Chemical Engineering Fluid Dynamics and Heat Transfer
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Lecture - 31
Fundamentals and Mechanism of Heat Transfer

Hello everyone, welcome to the first lecture on the Heat Transfer part for the online certification course on Chemical Engineering Fluid Dynamics and Heat Transfer. I am Arnab Atta from the Department of Chemical Engineering IIT Kharagpur. So, in today's lecture we will have the Fundamentals and Mechanism of Heat Transfer.

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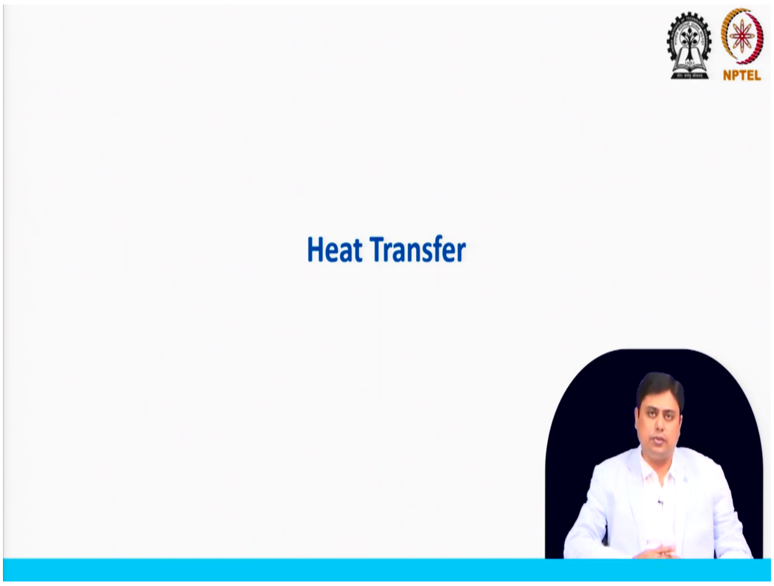

In this section rather because this course is taught by the two instructors, in this part, I will speak about heat transfer.

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The topics that I plan to cover or the concepts that would be covered in this part of the lecture are the fundamentals and mechanism of heat transfer, where we will discuss about different mode of heat transfer, it's rate equations, the differential equations of heat transfer for these three modes of heat transfer that is conduction, convection and radiation.

Then we will talk about steady state conduction taking one of the modes of this heat transfer, the steady state part in which we will look into the conduction in cylinders and spheres. We will talk about the importance of insulation and the concept of critical radius of insulation in conduction in this kind of geometry that is cylinders and spheres.

Then we extend our discussion on the extended surface, the heat transfer from the extended surface in the conduction part; now, this is about the steady state conduction. In the transient conductions; that means, unsteady state conduction we will understand what is lump system analysis, the modeling strategy and once those equations are formed how do we solve this by numerical method.

Then after that we move, we will move to the convection heat transfer where in convection heat transfer there are two modes further it is divided in two types of convective heat transfer; one is the forced, the other one is the natural convection. So, in forced convection we will see what is boundary layer that is in fact, has been covered in the fluid dynamics part of this course, we will see the analogies between energy and momentum transfer.

We look into natural convection its mechanism and several empirical relations for various surfaces. And we will also look into the other aspect of convection very briefly where we will have the overview of boiling and condensation. And finally, we will touch upon radiation heat transfer where we have where we will see different properties and the concept of view factor.

Now, first of all the question comes that why do we need to study heat transfer when we have studied or we will study thermodynamics. The point is, in thermodynamics we learn mainly that energy can be transferred by the interactions of a system and the surrounding, and it talks about the end state after the transfer. Now, the point is how the transfer is happening, what is the mode of that transfer, in which rate it is being transferred those are not answered in thermodynamics and this is particularly dealt in heat transfer.

And as per the sequence of this course if you look at the title. In the first half or the first section you already have gone through the fluid dynamics part which is essential to know for various aspects or in the modes of heat transfer when we particularly talk about convection where flow is involved. So, now let us get introduced with the different modes of heat transfer, to start with the first one that we have come across is the conduction.

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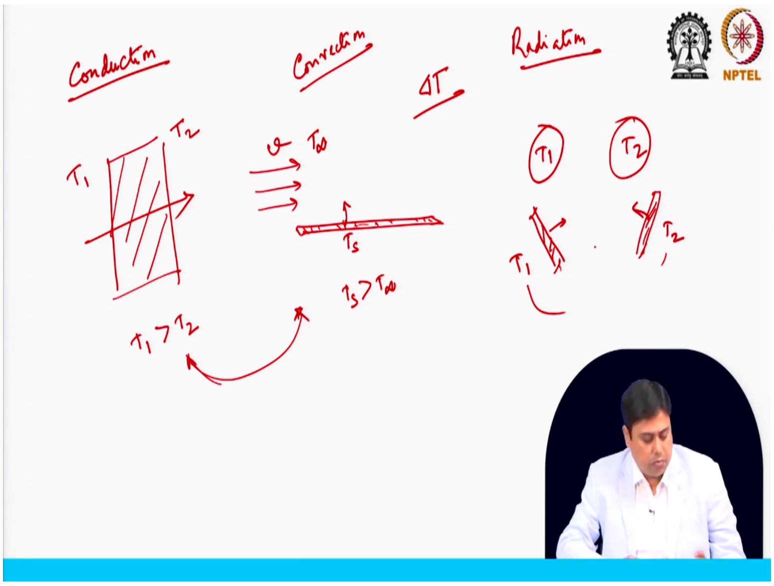

Now, conduction and before you go to the conduction let's also have a formal understanding of what is heat transfer? Heat transfer by textbook definition one can say that the heat transfer is a thermal energy in transit due to special variation of temperature, ok. So, in short this can be a definition of heat transfer that thermal energy in transit from one place to other due to temperature variation.

Now, wherever there is temperature gradient or say if i mention that as ΔT, where T is the temperature; wherever that exist there will be the transfer of heat. Now, say we have a slab; now, this slab at one end we have temperature T_1 the others end we have temperature T_2; now, say T_1 is greater than T_2. So, the heat transfer that will happen will happen from left to right or from the higher energy state to the lower energy state.

Now, this happens through a solid medium in this case in this example so, and this would happen we know that. So, this mode of heat transfer usually we call that as a conduction when this transfer happens through a solid medium. Now, the other situation consider that we have now some fluid flowing over this hot plate we have some amount of fluid a bulk fluid motion exists over a hot surface; say, if this is my hot surface some fluid is flowing over it with a velocity v.

Then if the temperature of the surface say T_s and the fluid temperature if I say that is T_∞, if these two are in equal or not equal then there will be a transfer of heat from one to other. Say for example, if $T_s > T_\infty$, then the temperature here would be transferred to the bulk fluid or the energy the thermal energy would be transferred from the surface to the bulk fluid.

Now, in this case if we consider this solid slab is having an uniform temperature $T_{s,}$ that means, it reached a steady state temperature which is T_s uniform. And from there the mode of heat transfer that is happening between a solid surface and a flowing fluid, this mode of heat transfer in this case is called the convection.

So, in convection we need bulk motion of the fluid; in addition to when we talk about the mechanism of conduction, we will see that that mode itself is also necessary for convection to happen. The other mode of heat transfer we call that as radiation; say now in these two cases what is happening is that we require a some medium for this transfer the energy transfer to happen.

In conduction it was solid medium, in convection it requires a solid surface and the fluid medium. Now, in absence of this medium this conduction and convection cannot happen, but radiation. Now, if we have two bodies at two different temperature, be it spherical be two surfaces of having different temperature these two body emits certain energy.

If the temperature of those bodies are non-zero, any body any object with a non-zero temperature emits energy. Now, when these two are different this T_1 and T_2 having different values, one would receive energy one would emit energy, I mean one would the energy the net energy flow would be in one particular direction.

Now, this can happen in absence of any medium in fact, radiation works perfectly or in it is works beautifully when there is complete vacuum. So, these mode of heat transfer we will talk we will discuss in detail one by one as per this structure that you have seen that initially we will go into the details mechanism how these are happening.

The very fundamental understanding of this mode of heat transfer, the differential equations of the governing equations to solve those transfer related problem in different modes. And then we take one by one mode of heat transfer, and we specifically focus on conduction, convection and then we talk about radiation. Now, if we look further into the mechanism say now if we talk about only conduction.

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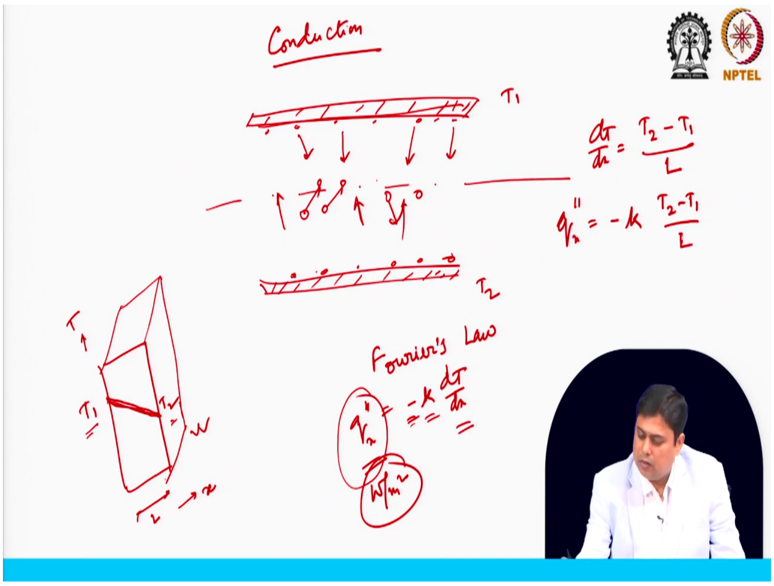

Now, conduction the this if we talk if we just focus on this word, it would immediately brings up the relevant terms that are the molecular and atomic activities. So, when this conduction happens, it happens at the atomic and the molecular level. So, the conduction this we can consider that is happening the transfer of energy from more energetic atom or molecules to the lesser energetic molecule or atom.

So, it is best described if we consider say enclosed domain and so this is say we have a temperature that is T_1 we have temperature T_2 of these two sides. And say my gas is enclosed in between these two sides in between these two sides which have two different temperature. Now, what will happen we know that the gaseous molecules has their Brownian motion.

Now, the molecules those are close to these surfaces or the respective surfaces it quickly attains the similar temperature. And then it moves across this imaginary plane centre line randomly some is coming; so, there is a net motion of this molecules. So, there will be some molecular activities when we have two different temperature on the two sides.

Because, this gas would occupy the whole space in between this enclosure having two different temperatures and along with its internal rotation, vibration etcetera it would also have its movement across this imaginary plane. Now, this we will try to have a equilibrium until and unless that happens this random motions continues. And even these motions does not happen this temperature also is not equal the motions are still there this collisions, attritions etcetera that has happening; so, this is how the conduction would takes place.

Now, in case of a liquid these molecules are closely spaced these molecules are closely spaced. So, the transfer happens in a more in compact manner and in case of solid this transfer happens one can imagine as a lattice vibration inside the medium or the solid body, because there it is further closely or tightly spaced. So, now if we try to quantify this that the amount of heat being transferred from one place to other place that requires a developing governing equations or the rate equations that we will see later.

Now, in liquid as I mentioned the moleculars are closely spaced and the molecular interactions are more stronger and more frequent in case of liquid phase. So, now the point is that these examples of conductions we see these in daily lives. For example, once you drop a spoon in a hot cup of tea, the tip of the other end which is exposed to the air it gets also heated.

Now, that happens due to conduction the temperature of the liquid is much higher that one end of a spoon is dipped into it and the heat is being transferred from one end to the other end which is open end. So, there are several examples of conductions that we know this is the elementary physics that we have already learned. Now, the point is for heat conduction the rate equation is called the Fourier's law, which if we consider this as a slab that in which we have one end at T_1 the other end we have a T_2.

So, this is the temperature profile that happens and if this is the temperature axis and this is the length of the slab this is the x direction. So, by Fourier's law we will see that this is also in details the heat flux is given as

$$q_x'' = -k\frac{dT}{dx}$$

This is the heat flux per unit which is the heat transfer rate per unit area usually that has a unit of watt per meter square.

k is actually a proportionality constant which is called the thermal conductivity of the material. And this is the $\frac{dT}{dx}$ that comes with the negative sign here which we will explain also later, but it is to be understood that the heat transfer is happening from higher temperature to lower temperature. So, the transfer gradient is negative and the heat flux in order to be a positive value we must bring negative sign in this relation.

So, when say this profile the temperature variations of the temperature steady state temperature distribution temperature profile is linear. Then this $\frac{dT}{dx}$ what we can write is say $\frac{(T_2-T_1)}{L}$ value so if you look at this figure :

$$\frac{dT}{dx} = \frac{(T_2 - T_1)}{L}$$

so, which means this heat flux is basically:

$$-k\,\frac{(T_2-T_1)}{L}$$

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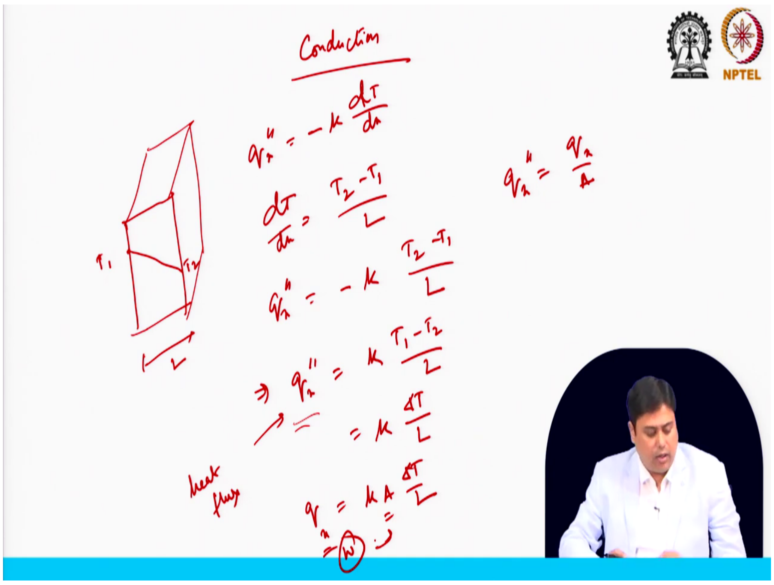

So, as and as I said

$$\frac{dT}{dx} = \frac{(T_2 - T_1)}{L}$$

so, which when we replace here it becomes:

$$q_x'' = -k\,\frac{(T_2 - T_1)}{L}$$

which means is equals to we have

$$q_x^{"} = k\frac{(T_1 - T_2)}{L}$$

which is $k\frac{\Delta T}{L}$. So, this equation provides the amount of heat being transferred per unit area or the heat flux that we called heat flux.

And the heat rate by conduction which is say simply q if we write it is

$$q_x = kA\frac{\Delta T}{L}.$$

where L or in other words:

$$q_x^{"} = \frac{q_x}{A}$$

So, the amount of heat if we try to get in watt is this equation that we follow that $kA\frac{\Delta T}{L}$. So, this is the mechanism and a very simple basic equation that we follow in order to calculate say the amount of heat being transferred through conduction.

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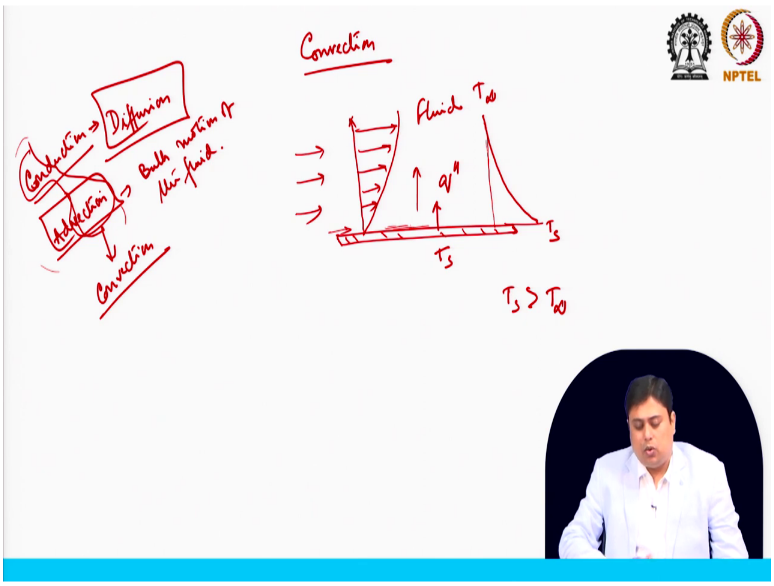

Now, here in case of convection, now in case of convection again convection if we talk about the convection mechanism. Then in convection as we discussed it requires a moving fluid on a solid surface for this convection to happen; which means, in conduction that we are saying that there were due to the random motion of the molecules of the atoms which we typically called diffusion.

So, conduction is essentially due to diffusion of the molecules. In convection along with this diffusion we require bulk motion of fluid which we called advection; advection is the bulk motion of the fluid. So, in conduction we had molecular diffusion along with that now we have momentum transport. So, this conduction plus advection results in convection; along with the molecular diffusion, we need molecular momentum transport as well.

So, if this happens then we get or we have the convection heat transfer in place. Now, when as I mentioned in the last example when we have a flat plate which is hotter and a fluid is flowing over it. You know by now that there is a velocity gradient the velocity distribution, along with that if the temperature of the fluid and this solid surface are different then there will be a profile for the temperature as well.

Where if this is the T_s and this is say the T_∞ this is the temperature distribution. And here what we have considered is that $T_s > T_\infty$; that means, the surface is at a higher temperature than the fluid temperature. And in that case the heat transfer will happen from the surface to the bulk fluid.

Now, here the concept of boundary layer comes, because now you know that in such case when there is a flow over a flat plate there is hydrodynamic or the velocity boundary layer. Along with that in convection we will see thermal boundary layer. Now, the relative thickness of these two depends on the temperature of the fluid and the surface, this we will discuss later.

But the point is that the thickness of these two boundary layers can be equal or greater than or less than the others depending on certain condition. But it is important to understand that the convection heat transfer mode is sustained by random molecular motion and the bulk motion of the liquid, this we must not forget.

So, when the fluid immediately touches the closest layer near to the hot surface or the hot solid surface or the hotter solid surface, what happens there? There the velocity as we are considering here there is no slip condition, the velocity here is 0. So, eventually there the heat transfer is happening by the mode conduction at the closest layer that have been possible where the velocity is 0, that the solid and the fluid contact point.

As we move along in this direction we see there is a velocity gradient and it reaches a velocity boundary layer where the fully developed profile are obtained and the mode of advection dominates than the mode of conduction. So, at the vicinity of the wall, we have conduction mode of heat transfer in the case of convection.

And that is why we mentioned that these two are essential for convection to understand and that is why we will at first study conduction and then go to the convection. So, with this understanding I will stop here today and in the next class I will come back with the short introduction on radiation and we will then discuss in detail that this topic of getting differential equation for the conduction mode of heat transfer.

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The textbook that we plan to follow here in this course throughout the course are mainly Fundamentals of Heat and Mass Transfer by Incropera and Dewitt and also the second book can be referred for the overall purposes. So, these are the references that we will follow.

With this I stop here today and we will see you in the next class with a different topic.

Thank you.