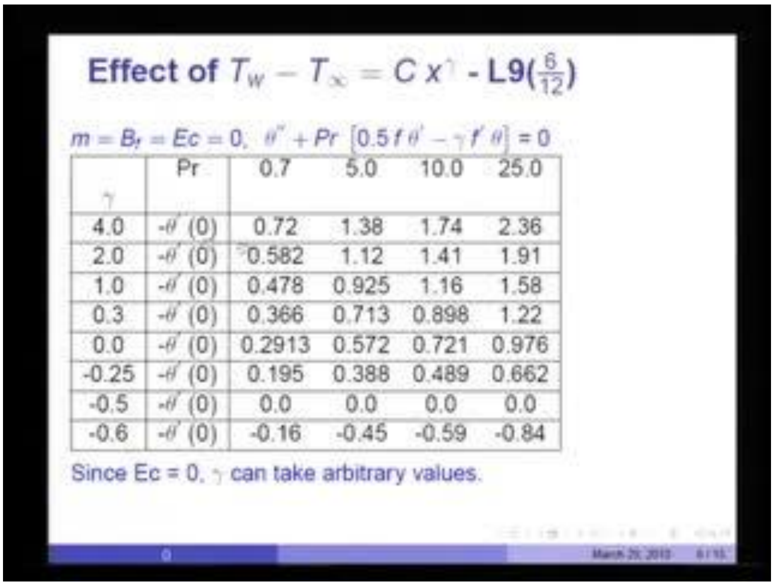

So, what do we find? Let us look at results at any 1 Prandtl number and you will see compared to gamma equal to 0 where wall temperature is constant. There is as gamma increases, this wall temperature increases in the x direction. Then, so does the Nusselt number or the solution which is minus theta prime 0 increases, when the temperature decreases with the x. You, in fact the heat transfer decreases and in fact you heat the situation at gamma equal to minus 0.5, where there is absolutely no heat transfer. This is called the adiabatic case. If you reduce gamma, still further, then you will actually get negative heat transfer although the wall temperature is bigger than the free stream temperature, you will actually get a negative heat transfer.

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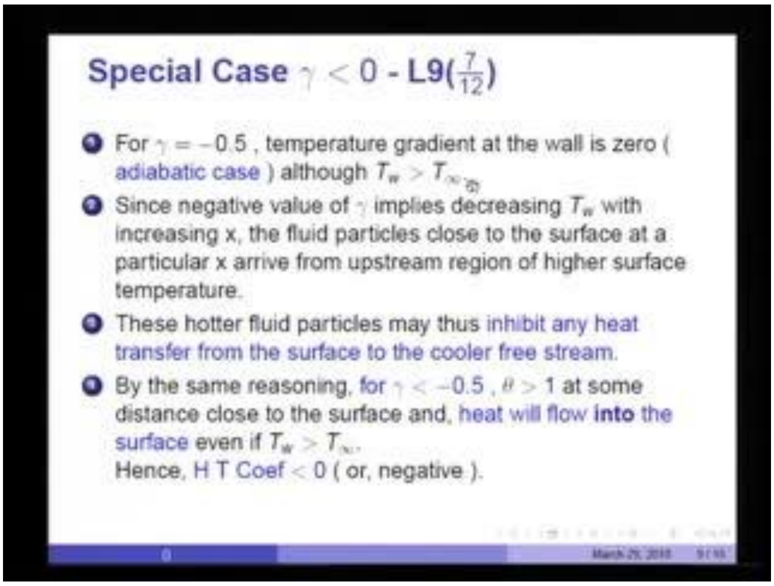

Now, I have allowed gamma to take any arbitrary values simply because Ec is equal to 0 and we did say that gamma is restricted to 2 m only when Ec is included. We have not included Ec, and therefore, this is a remarkable result that when the wall temperature decreases with x, you could get a situation of adiabatic heat transfer or in fact even negative heat transfer. We did alert in the beginning that we are interested in looking at situations like this. For gamma equal to minus 0.5, temperature gradient at the wall is 0 is an adiabatic case although T w is greater than T infinity.

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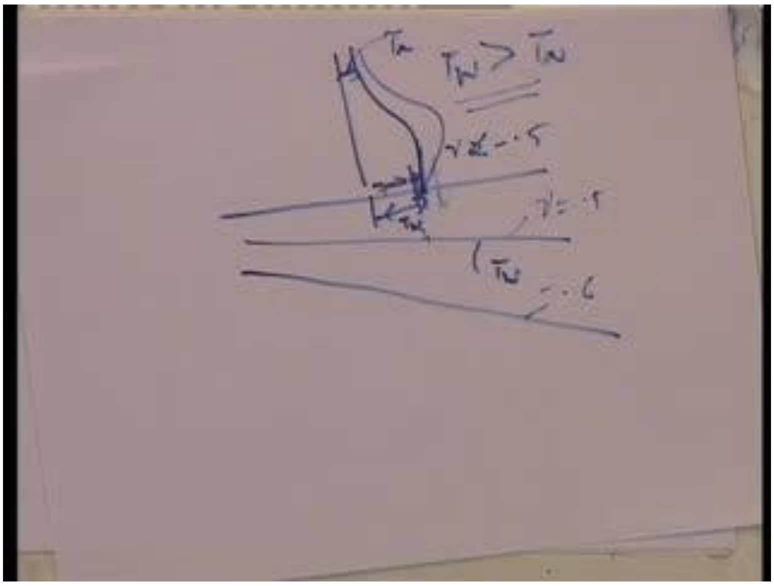

Now, we can explain this why this happens. So, let us take our flat plate and the wall temperature is now decreasing with x. This is the wall temperature. So, you can imagine at any x, the particles close to the surface would arrive from a region of higher temperature, so much so, that the convicted heat into the layer, the temperature here could well become absolutely equal to the temperature of the wall at that point.

So, in effect I get a situation where I have a profile which will look like that. So, basically although T w is bigger than T infinity, I could get a situation where it is like that - if the slope is still negative, this is corresponding to gamma equal to minus 0.5. I could even get a situation which is like that. This is gamma less than minus 0.5; this is, let us say minus 0.6 as I have shown. (Refer Slide Time: 25:23)

So, you could get situation where the heat transfer will be going in, although T w is greater than T infinity. The situation arises because the fluid particles coming from the upstream region would be a hotter than the value of the wall temperature itself.

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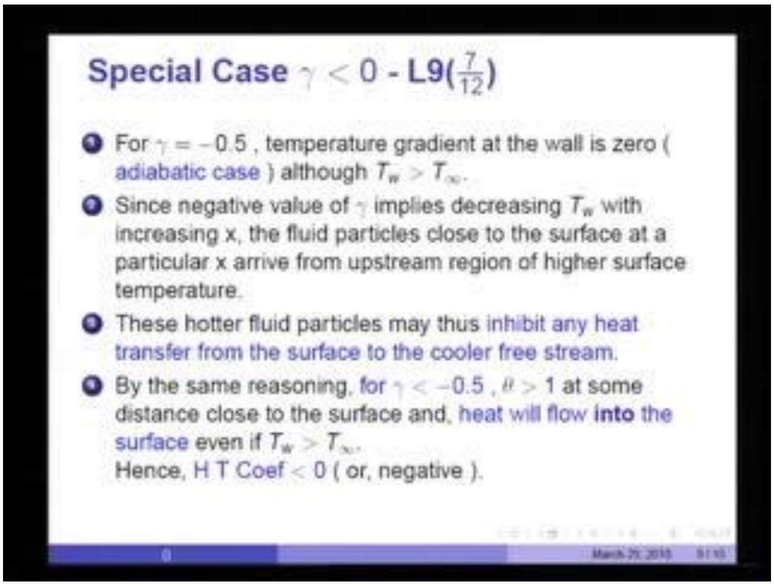

So, these order fluid may thus inhibit heat transfer from the surface to the cooler free stream. By the same reasoning for gamma equal to minus 0.5, theta would increase beyond 1 at some distance close to the surface and, heat will flow into the surface even if T w is greater than T infinity. Hence, T heat transfer coefficient will be negative.

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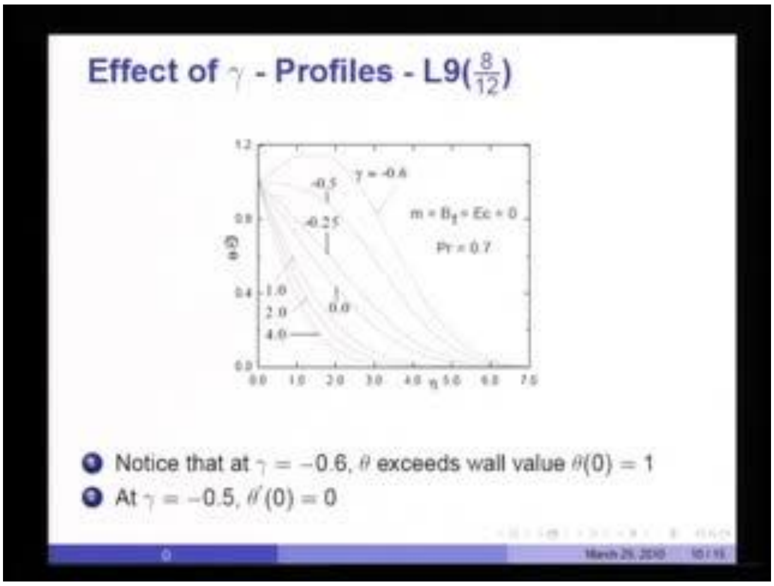

We verify these in the next slide where I have shown effect of value of gamma on the predicted temperature profile. The curve here shows the constant wall temperature case. The Prandtl number is chosen to be 0.7. Therefore, the boundary layer thickness is slightly bigger than 5. Let us look at on the acceleration side, this is gamma equal to 1; this is 2; this is 4; and the U get steeper gradients and near the wall and thinner and thinner Temperature Boundary Layer thickness as wall temperature increasing with x, but on the negative side that is wall temperature decreasing with x, you get a shallow or gradient near the wall, their boundary layer thickness itself goes on increasing at gamma equal to minus 0.5. You can see very clearly the 0 gradients and for gamma equal to minus 0.6, value of theta, at this point has exceeded the value at the wall which was 1. So, our temperature solution does indeed conform what we anticipated.

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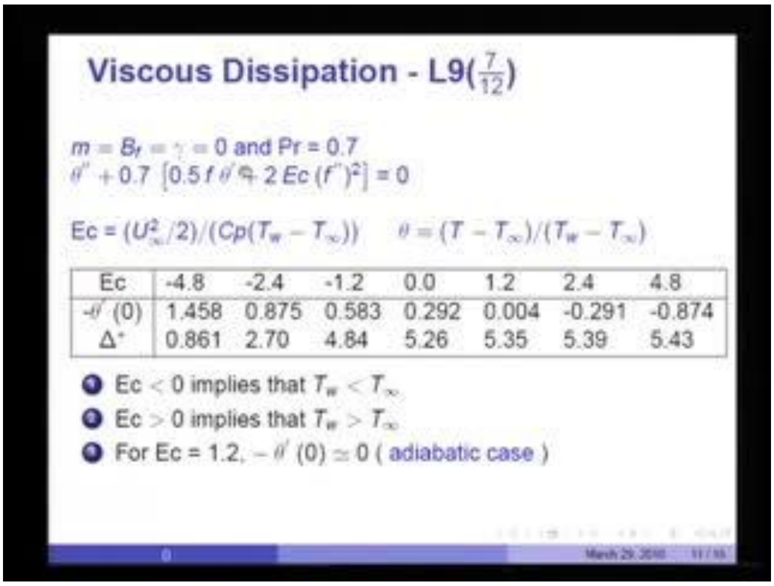

Now, we look at the effect of viscous dissipation and viscous dissipation typically is accounted when you have very high velocity gradients du by dy whole square or when you have very high viscosity which is mu. So, I am taking here a case of Prandtl equal to 0.7 and assuming that the velocity gradients near the wall are very high. Then the solution would be - and the wall temperature is constant, there is no suction or blowing and pressure gradient is 0. Then the governing equation will be this and because the wall temperature is constant, Ec would be simply this and theta is this. (Refer Slide Time: 27:49)

So, Ec less than 0 implies that T w is less than T infinity and Ec greater than 0 implies T w is greater than T infinity. So, here are the solutions to - so this is 0.292 for Prandtl number 0.7 is the value of theta dash 0 with 5.26 as the Temperature Boundary Layer thickness when Ec is positive that is when T w is greater than T infinity. You in fact do find an almost adiabatic situation at Ec equal to 1.2 and negative heat transfer when Ec becomes 2.4 and 4.8.

On the other hand, when Ec is negative that is if T wall is less than T infinity that is a cooling case, then you find that the heat transfer rate increases in the presence of effect of A.

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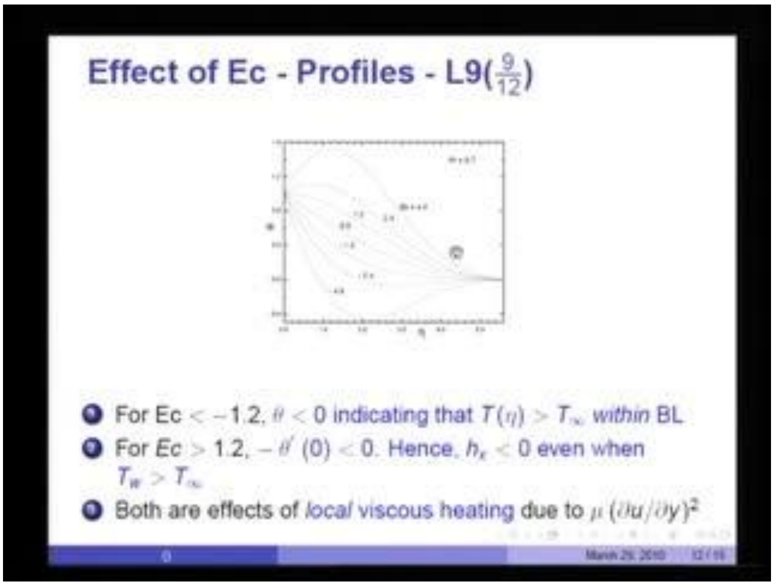

So, Ec equal to 1.2 is a special adiabatic case is a very special adiabatic case and here are the solutions for different values of Ec, the Eckert number. So, here the solution is for Eckert number equal to 0, this is theta dash eta and the wall the value is 1. You do see that at 1.2, the gradient is 0, and therefore, it turns out to be an adiabatic case, and for 2.4 the temperature is exceeded value of 1 and it has exceeded value of 1. So, although T w is greater than T infinity, you will get negative heat transfer for these 2 values of Eckert numbers.

On the negative side, you see the temperature gradient become sharper and sharper because of the viscous dissipation. See at some point, the temperature actually goes below the free stream temperature because it is less than 0. So, just as wall temperature is exceeded for positive, free stream temperature is exceeded. So, Ec less than 1.2 theta is less than 0 at some positions indicating that t eta E can be greater than T infinity within the boundary layer and Ec greater than 1.2 minus theta h x is less than 0 even when T w is. Both these are effects of viscous dissipation due to mu du by dy square. This kind of viscous heating is of great concern. A viscous heating effect is from re-entry vehicles of into the space and from the space into the upper atmosphere. When sudden increase in viscosity of the atmosphere would generate and the re-entry vehicle is hurtling down at very high velocities of the order of 5 to 6000 meters per second. You get enormous velocity gradients very close to the wall, and as a result, the viscous dissipation term becomes very dominant.

You would generate large amounts of heat. If the effect number turns out to be bigger than 1.2, then you could well get heat transferred into the re-entry vehicles surface a dangerous. That is why the re-entry vehicles are coated with a bleating materials, so that when the heat transfer takes place inside and the surface temperature goes up the material evaporates and carries away the heat of which has been in grace from the outside into the wall of the re-entry vehicle. So, study of such effects is of great consequence in practice.

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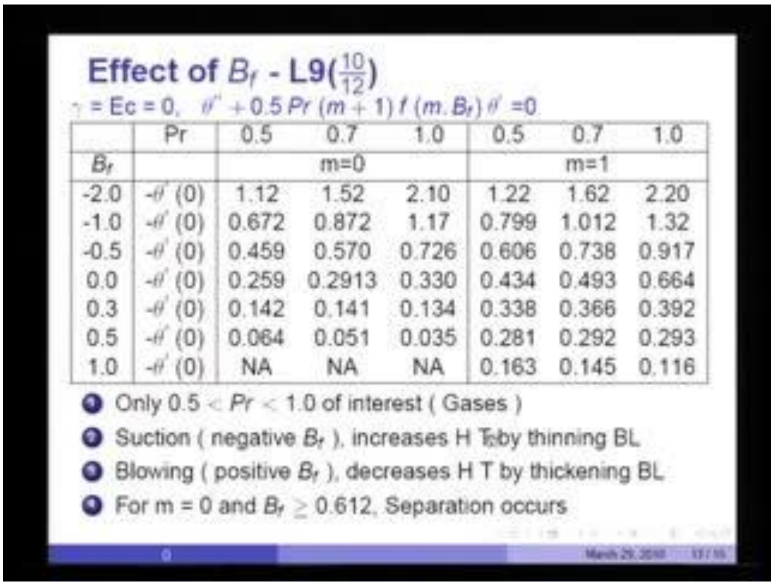

	Pr	0.5	0.7	1.0	0.5	0.7	1.0
B_f			m=0			m=1	
-2.0	$-\theta'(0)$	1.12	1.52	2.10	1.22	1.62	2.20
-1.0	$-\theta'(0)$	0.672	0.872	1.17	0.799	1.012	1.32
-0.5	$-\theta'(0)$	0.459	0.570	0.726	0.606	0.738	0.917
0.0	$-\theta'(0)$	0.259	0.2913	0.330	0.434	0.493	0.664
0.3	$-\theta'(0)$	0.142	0.141	0.134	0.338	0.366	0.392
0.5	$-\theta'(0)$	0.064	0.051	0.035	0.281	0.292	0.293
1.0	$-\theta'(0)$	NA	NA	NA	0.163	0.145	0.116

Now, we look at finally the effect of B f, the suction and blowing parameter and I am going to consider again the constant wall temperature and ignore viscous dissipation, but I will allow offer effect of Prandtl number and B f's. So, we are looking at 3 parameters here - B f, Prandtl number, and m. I am restricting this to the case of gases, because these B f cases are of interest in gas turbine cooling problems.

So, you will see in suction case, when B f is negative compared to B f equal to 0 which has no suction and I am looking at a flat plate solution. Then, when there is suction, there is increase in heat transfer, but when there is blowing, there is a decrease in heat transfer.

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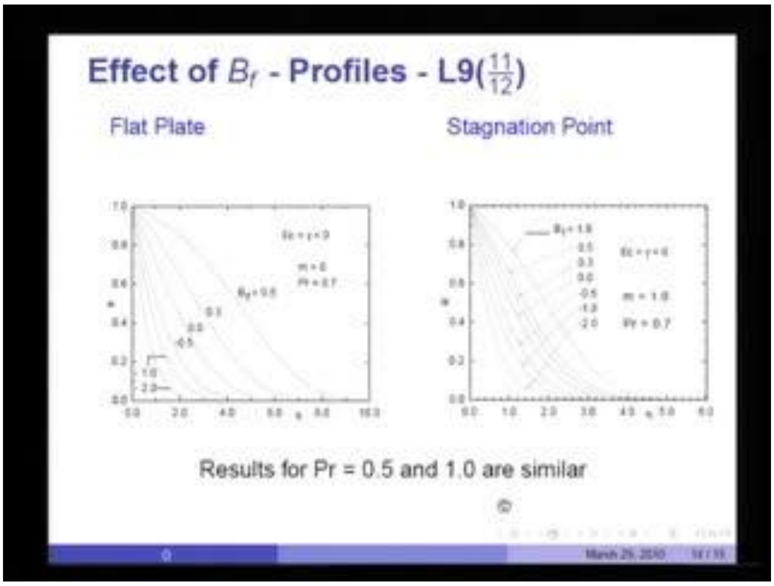

You will note - recall that B f equal to 0.612 was the case where separation occurs. So, we are not interested in B f equal to 1, but we are interested for m equal to 1 in which you will see that the again the same thing prevails, that the heat transfer increases on the suction side, whereas, heat decreases on the blowing side. This essentially occurs because the thickening and thinning of the boundary layers associated with suction or blowing. Suction thins the boundary layer, and therefore, increases the rate of heat transfer. Blowing thickens the boundary layer, and therefore, lowers the heat transfer coefficient. For m equal to 0, B f equal to 0.612 is a very special case and that is where the separation occurs.

You will see on the next slide, the graphs, these are the flat plate solutions and these are the stagnation point solution. This is B f equal to 0.5, 0.3, 0, minus 0.5, 1, and 2; as I said B f equal to 0.612 is an adiabatic case. You will see on the suction side, we get very large temperature gradients and on the blowing side, we get shallower temperature gradients compared to m equal to 0.

Now, if I were to compute this for Prandtl number 0.5 or 1, the results are very similar, and therefore, not shown here.

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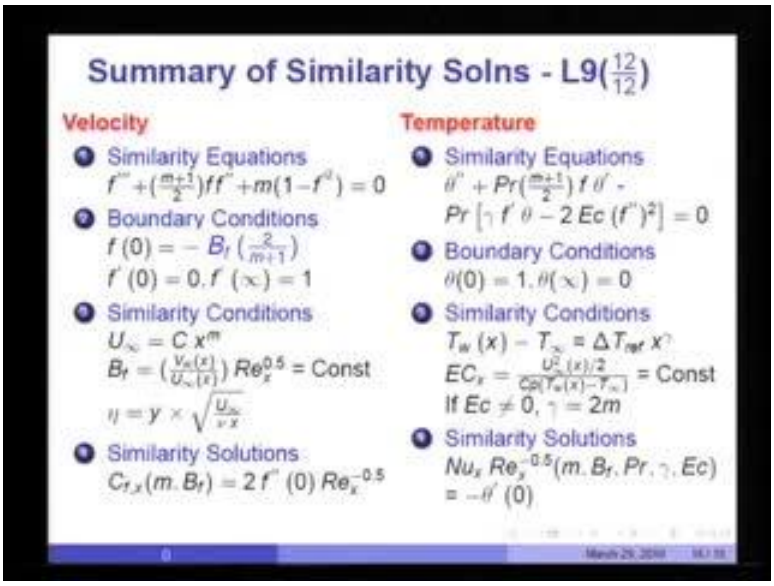

So, with this I conclude my discussion on the Similarity method as a whole, and therefore, it is time that we looked at the summary of the equations in the boundary conditions. For the Velocity Boundary Layer, similarity equation is this - f triple prime plus m plus 1 f f double prime plus m 1 minus f times square equals 0, where m is the pressure gradient parameter.

The suction and blowing parameter comes in through the boundary condition f 0. The similarity conditions or the variables are U infinity is equal to C x raised to m B f v w x u infinity x Re x to the half must be constant and the variable eta must be y under root U infinity by nu x and the similarity solutions are C f x m B f which is the function of m and B f equal 2 times f double prime 0 Re x to the minus 0.5.

Likewise, the temperature equation is theta double prime into Prandtl m plus 1 by 2 f theta prime minus Prandtl into the wall temperature gradient parameter in and the viscous dissipation parameter. The boundary conditions are simply, this theta 0 is equal to 1; theta infinity is 0. The similarity condition is that the wall temperature can vary only as x to the power of gamma. If Eckert number or the viscous dissipation is present, however, gamma must remain equal to m, and the similarity solutions as a whole are multi parameter solutions involving pressure gradient, m Prandtl number, suction, and blowing parameter, wall temperature, and Ec that is what I have shown. We have seen a wide variety of the solutions of this type. It is not very difficult to write computer programs both for solving the Velocity Boundary Layer equation as well as the Temperature Boundary Layer and I have already given you the method in the last two lectures. So, I suppose with that I conclude my discussion of Similarity method. In the lectures to follow, we will take up integral methods of solving boundary layer equations.