Modeling of Tundish Steelmaking Process in Continuous Casting

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Lecture - 26
Introduction to Heat Transfer Phenomena

Welcome to the lecture on Introduction to Heat Transfer Phenomena. So, as we are going to have the study on the tundish flow. So, in tundish, there is a flow of molten steel or you know any molten metal which is at very high temperature. And since it is flowing, so we have studied about the basics of the fluid flow phenomena.

Then, also in that flow we talked about the turbulence and we had some idea about how to model this turbulence because of the turbulence certain extra terms are coming in those equations. So, how to model them. So, that we have studied in the you know earlier lectures. Now, we will have to have a some fundamental understanding about the heat transfer phenomena because the heat transfer is an essential part of that process. Heat transfer will be taking place by different modes and that affects the process that affects the flow configuration also in many cases.

So, we need to have the understanding about the heat transfer phenomena. Now, coming to the heat transfer as you know, there are basically three modes of you know heat transfer and that is conduction, convection and radiation. So, as you know that you know whenever there will be a you know gradient of temperature will be there. So, when there will be change of temperature there in the body. So, there will be you know transfer of energy task will be there from higher temperature towards the lower temperature side and you know that is your conduction.

Then, we will talk about the convection where because of the you know fluid motion or fluid in contact comes into picture. So, that time you have convection and then you have the radiation. So, that is because of the electromagnetic radiation which is emitted by the temperature maintained at higher you know by the body maintained at higher temperature.

So, you have three modes and all these three modes are active in the case of the steelmaking process. For example, if you talk about a normal tundish. So, you have the inlet and then, you have the you may have the outlet. So, this is your inlet and these are the outlet.

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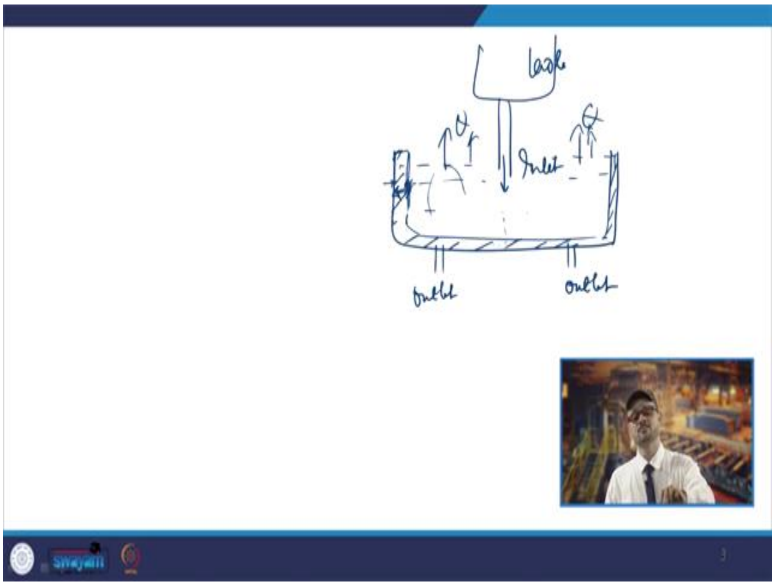

So, what happens that the high temperature metal which is coming. So, you have a you know ladle here. So, from the ladle your high temperature metal will be coming and getting poured into the tundish. Now, this will be striking at this point and then, it will be going and moving inside. So, they will be having contact with these walls of the tundish.

Now, these tundish walls are normally refractory lined, but still there is heat transfer taking place. So, those heat transfer which is taking place from here. So, the heat transfer in between these places which take place there and then, also heat transfer it should be there are the surface because of the fluid motion. So, that will be a convection further and then, the heat transfer is also taking place from these surfaces.

So, from the here, it is the heat will be going out. So, they will be normally by the in the form of a electromagnetic radiation that is by radiation mechanism. So, all these three kind of you know heat transfer modes are there in the case of tundish and we need to understand and we also will see that where it will be required in our case; basically when we try to solve the equations.

So, we will have the energy conservation equation that we have already seen in our you know previous lectures. So, we are solving for the temperature and that we need to supply these you know the boundary conditions and we need to give that in what way the heat transfer is taking place. So, suppose from the inlet, you will have to specify the temperature of the material or the metal which is going into; but then, the heat transfer which is taking place you know from these walls need to be shown.

So, you will have the heat flux which is there from these walls or from the top surface they need to be provided. So, this will be the input to the model and then, we will get the you know we will have to solve the equation and get the temperature distribution inside the tundish.

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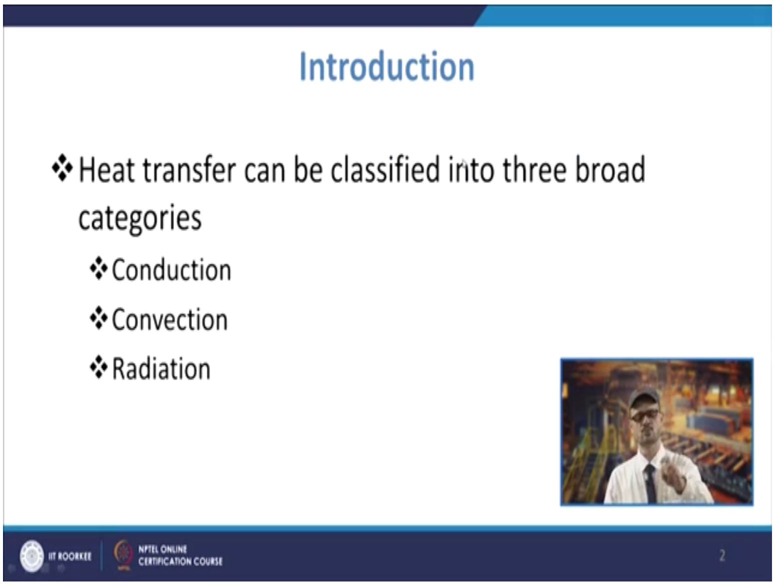

So, coming to the you know conduction.

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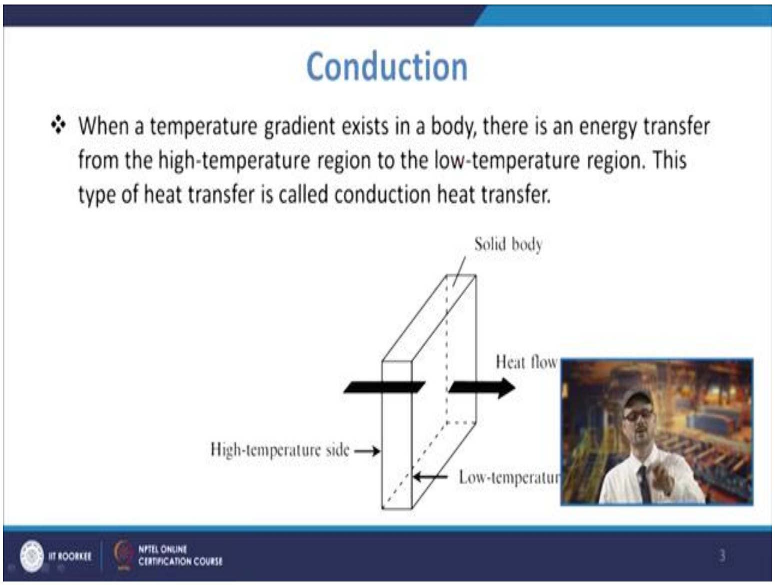

So, the conduction is that when the temperature gradient will be existing in the body. So, there will be energy transfer from the high temperature region to the low temperature region. So, this type of heat transfer is called heat. So, in the body itself you have when you have the temperature gradient, so, just like you can see if you see this tundish if you have a tundish and you have the you know these there will be refractory lining. So, if you talk about the you know lining, now in this case this temperature is quite high and this is closed; this is exposed to the you know external atmosphere so that is surrounding.

Now, in that you will have the typical temperature gradient. There will be you know propagation of heat. So, there will be that will be done by conduction in this because through this material so that is by conduction. So, that is the conduction. So, you have a solid body this one side is a heat temperature side. So, in the case of tundish the face of the wall which is in contact with the molten steel. So, that is having high temperature and the external phase of the tundish which is a steel shell normally. So, that is at a lower temperature.

So, certainly in between you have the refractory material. So, there will be transfer of heat through that medium and that material and from the high temperature to the low temperature region and this type of the heat transfer mode that will be your you know conduction mode.

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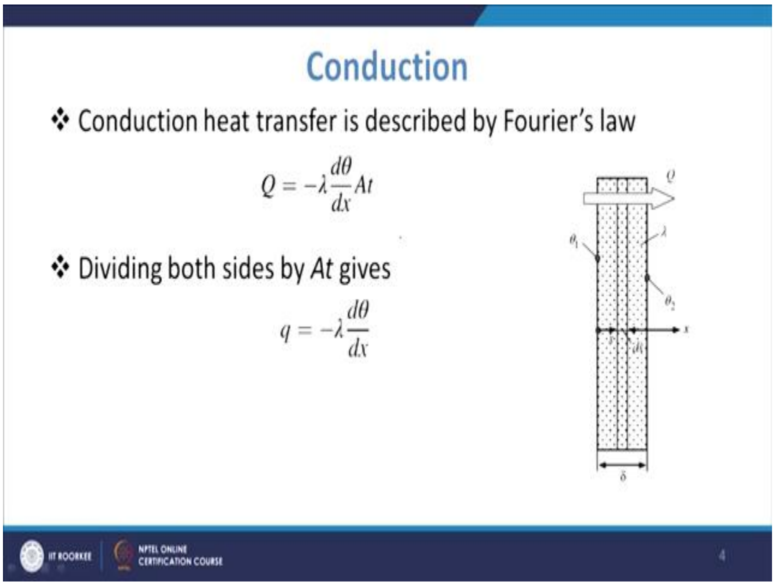

So, in the in conduction normally, now we use the Fourier's law of heat conduction and basically what has been seen that the heat transfer which is there, it will be proportional to the temperature gradient, then area and also the time. So, if you talk about. So, this is dθ is nothing but the theta 2 minus theta 1 is if you have you know a reason, that is the higher temperature side and this is a lower temperature side.

You have the this side the temperature is θ_1 and this side the temperature is θ_2. So, there will be you know flow of heat from this side to this side. Now, that will be proportional to what has been found by Fourier that it is proportional to the temperature gradient. So, how much is the gradient that is dθ and that. So, that is $\frac{d\theta}{dx}$ basically. So, this is $\frac{d\theta}{dx}$.

This is the you know dx for any element, if you take dx. So, this is a length dx, if you take x in this side. So, dx will be a smaller part of it. So, dx incremental part. Then, it will also be proportional to the area of which is there in contact. So, if a higher is the area higher will be the heat transfer. Similarly, higher will be the heat transfer, similarly higher will be the time, it is you know the heat transfer is.

So, if you calculate for higher amount of time, it will be more; there will be more heat transfer. So, then in that case that there was a constant of proportionality added and that constant of proportionality gives you that is λ or many times, we call it as a k also that is the thermal conductivity of this material. So, this way you know we find this q. Now, if you try to have 4 per unit area and also rate of the heat transfer. So, we divide by A and t. So, in that case q will be becoming minus of $\lambda\frac{d\theta}{dx}$.

Now, the minus sign as you know you must have the idea that we normally give this minus sign because $d\theta$ term is negative. So, because θ_2-θ_1.., this term will be negative in this case. So, that is why we are putting it you know minus. So, that you have altogether you will have the positive term. Now, what we need to do when we try to if you try to see the you know tundish in that also we need to so if you are the modeling in tundish flow.

So, in that case you need to have the dimensions of this part; also you need to must you can specify the temperature on this side and temperature on this side and also you need to. So, basically you know if the dimension is known and the temperature is also known on these two extreme sides; then, $\frac{d\theta}{dx}$ will be known and then if you know the k so, or λ. So, that is what is required.

So, that way you can have the conduction heat transfer, you can find in those cases. So, what is what will be required when you go to the modeling of the tundish flow and you are required to give the boundary conditions for the temperature or thermal boundary conditions. So, on the wall you need to specify the material of the wall.

So, if you have the refractory you need to provide the refractory material with the appropriate value of the thermal conductivity. So, that is what the there will be the use will be for the thermal conductivity of the material. So, that will be varying for different materials and you can have the appropriate value of the thermal conductivity of the material.

So, there may be ceramics of different type and you can have the thermal conductivity value from the literature for those you know values. So, accordingly, we try to model the conduction part.

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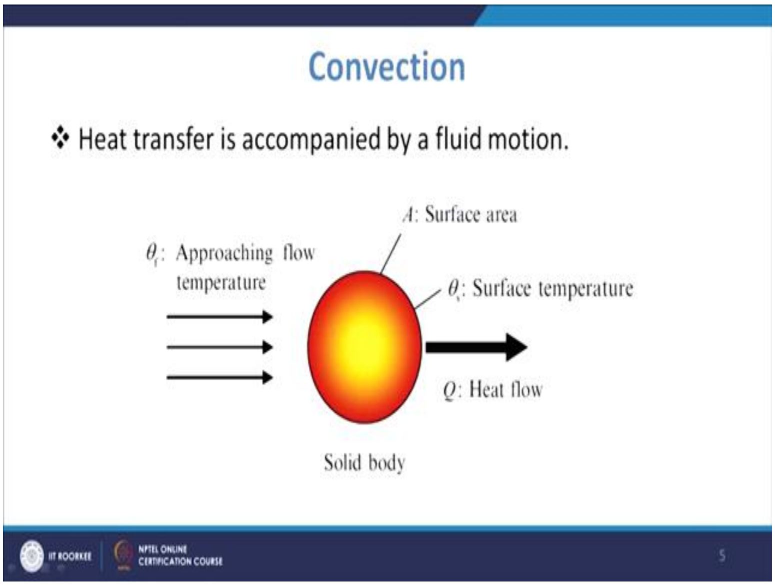

Now, coming to the convection. So, in conduction, we know that we need to have the value of the thermal conductivity and this is the property of the material and that will be required to have the value of the conductive heat flux or conductive heat you know which is transferred heat transfer by conduction. Now, heat transfer is also accompanied by the fluid motion.

So, you will have the this is your surface area A and this you have the surface temperature θ_s. So, and if the Q is the heat flow and you are approaching flow temperature is you know Q_f.

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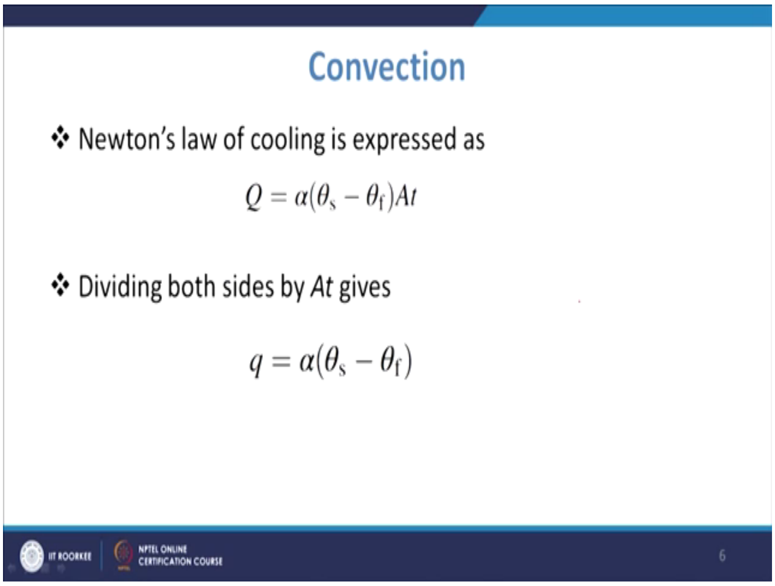

So, in that case what we see that we get the you know expression for the you know heat conducted by the Newton's law of cooling. So, Newton law of cooling tells that q is basically equal to $\alpha(\theta_s - \theta_f)At$. So, again you can have the expression for the $\alpha(\theta_s - \theta_f)$. And in this case, you know we have the term that is the heat transfer coefficient which is coming into picture in such cases in the case of you know convection.

So, you will have these values and we are using this many a times, we also denote it with h in place of alpha; in most of the cases we also try to have. So, heat flux what you see you know q which it will be proportional to the temperature difference here and you will have the values of alpha into theta s minus theta f.

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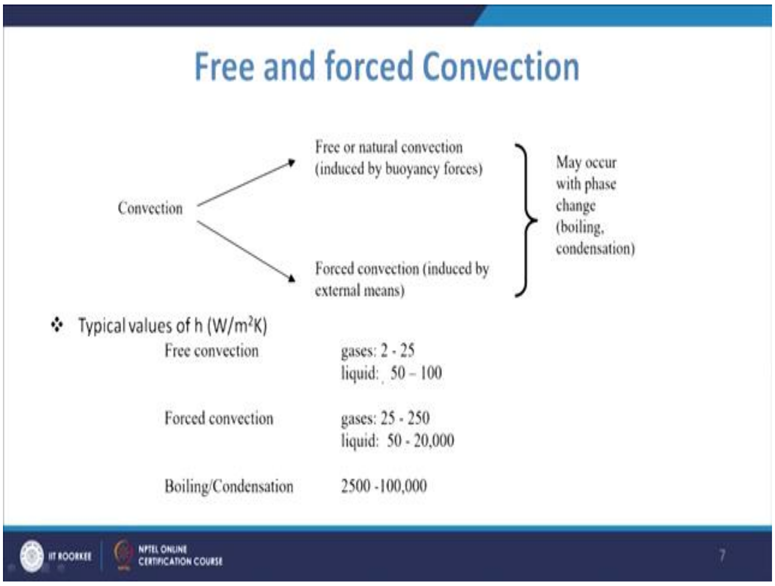

Now, what we need to know that when we talk about the convection, then there are two types of convection mechanism; one is the free or natural convection and one is forced convection, which is induced by the external means. Now, in the case of free or natural convection, you know what happens that because of that so that is basically induced by the buoyancy forces and it is basically in those cases when there will be change in the density.

So in that case you will have and the loop formation or the there will be a convection current which will be generated because of you know those you know natural you know drop in the temperature or because of the change in the density or so. So, that happens so also in the case of tundish, where it has been seen that in case of tundish when you have the temperature difference in the tundish, you know and it is of the significant magnitude, larger magnitude in that case because of that you will have a convection loop which is formed and you that will be affecting the velocity profile in the tundish also.

So, that is because of the buoyancy forces that is induced and they may occur and this free convection or forced convection that may occur with phase change boiling or the condensation processes. Now, if you talk about the free the value of h that is heat transfer coefficient, which is have a unit of watt per meter square Kelvin. So, in the case of free convection your for the gases, you are getting the values as you know 2 to 25 and for the liquids, you have 50 to 100. Whereas, when you have the forced convection, in that case you have the if you look at the value of these heat transfer coefficient, it is a multiplied 10 times as compared to that in free convection for gases.

And then, for liquids also it is going maybe close to more than 200 times about 200 times. So, that is the you know heat transfer mechanism for I mean that is what is required of you know that is how the heat transfer, you know is changed when you have the forced convection taking place. In the case of boiling and condensation that is even more it goes to 2500 to over 100000 water per meter square Kelvin.

So, that is how the heat transfer you can see that how you know these a heat transfer order can be seen to change when you have the different in different way your you know whether the convection is by free mechanism or by the force mechanism. So, in those cases you are having these values.

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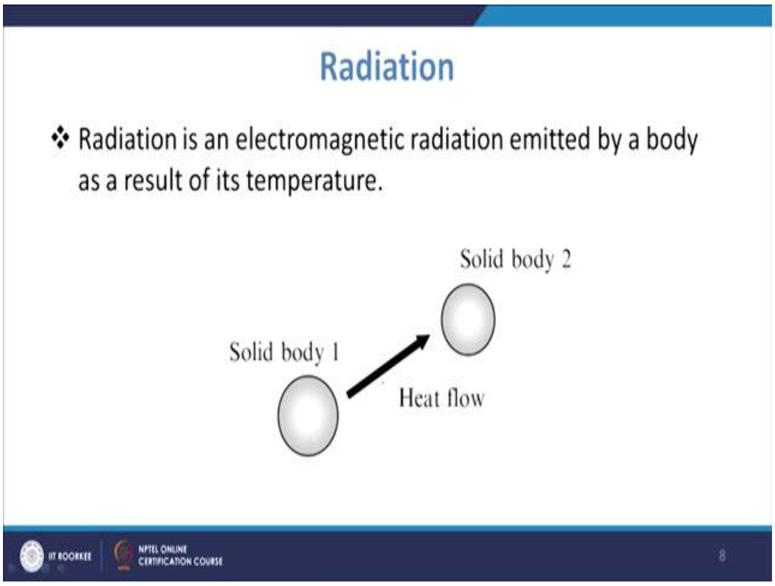

Then, you have another you know part is the radiation. So, radiation is again it is an electromagnetic radiation whereas, it is emitted by the body as a result of its temperature. So, in that case what happens that you have a body which is at higher temperature. So, it will be emitting the radiation towards the body of lower temperatures. So, that is the principle.

So, that basically in terms of so, this flow which is going to take place that is basically in the form of electromagnetic radiation. So, that is why it is called as the radioactive heat transfer. Now, in case of tundish what happens that you have many surfaces which are open. So, you have the top surface of the tundish, where you have slag layer or so which is also at higher temperature.

So, there will be heat transfer taking place from that surface because it is exposed to atmosphere and that is slag is in touch with hot metal and slag is also at very high temperature. So, they will be losing the heat to the surroundings and that is done by the radiation mechanism. So, again here also you will have the similar you know process, but here the temperature you know the exponent which we use on the temperature that is different and that is by this Stefan Boltzmann law. So, that we will see.

So, that way it is changing. So, whenever we are dealing with these you know thermal condition, so in that case you will be asked whether you want to give a condition where there is radiative heat transfer or not. So, that you can you know accordingly you can supply those conditions. So, if you talk about the radiation heat transfer it is basically described by the Stefan Boltzmann law.

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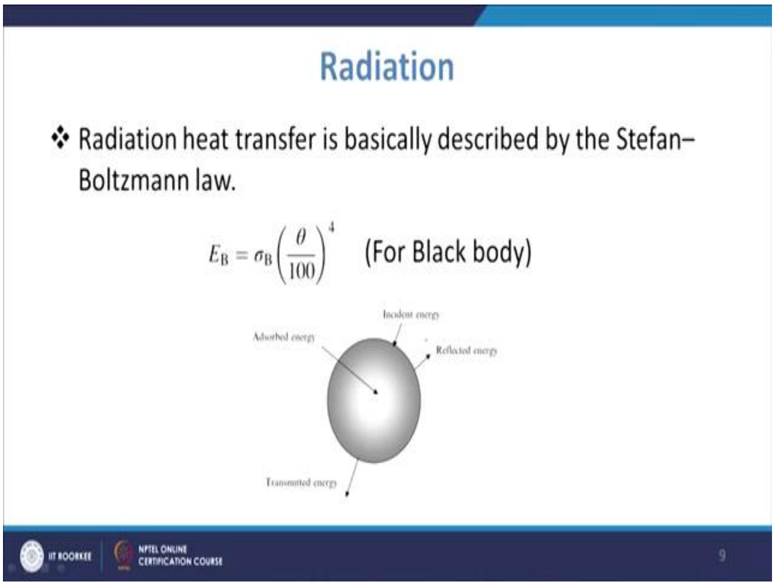

And that is you know by the expression $\sigma_B \, (\frac{\theta}{100})^4$. So, basically that is for the blackbody. So, what happens that normally you have as you see that it will be a function of the you know fourth power of that temperature turn. So, you will have if you look at these material, you have a you know body. So, absorbing you will have instant energy, then you have reflected and then, you have transmitted energy. So, that way we also try to have the radiative heat fluxes. We also try to provide you know on the on those surfaces from where the radiation has to take place.

Now, after that we need to know also few terminologies like you have the hydrodynamic boundary layer and the thermal boundary layer. So, the hydrodynamic boundary layer will be defined as that region of flow, where the viscous forces are felt. So, as we see that you will have a region close to the wall, where you will have the viscous forces are in dominance and that layer. So, you will have the formation of the hydrodynamic boundary layer.

Similarly, you will have the thermal boundary layer also and this is that reason, where the temperature gradients are present in that flow. So, you will have the temperature gradients you know that will be seen in that you know thermal boundary layer. Now, these temperature gradients would result from the heat exchange process between the fluid and the walls. So, that is what we discussed that you have the fluid and the wall. So, you will have you know the heat exchange process taking place between them and because of that these temperature gradients will be resulting into.

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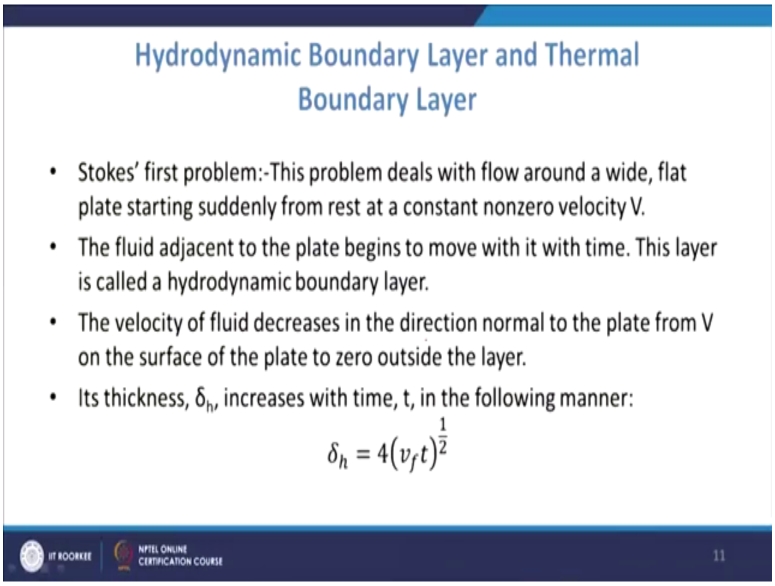

So, normally there has been the description of the hydrodynamic boundary layer and thermal boundary layer by dealing with the stokes first problem and where it is dealt that the you know you know there will be flow around the wide flat plate which is suddenly moved from rest to a constant velocity and then, what will happen that the fluid which is adjacent to the plate will be moving with times, once you are moving. Now that layer which is this layer will be called as the hydrodynamic boundary layer and the velocity of the fluid will be decreasing in the direction normal to the plate.

So, as we know that it will be decreasing in that direction normal to the plate from v on the surface to the plate to 0 outside that layer and the thickness also is found to be increasing with time by this expression. So, δ_h will be $4v_f t^{1/2}$ o. So, that way you are getting this you knowv_f and this is v_f is nothing but the this is kinematic viscosity of the fluid. So, you know if you look at the development of the this is a v_f.

So, this is if you look at the you know hydrodynamic boundary layer formation. So, they are you know they are very much the growth of these a dynamic boundary layer, they are function of these economic viscosity of the mud. So, in that case it is a measure of the momentum exchange of the flow.

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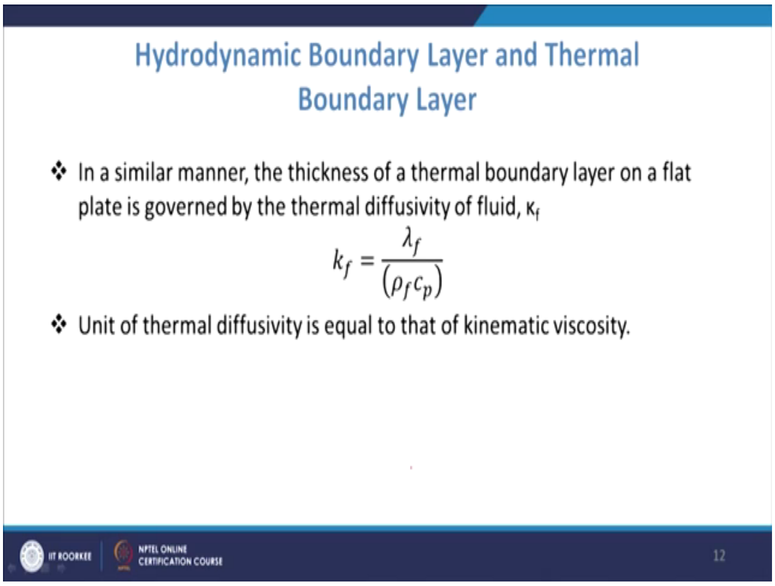

Now, in the same manner, you can have the thickness of the thermal boundary layer also on the flat plate and that is governed by K_f. The properties K_f that is your thermal diffusivity and that is $\frac{\lambda_f}{\rho_f c_p}$.

So, it is also sometimes seen in some terminology, you will be as $\frac{k}{\rho c_p}$. So, k is nothing but λ_f that is a thermal conductivity. Then, this is you know ρ and this is the c_p. So, this ρ is density and this is the specific heat at constant pressure. So, that way you know we try to have these you know thermal boundary layers also. So, that will be governed by these processes.

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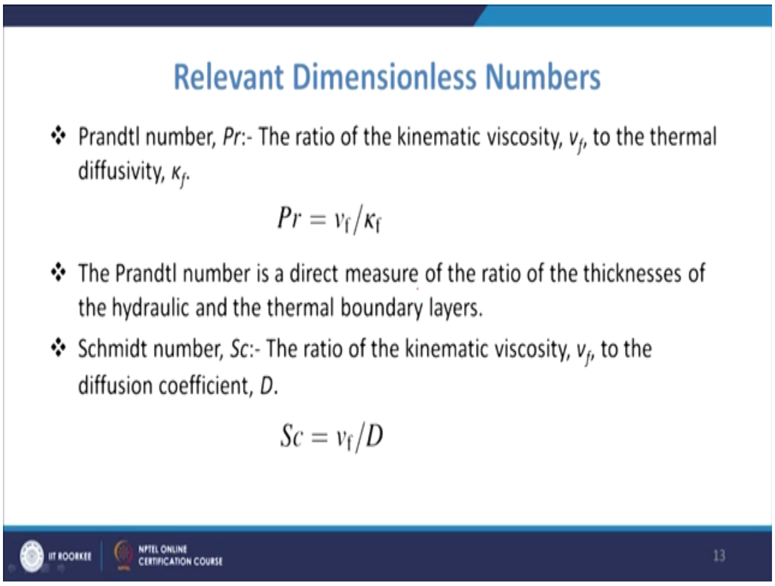

Coming to the different types of you know the dimensionless numbers, which we will be required which will be coming across you know in our study and that will be you know. Firstly, the Prandtl number. So, this Prandtl number is the ratio of the kinetic viscosity that is ν_f to the thermal diffusivity K_f. So, that way we define this $\frac{\nu_f}{k_f}$. So, it is basically the direct measure of the ratio of thickness of the hydraulic and the thermal boundary layer as we have seen.

So, it will be measuring the ratio of the thickness of the hydraulic and the thermal boundary layer. You have another you know relevant dimensionless number that is your Schmidt number Sc and this Schmidt number, it is the ratio of the kinematic viscosity to the diffusion coefficient D, we have already seen earlier also. So, in that case also you take the ratio. So, that is your many a times we have the turbulent speed number and all that.

So, this basically will be talking about the ratio of the kinematic viscosity ν_f to the diffusion coefficient d and this is the Schmidt number. So, these are you know these are the apart from that you will have there are many other numbers which will be coming into picture like when we talk about the you know natural convection. In that case as you know that that deals with the numbers like guess of number or so, and when we deal with that we have already seen that there is another number that is Tundish Richardson number that also is used many a times while we deal with the thermal analysis of the tundish flow.

So, these you know I mean these terminologies will be useful while analyzing the output which we get by after post processing operation. So, in those cases you can have the idea of you know the value of these you know parameters or these numbers and by that you can compare you know the processes or the compare the different cases. Apart from that we will have also we will be dealing with certain phenomenon like the phase change or so that what we had seen earlier.

So, you know you need to also see that how there will be you will have the different models which talk about the phase changes during the heat transfer. So, many cases and mostly in metals when you your temperature goes below certain limit. So, that starts changing two different phase. So, the liquid phase will be changing to the solid phase and in that case, if that phase change is taking place many a times we have the change in the properties when we are there is change in phase.

So, you will have the conductivity values or a transfer coefficient values which is used specific conductivity values will be different when we have the phase change taking place. So, those also need to be looked into so that will be governed by the material properties also because and that will only say that when the temperature becomes lower than that, you will have basically the change of phase from one phase to other.

So, you will have different equations which will be talking about the you know transformation of one phase to other in a gradual manner and then, how the it will be affecting the heat transfer of fluid flow you know in that domain. So, these things may be it used by us in our you know lectures to come, when we deal with that particular situations.

Thank you very much.