Conduction and Convection Heat Transfer

Prof. S. K. Som
Prof. Suman Chakraborty
Department of Mechanical Engineering
Indian Institute of Technology- Kharagpur

Lecture 3

Now convection heat transfer we refer to that mode where usually heat is transferred from a solid surface to a fluid adjusting to the surface, which is a motion.

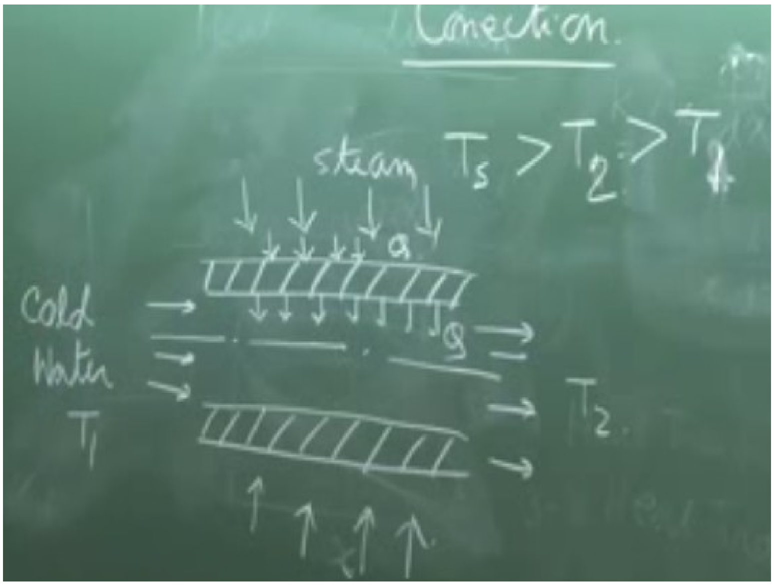
Heat may go from the solid surface to the fluid, heat may come from the fluid to the solid surface. Fluid may be liquid or gases. So, direction of heat flow will depend upon the temperature difference that means it is from the hot surface to a fluid. Tremendous example, I just cite two examples, before that I tell you this type of convection heat transfer where the heat is transferred from fluid from a solid to a fluid or from fluid to solid when there is a fluid adjust into a solid surface and in motion.

The motion can be caused by two ways. One is by artificially that forced, forced flow that means we can have a fan, we can have a blower, we can have a pump depending upon the type of fluids where there it is gas or liquid to flow pass the solid surface. This is known as force convection. But even if we do not have any external aid to cross the flow because of the temperature difference because heat transfer you have to have a temperature difference.

Like (()) (28:41) to get mechanical power you have to have a delta T. Somehow with one first temperature reserver you cannot get work continuously. Similarly, you have to have a temperature difference, so because of the temperature difference a flow naturally occurs without any external aid, this arises because of the density difference and that is known as buoyancy driven flow.

That means which is caused by the difference in density and its direction is a determined by the density variation which direction the density is decreasing or increasing. So, this is known as buoyancy driven flow. As you know, if you heat something from the bottom, this becomes light at the density is reduced and this goes up and the high-density liquid comes down. So, this type of situation where the flow is induced naturally by the density difference or density variation originating from the temperature difference is known as natural convection.

(Refer Slide Time: 29:56)



I will give two examples, consider steam condenser in a power plant. You have read power plant in thermodynamics. Let us consider a pipe through which circulating water flows. Let this is the thickness of the pipe, I am showing with little amplification or enlargement for your understanding. This is a pipe typical condenser pipe, there are a number of pipes one pie where the cold water is flowing like this.

This is cold water at some temperature T1, which is obviously the ambient temperature. We get cold water from ambience and cold water is flowing out, this is the cold water at a temperature T2 and what happens that steam from the turbine flows like this. This direction does not mean that it goes inside the tube. Tube is impermeable. This is of the metal. So, this flows around the tube.

There is a cross flow, the direction of this steam and direction of the cold water. Now what happens, try to understand because of this flow of steam, steam let us consider have a temperature Ts which is greater than T1 which is greater than T2. The steam temperature is the saturation temperature corresponding to the pressure at which we get. Any high temperature at this moment you are bothered much of the saturation state or all these things. Now first of all this heat from the high temperature steam, will heat the surface.

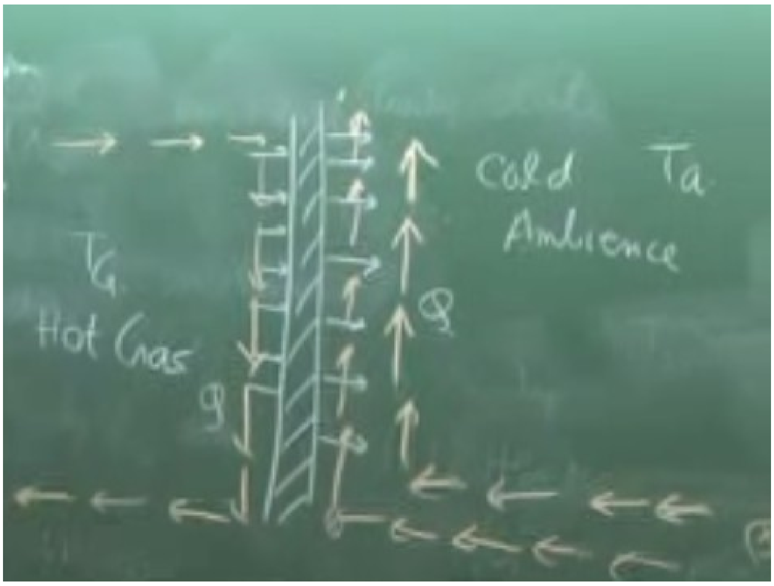
We use any temperature measuring instrument thermocouple or any other temperature measuring instrument we read Ts and we will see that this temperature of this surface were little less that means heat will flow from this steam to this surface and that is the mode known an convection that I will describe just after this. So, this is the convection mode. Then, heat which enters into the tube wall is a solid material it will come from this outer wall to inner wall because of which there is a difference in temperature.

That is the inner wall temperature is little lower than the outer wall temperature and that mode is pure conduction which I discussed, pure conduction. Then, what will happen the heat therefore this is the heat Q and the same heat now at steady state, the same heat will come to the inner fluid from the inner wall. Inner fluid is water. So, this is again convection. So, one convection from steam to this outer surface.

Then conduction from outer surface to inner surface to the solid, then from inner surface to the cold water heat will be transferred by it is just like a relay race. And water will carry this heat or rather advect this energy and goes out with a temperature. I am sorry, I am extremely sorry T2 greater than T1. T2 greater than T1. So, we will come out with a temperature T2, which will be higher than the T1, water will be heated.

And that is an example of force convection. Here we are causing a force flow of the water and here also steam is flowing and there a pressure difference because of this flow this is a forced convection heat transfer.

(Refer Slide Time: 33:57)



Now, another example I tell you that let us consider the wall of a vertical furnace for example the wall. Now what happen there is hot gas, usually outside cold ambience, this is temperature of the ambient is here and this is hot gas TG. The furnace wall loses its heat to the ambience. It is hot but it is cooled naturally. Sometimes, the situation is such depending upon the situation.

We do not require to flow air pasting. This is a furnace wall, this may be a circuit board of an electronic circuit, board of an electronic circuit. So, what happens here also the convection heat transfer takes place from the gas to the inner wall and the same heat is going by convection from the outer wall to the cold ambience. And here a flow is induced like this passed the surface.

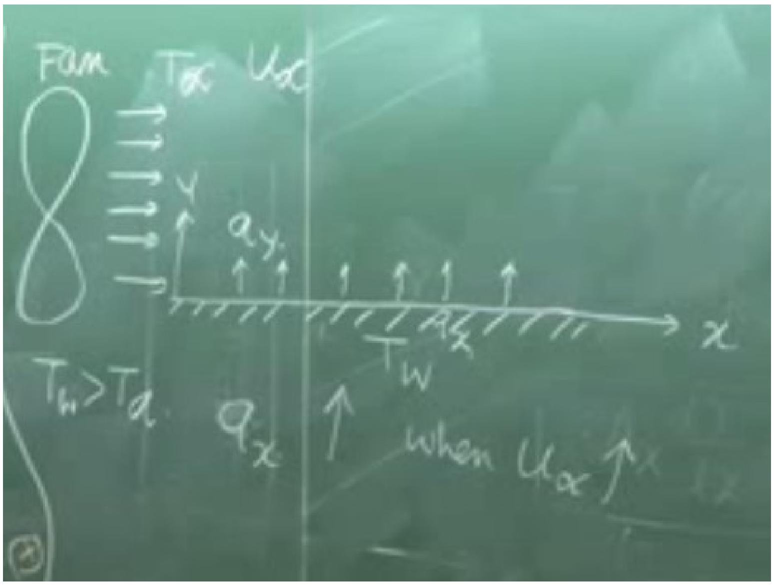
A flow is induced like this, to show the flow I draw with a different colour, a flow is induced I do it by the different colour. The flow is induced like this. The white one is this. This is this colour is the flow. A flow is induced like this because of the density difference. How, you see since this is hot compared to this at any point here the pressure represents, if you consider the pressure at any higher altitude is the same at this two points, the same elevation.

So, pressure here represents a pressure over that atmospheric pressure by a height of the column whose density is at high temperature, density is low. And if you consider somewhere here in the free stream air pressure that I will explain afterwards in more detail because this is a cold air column, so at this point the pressure is relatively high because the density is high. So, this allows the air to flow like this.

This is known as chimney effect. That if you have a chimney, if you increase the height chimney you get a lower pressure at the base because of the reduction in density due to high temperature as compared to the outer ambience. So therefore, the flow is induced from the outer ambience like that. Whereas in this case it is been in the other direction because here the pressure at this point near the wall is higher than that at the free stream.

So, this way a density difference due to the temperature difference causes a buoyancy driven flow and it is known as natural convection. So therefore, convection is a heat transfer mode where heat has been transferred from a solid surface to a fluid or from a fluid to a solid surface when the fluid being adjusting to the solid surface is in motion either due to forced flow imposed on it or naturally because of the buoyancy driven flow due to the density difference.

(Refer Slide Time: 38:21)



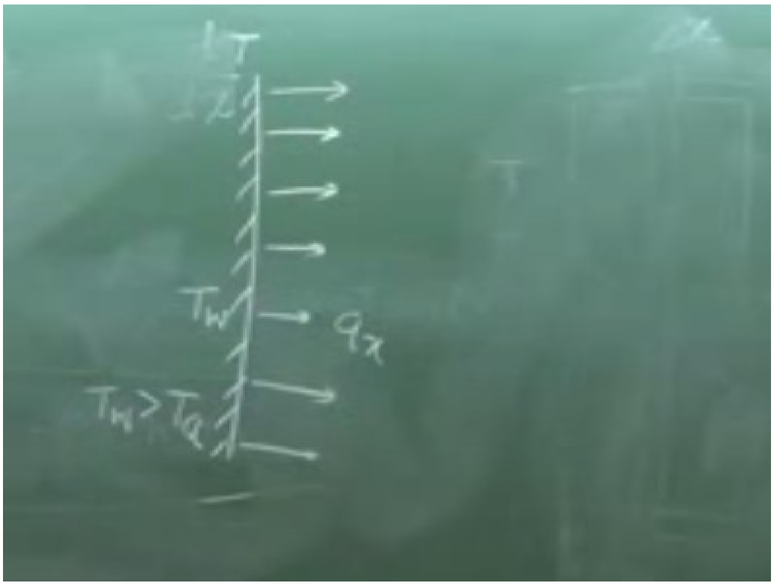
Now with this, preliminary thing in mind, I just like to tell you the convection heat transfer. Let us quantification of thus. Let us consider this practical example by a stimulation like this. Let us consider a flat plate or a flat surface. Let us consider a flat surface. These are examples a little simpler version for our basic understanding. Keep at a constant temperature Tw okay. Let us consider air, cold air flows over the plate.

And this flow is made to happen by a fan or blower and the temperature of the cold air is Ta or rather T infinite. This nomenclature I will give. The implication of it will be understood afterwards. Cold air is flowing through hot plate, this means that Tw is greater than Ta, then what will happen, heat will flow in this direction. Let us consider this as x and this direction as y so we can tell that heat is flowing in this direction.

At any point, we define this as a heat flux qy. Heat is flowing in this direction. Now if you see one thing that by our common experience we know we if increase the velocity let this is moving with a velocity uniform velocity U infinity which is coming out of the fan. Let us consider uniform velocity U infinity. Now if we increase the flow rate that means increase this U infinity velocity coming out from the fan.

The plate is cooled at a fasterly. That means rate of heat transfer increases when you increase the flow rate this is our common experience. Similar that means the heat flux if you define heat flux at any point qx, so qx increases when U infinity or the flow rate increases. So that means the rate of heat transfer from the plate to the fluid is being influenced by the flow of fluid.

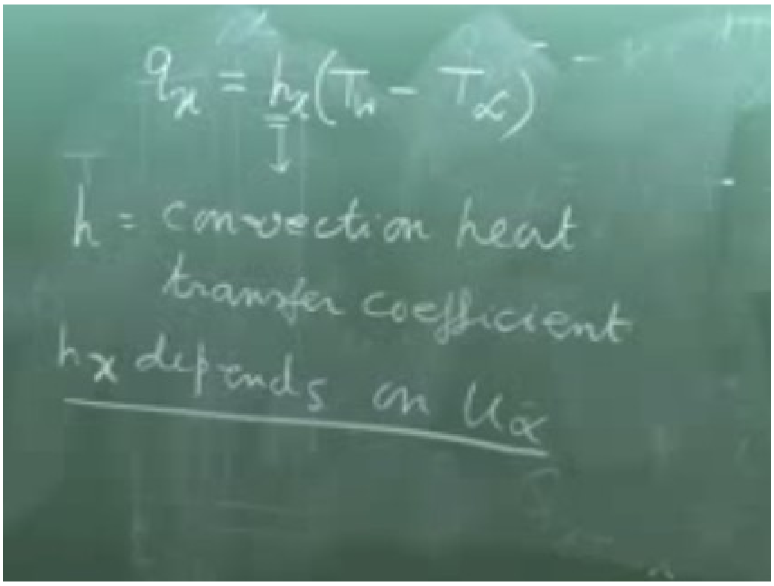
(Refer Slide Time: 41:05)



Similar is the case that when you have a vertical plate that I have told earlier at some temperature Tw where Tw is greater than Ta, the heat is transferred by convection in this direction. Here it is qx if we write the heat flux okay. Now the flow situation is like that this is a free convection case and this is a forced convection.

Now in both the cases this heat flux taking place from the surface we have to know the mechanism. What is that mechanism. First of all, we will see that this is being enhanced as the flow rate is increased.

(Refer Slide Time: 42:21)

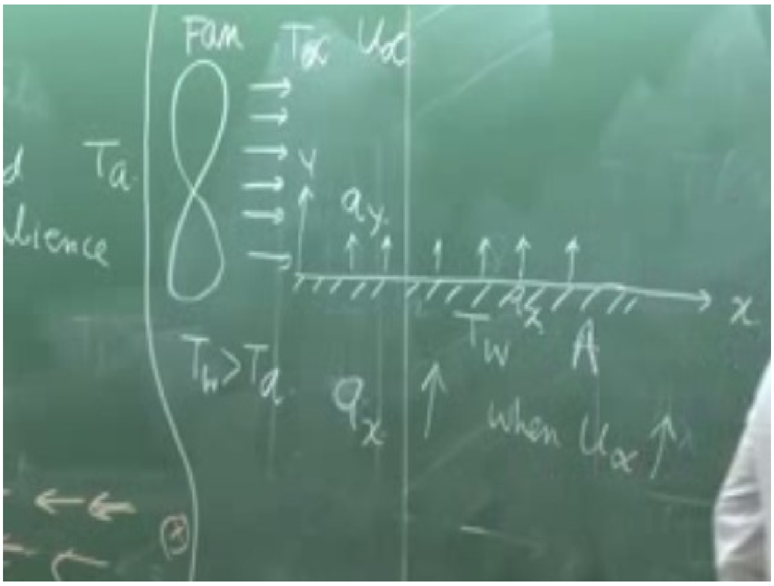


In convection heat transfer, the heat flux is defined or heat flux is determined by an equation qx in both the cases is equal to Ah into in this case Tw minus T infinity where Ah is known as convection heat transfer coefficient. Either it is forced convection, this forced convection heat transfer coefficient, it is free convection heat transfer coefficient. So qx at any point is defined as heat transfer coefficient hx at that local point hx ,all are point functions.

Tw is the temperature at that point in case of a constant temperature it will be constant and T infinity is the free stream temperature, which is unaffected by the plate. This equation defines the heat transfer coefficient. The way Fourier heat conduction define the thermal conductivity. So this way the heat transfer coefficient is defined, but to the working group who do not bother much with the concept they can find out the heat flux from this equation provided they have the information on hx, they have the information on hx.

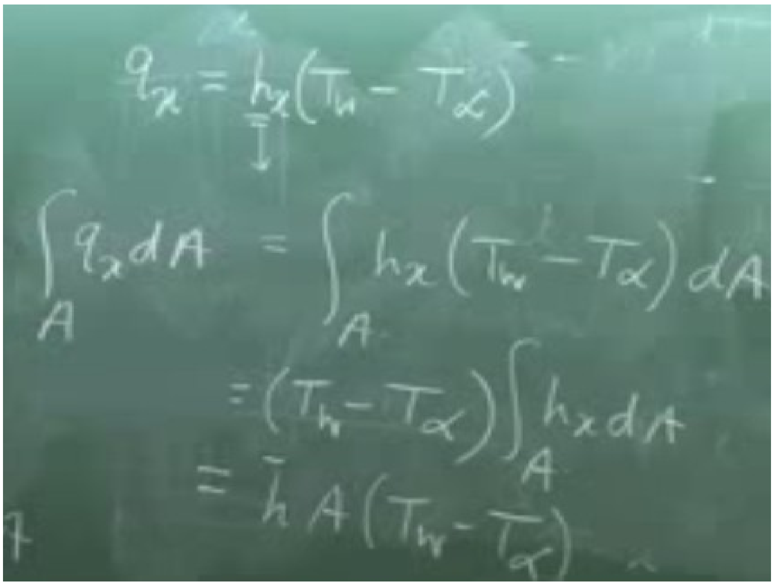
But one interesting thing is that since heat flux increases with U infinity that means hx depends on U infinity. So hx cannot be in this situation by our common observation if you express heat flux like that do define heat transfer coefficient it cannot be a property because it is a dynamic parameter which changes with the flow rate, which changes with the velocity because if you increase the flow the heat flux is increased, plate is cooled, the surface is cooled fast.

(Refer Slide Time: 44:59)



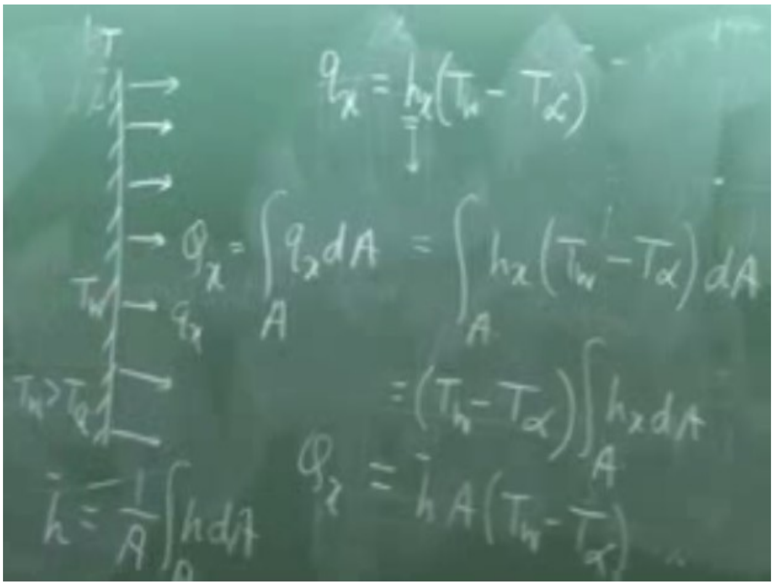
So therefore, hx depends on U infinity, it is not a property. Now this is the relationship that defines hx, the local heat transfer coefficient.

(Refer Slide Time: 45:02)



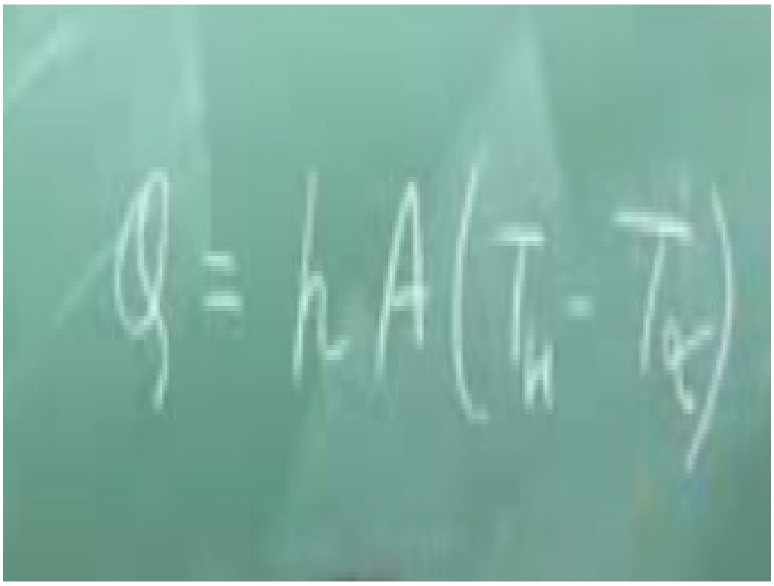
Now if you have to find out the total heat transfer from a surface of area A then what you have to do you have to integrate qx dA over the area A that means you integrate hx Tw minus T infinity times dA. Now this becomes a mathematical task if I know the variation of all these quantities with area.

(Refer Slide Time: 45:50)



Now for this case a constant wall temperature and free stream temperature this becomes is equal to Tw minus T infinity times hx dA over the area A. Now if I define an average heat transfer coefficient over an area A as the area weighted average. Then this can be written as h bar A into Tw minus T infinity that means we can find out the total heat flux qx over an area A is the average heat transfer coefficient over that area which is defined like this because this has to be made like that integrated over that area into the area.

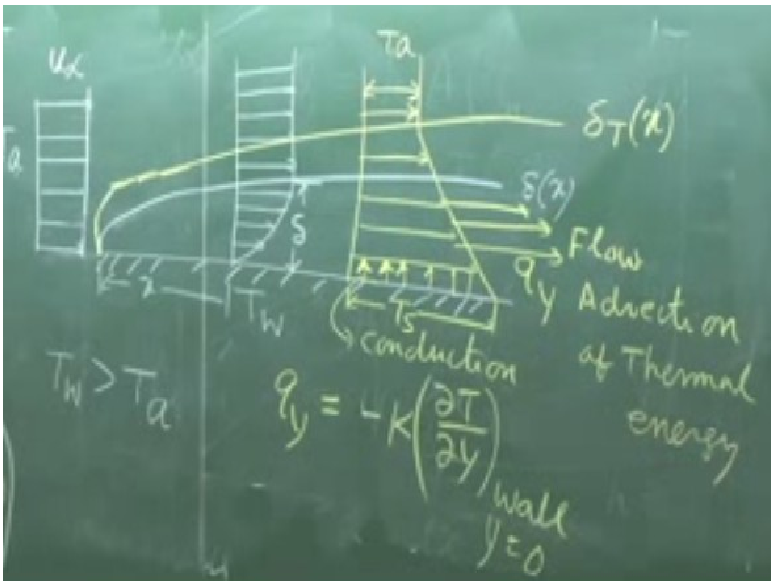
(Refer Slide Time: 46:42)



If the heat transfer coefficient becomes same constant than h bar and h is same so therefore Q's value, we write Q is equal to hA in this case Tw minus T infinity where h is either a uniform heat transfer coefficient same over the section does not vary or in area average heat transfer coefficient h bar. But the question remains that this is a definition, this is a not mechanism. I forcefully define that convective heat flux will be h time delta T that means Tw minus T infinity.

But by doing so and clubbing with our common experience that if you increase the flow, heat flux increases we find that h is not a property that means h depends upon the flow velocity. So therefore, what is the mechanism of heat transfer from the surface to the fluid and how is it affected by the flow as to be understood and that is the central point of understanding of convective heat transfer, which I will explain you now.

(Refer Slide Time: 48:40)



Now which I will explain you now let us consider the plate. Now to understand the mechanism consider the plate at Tw and let us assume that fluid is flowing or approaching to the plate leading edge of the plate with a velocity of U infinity. This is a recapitulation of your basic fluid mechanics concept which you have already read U infinity. And with a uniform temperature of Ta.

Now you know, when this situation happens from your fluid mechanics you know a hydrodynamic boundary layer developed, which is a function of x. What is this hydrodynamic boundary layer, that means that at any section x if you see the velocity profile, it will look like this? Recapitulating the fluid mechanics concept what happens, that the fluid velocity at the solid surface is zero related to the surface which is known as no-slip condition.

In the domain of continuum, the fluid particle cannot slip over a surface because of strong molecular addition. Under very special cases even in the domain of continuum an effective slip appears at the surface these are very rare cases in a very very small channel whose dimensions in the order of micrometer or nanometer, but usually in engineering applications except those cases and in the domain of continuum.

As you know that fluid particle cannot slip over the surface known as no-slip condition because of the addition between the fluid and the solid zero, momentum becomes zero. Then because of this momentum transport and the momentum retention relative affair between this two which is manifested through the kinematics viscosity, the fluid flow is adjusted in a way that the velocity starting from zero, no-slip condition because the plate is at zero reaches the full free stream velocity after certain distance.

Though it never reaches the full free stream velocity, it reaches asymptotically but usually we assume that after some distance where 99.5% is assumed which we take as full U infinity as the delta the boundary layer thickness and within which the velocity variation takes place and this thickness of this boundary layer depend upon the flow velocity and the liquid property and you know as a whole it depends upon the Reynold's number of flow.

Similar is the case for the temperature because this is higher than Ta Tw is higher than Ta. So therefore, a thermal boundary layer also will be developed in these way and let us consider, I a thermal boundary layer whose we designate as delta T as a function of x and what is the implication and what is the implication of this thermal boundary layer, similar to velocity boundary layer at this section if we plot the temperature variation which I show you what the clarity here.

Here we cannot draw but at the same section we will see the temperature scale will be like temperature variation will be like this. So, this is your wall temperature Ts and this is the temp, then temperature also because of its conductivity and retention capacity by heat capacity which I will tell afterwards known as thermal diffusivity.

The temperature field is also adjusted in a way that temperature from the surface temperature in the fluid decreases after certain distance away from the fluid remains constant and this is Ta free stream temperature, cold air temperature. So, this is the picture the development of thermal. Here I have drawn a figure where delta T thermal boundary layer is higher than the velocity boundary layer.

But you do not think that it is always so, this is a particular case I have done. The boundary layer may be smaller than the velocity boundary layer may be higher than that. Both the options are there. For gases like air the thermal boundary layer is always higher than the hydrodynamic boundary layer. So, this picture is for air, for example air. So now the important thing is that at this surface there is no velocity.

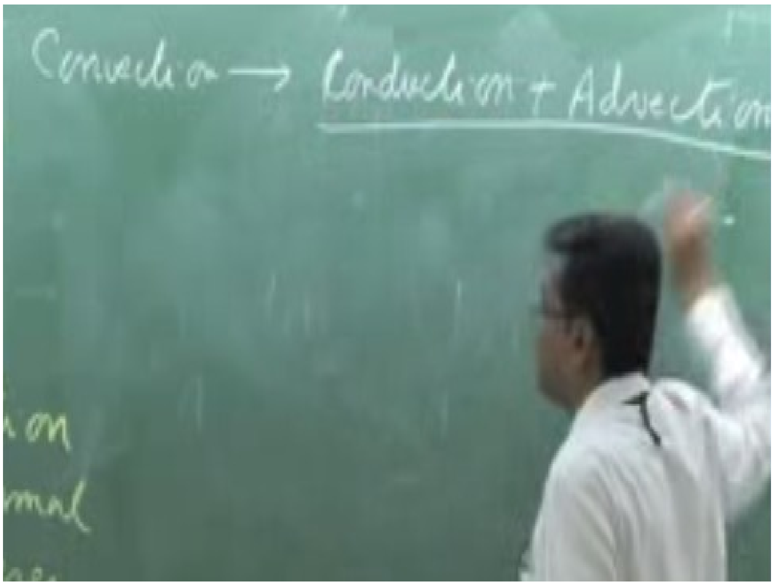
So therefore, the heat which is going from the surface at the surface from solid to the surface if you consider a layer at the surface, a nanometer layer for example which is almost at rest.

This heat qy can be written as qy is equal to minus K del T/del Y at the wall that means y is equal to zero. That means there is no other mode pure conduction, which is not affected by the flow because there is no flow. This is the conduction mode of heat transfer from the surface.

But what happens just above the surface there is a flow. Now this flow conflux the thermal energy, advects the thermal energy away. Because of what, the thermal boundary layer is set up that means at least some distance from the wall the fluid gets the opportunity to reach the free stream temperature because of the advection of the energy. So therefore, the temperature distribution will be affected by the advection of this flow.

And therefore, the temperature gradient will be determined by the advection of this energy flow. Advection of the flow means the advection of the energy, flow of this energy. So therefore, in this direction energy is advection of thermal energy.

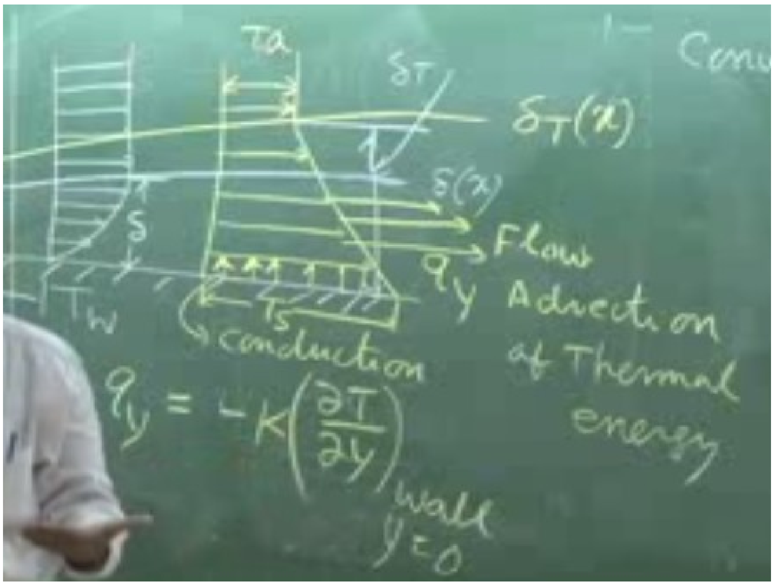
(Refer Slide Time: 57:17)



Advection convection is a phenomenon which is guided by both conduction and advection. I will do it in more detail afterwards in the introductory class of convection. Conduction and advection. Now when the flow is increased, what happen as you know from fluid mechanics concept the boundary layer will be reduced and moreover free stream velocity we will increase, which will make the velocity gradient at the wall more for which the stress is increases.

Similar is the case when the flow velocity is increased, this delta T will be reduced. That means this value of delta T, here the value of delta T is the distance from here to here. This is the delta T.

(Refer Slide Time: 58:15)



This is the, this value is delta T, this is being reduced while this is reduced mathematically you see the temperature gradient that del T, del Y at the wall is increased. You understand because the thermal boundary layer is reduced that means the fluid attains the cold temperature free stream temperature at a very close distance from the plate, but the plate temperature remains same that means the temperature curve is more steep.

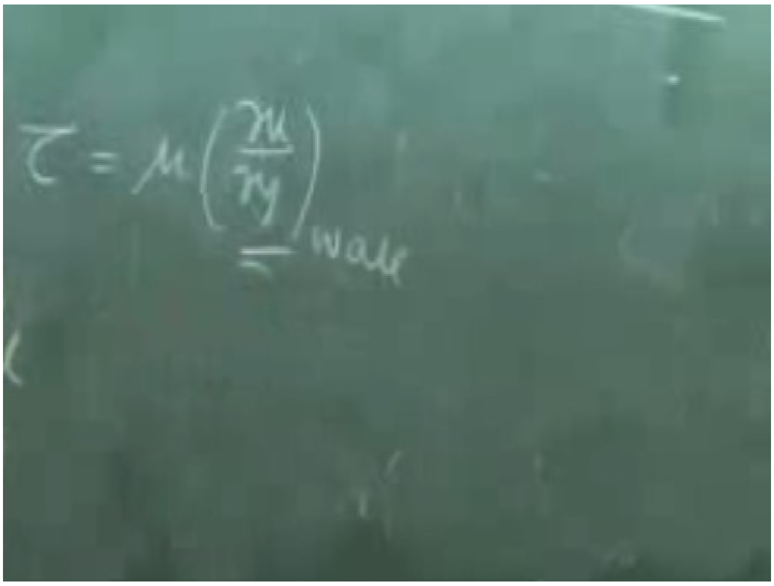
This is precisely the phenomena that the flow velocity increases the heat flux and why this temperature gradient becomes steep why the fluid gets the opportunity to attain the free stream temperature at a shorter distance from the plate because the advection of thermal energy becomes higher because of the more flow. More is the advection fluid is cooled. So that fluid gets an opportunity to reach the cold temperature very close to the surface which means that thermal boundary layer is reduced.

So therefore, the conduction of heat from the surface where the velocity is zero to the fluid is totally governed by the advection of energy associated with the flow. More is the advection with the increased flow fluid gets the opportunity to be cooled quickly and gets a temperature of the cold air close to the plate by defining a thermal boundary layer. Nevertheless, at the plate.

There will be plate temperature because thermal equilibrium will be there at the plate y is equal zero, solid and fluid cannot of different temperature so therefore what happens thermal boundary layer goes thinner and thinner. Nevertheless, it becomes zero like the hydrodynamic boundary layer. So, no-slip condition at the surface with respective velocity that means it is zero because the plate is at rest and no-slip condition at the surface as far as temperature is concerned that means it is the surface temperature has to be maintained.

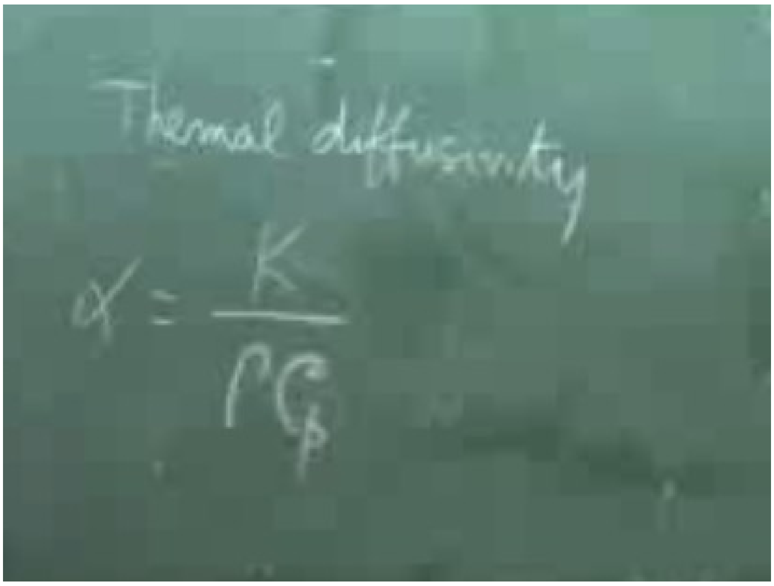
So therefore, with that if the thermal boundary layer and hydrodynamic boundary layer become short at due to higher flow rate both the gradient del U del Y.

(Refer Slide Time: 1:00:46)



For example, in this case I can write Tau is equal to Mu del U/del Y at wall both gets increased and therefore this shear stress and the rate of heat transfers or heat flux gets increased clear. So, this is the mechanism by which flow influence the heat transfer which is basically by conduction and at the surface the only mode of heat transfer is conduction. So up to this is the introduction to convection, but again I will come back at the beginning of the convection course in more detail to give you physical concept of convection.

(Refer Slide Time: 1:01:25)



But before I end, I tell you one property known as thermal diffusivity alpha is defined as K/Rho*Cp where K is the thermal conductivity, Rho is the density and CP is the specific heat at constant pressure. Now you know that there are thermo physical properties of any physical problem related to any physical problem which can be classified into two groups.

One is the transport properties which appear in the equation showing the rate of transport of a quantity with its potential difference like thermal conductivity, like mass diffusivity, viscosity, momentum transport. It defines the momentum transport. These are the transport property whereas Rho and Cp are thermodynamic property. This is rheological property specifically.

So, the ratio of these K/Rho*Cp is known as thermal diffusivity which is an very important parameter but just by knowing the formula will not do you have to understand physical concept and implication of it. This thermal diffusivity as it is defined K/Rho*Cp you see the numerator is a property which tells how the heat is being conducted and denominator is a property which tells how the heat is or the thermal energy is stored.

So therefore, the ratio K/Rho*Cp alpha thermal diffusivity denotes the ability of a material of a medium to transport heat or conduct heat with respect to our relative to its ability of storing thermal energy. That is the physical implication a system with a very high value of alpha conducts it first as compared to storage of thermal energy and this type of material if it is put chained environment quickly respond to it in stabilising a steady temperature field well in conducting the heat.

As I told initially when I came to the class immediately class silence that means your thermal diffusivity is high whereas for the system or the material whose thermal diffusivity is low does it more sluggish that is the thermal diffusivity and here I end the introductory chapter.

Next class we will deduce the heat conduction equation in general that means that will give you the basic governing equation relating the temperature with the space coordinates and time for conduction heat transfer and which will be derived from by utilising the principle of conservation of energy and that part will be taken by Professor Suman Chakraborty in the next class or in the next session, okay. Thank you.