Chemical Engineering Fluid Dynamics and Heat Transfer
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Lecture - 46
Forced Convection

Hello everyone. Welcome back once again with another lecture on Heat Transfer in the NPTEL online certification course on Chemical Engineering Fluid Dynamics and Heat Transfer.

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Over the last couple of lectures, we mainly focused on the heat transfer by conduction and different analysis, different with source, without source different mechanisms. Now, from here onward we will look into the another mode of heat transfer that is by Convection. So, in general we already had an introduction on convection, but to have the continuity let us again refresh the memory on the convection. So convection happens along with conduction.

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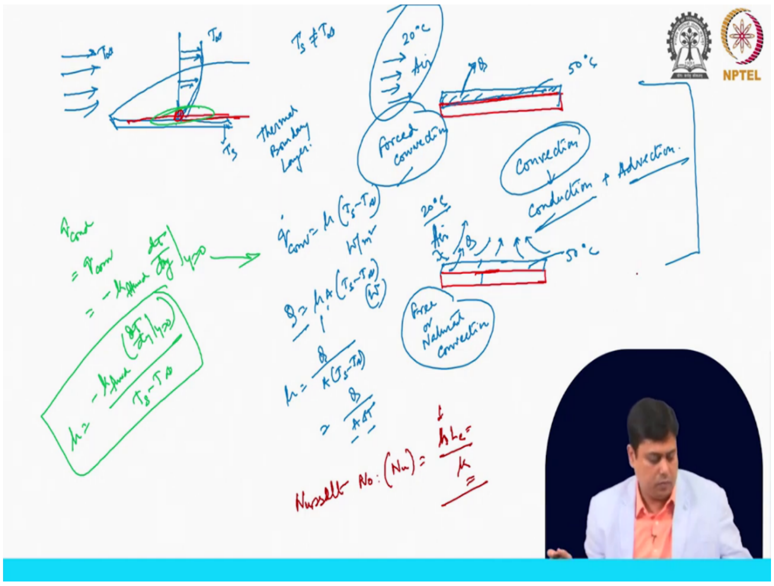

So if we have a flat plate and consider there is a pool of liquid on top of it. Now, there is a wind or air is blown over this surface, where this is at 20 ºC and air is blown over this surface. And this liquid is at 50 ºC. Now, in this kind of scenario there are two things that we can think of immediately.

One is if this system that is the liquid pool on a plate is at steady state which means this substrate or this plate temperature also, we are considering uniformly at 50 ºC. Now, if that is the case then what happens? As the air blows or it flows over the upper surface of the liquid the temperature of this liquid pool gradually drops because the net heat transfer will happen from the liquid to the air.

Now, as the liquid is in contact with the solid surface the solid liquid interface at that point or even inside the liquid inside the solid, the width if we consider it is a substantial amount of width is there, then there will happen conduction as well. So, at the solid-liquid interface or the junction the heat transfer is by conduction as well as from here from the liquid to the air this is happening by convection.

Now, if we go into the definition of convection, if you remember, itself when this is happening in a medium, it happens with a combination of these two process that is the conduction and advection. So, advection that is the bulk motion of the fluid and conduction that we have already understood.

So, here what we have, the bulk motion of the fluid that helps further augmenting the heat transfer rate and eventually the convection is termed based on the conduction and advection part of it. Now, in absence, so the question naturally may arise that in absence of this air or say if we do not blow over it would that liquid cool down? Of course, it will. So, if say the similar scenario again, but now we do not have the air flow over the same substrate. So, this is at 50 ^{0}C.

Now, there is simply air. But we are not forcing the air to flow over the surface. In that case also when this air which is at a lower temperature, say the ambient temperature is 20 ^{0}C will come in contact with this hotter fluid, what will happen? The net heat transfer eventually will happen from the hotter fluid to the colder fluid, and as soon as it happens the density of air decreases.

Now, as it decreases immediately that goes upward and this place is filled by again a fresh air of a higher density which is at a lower temperature, relatively lower temperature. And so, there will be a natural circulation of air around this interface of the liquid and air. So, this two type of convection can happen. So, this is also convection. Because here what is happening?

As we have conduction in the solid medium as well as we will see in liquid medium how conduction is possible when we go into the details. Apparently, there is convection or the advection or the bulk motion of fluid on top of the gas liquid interface. So, now these two scenarios are termed in a two different way of convection. Here we are forcing the air to flow over it. So, the name it is called as forced convection.

And here it was not forcibly flown over it, if there was a natural circulation of air. So, it is called free convection or natural convection. So, these two modes of convection, we will study over the next couple of lectures. We will see how to estimate heat transfer coefficient in those cases, what are the specific scenarios, and what are the governing equations.

Now, when we talk about convection and we talk about forced convection, particularly in this next couple of classes when we talk about forced convection there is a upstream fluid that comes on top of the substrate or on top of a plate. Even if there is no liquid on top of it, and if this substrate or the plate is at a different temperature than the upcoming fluid that is flown over it in that case we know by now that there is the development of velocity boundary layer.

Now, that concept is extremely important and the understanding of convection. Now, there we have seen that when we have a flat plate liquid is or say any fluid is flown over it, we see the development of velocity boundary layer. Now, similarly there is the concept of thermal boundary layer and that happens if this plate if I say, T_s and this T_∞ $(T_s \neq T_\infty)$.

If these two are at two different temperatures, then there will be the development of another boundary layer which we call as the thermal boundary layer. And these two happens simultaneously in case of convection, because there is a bulk motion of the fluid for which velocity boundary layer developed and due to the temperature difference there is thermal boundary layer.

Now, the point is from the Newton's law of cooling what we can estimate in convection the amount of heat transfer. That is if we see or if we write that:

$$q_{conv} = h(T_s - T_\infty)$$

The unit is in W/m^2 or if I say the amount of heat transfer it is: $Q = hA(T_s - T_\infty)$ the unit in Watt (W) where h is the convection heat transfer coefficient, A is the heat transfer surface area, T_s is the temperature of the substrate this a surface, and T_∞ is the temperature of the fluid that is sufficiently we say far away from the plate. So, now what we can see here that h can be defined that this convection heat transfer coefficient can be defined as the rate of heat transfer between a solid surface and a fluid per unit area per unit temperature difference.

The h is essentially:

$$h = \frac{Q}{A(T_s - T_\infty)}$$

In short form what we can write is this:

$$h = \frac{Q}{A\Delta T}$$

So, h convection heat transfer coefficient, what we are defining? As the rate of heat transfer between a solid surface per unit area per unit temperature difference. Now, as we see that the concept of velocity boundary layer eventually based on the assumption that there is no slip boundary condition exists. That means, the velocity here on the surface is 0, for the fluid layer that is attached to the surface.

Similarly, it can happen when there is a contrast in temperature, if the two bodies are at different temperature, and if those are brought into contact, so heat transfer will occur until both of them attains a same temperature at their point of contact. Now, this is called as the no temperature slip condition or jump condition. Because here at the point where the fluid is in contact with the surface the boundary condition that we consider here that this fluid temperature is same as that of the surface temperature.

So, there is no discontinuity in the temperature profile. So, if we consider this, then what we can write, since the fluid layer which is attached to this surface is motionless. If we consider in any of this scenario that once it is in contact with this surface, there is no slip boundary condition, the velocity is 0, motionless.

And also, with this condition of no temperature jump what eventually we can write is:

$$q_{cond} = q_{conv} = -k \frac{dT}{dy}_{y=0}$$

So, $\frac{dT}{dy}$ is the temperature gradient at the surface if we consider it.

So, that means, the heat is convected away from the surface as a result of the fluid motion. So, the point is that from this expression what we can write and combination of these two,

$$h = \frac{-k_{fluid} \left.\frac{dT}{dy}\right|_{y=0}}{(T_s - T_\infty)}$$

So, which means at the surface we can determine the convection heat transfer coefficient when the temperature distribution in the fluid is known to us. This expression helps us to determine the value of h. Now, as we have discussed earlier, always in the heat transfer problem be it whatever its mode, the point that we look into is how to estimate the value of h.

Because once we get the value of heat transfer coefficient be it h in this case that is the convection heat transfer coefficient, we can always calculate the amount of heat transfer that is happening. Now, when we talk about this convection, we will see there are several parameters that appears and in order to streamline those, it is always beneficial that we now introduce like the fluid flow the fluid dynamics we had introduced Reynolds number, we introduce couple of non-dimensional number in order to generalize the concept or the influence of several parameters on convection or related to convection.

So, one of such and the vital non-dimensional number is the Nusselt number. We write:

$$Nusselt\ No.(Nu) = \frac{hL_c}{k}$$

where k is the thermal conductivity of the fluid, L_c is the characteristic length, and h is the convection heat transfer coefficient. Now, this is extremely important because this is a dimensionless quantity which can be considered also as a dimensionless heat transfer coefficient value. Now, so to understand its importance we consider that we have a fluid layer of thickness L.

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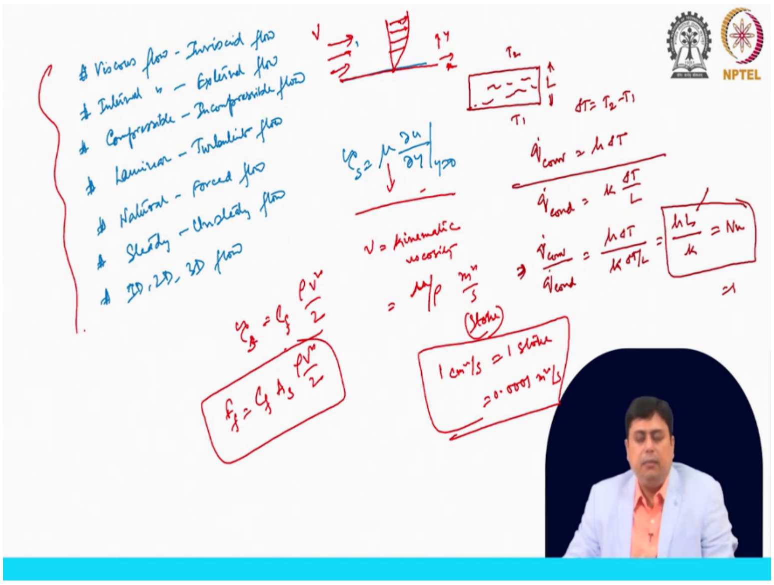

So, we have a fluid layer of thickness L. The temperature difference say is T_2 and T_1. So, $\Delta T = T_2 - T_1$. Now, heat transfer through this fluid layer will be by convection when the fluid involves some motion and it will happen by pure conduction when the fluid is motionless. There is no bulk motion of the fluid.

This part we are clear that if we have a fluid layer of thickness L and if there is a bulk motion of the fluid, then the heat transfer will happen by convection. If there is no bulk motion of the fluid the heat transfer will happen by conduction. Now, in that case, what we can write, the heat flux in both the cases what we can write in case of convection what we write is $\dot{q_{conv}} = h\Delta T$. In case of conduction, we write $\dot{q_{conv}} = k\frac{\Delta T}{\mathrm{L}}$, heat flux by both the mechanism.

Now, its relative importance if we take the ratio of these two, what it gives that:

$$\frac{\dot{q_{conv}}}{\dot{q_{cond}}} = \frac{h\Delta T}{k\frac{\Delta T}{\mathrm{L}}} = \frac{hL}{k} = Nu$$

We term this as the Nusselt number after the scientist Wilhelm Nusselt.

So, Nusselt number represents the enhancement of heat transfer through a fluid layer as a result of convection. This way you can consider. If the Nusselt number is 1; that means, there is pure conduction. A fluid layer represents the heat transfer across which the heat transfer is happening by pure conduction, if Nusselt number is 1. Larger the value of Nusselt number, larger the enhancement of heat transfer by convection.

So, now the point is that and that is why we try to enhance the mode of convection because if we want to enhance the heat transfer to happen, either say for example, in our daily life in order to cool, a hotter coffee or hot coffee immediately for a sip, we blow over it some air that introduces forced convection. And it increases the value of this h and eventually it results in the larger value of Nusselt number, and the heat transfer rate enhances as we introduce convection.

So, now this Nusselt number we will try to find out in various cases because if you remember this heat transfer by different modes is eventually, we try to find out what is the heat transfer coefficient in different scenario. That was one of the major goals that how we find out the value of heat transfer coefficient. If we find out then we can use different equations for example Fourier's law, Newton's law of cooling or similar in case of radiation in order to estimate what is the amount of heat transfer that is happening.

So, now as a part of fluid dynamics, you have already understood several flow classification. That we will not go into the details, but I will just highlight a few names.

The names are say viscous flow and inviscid flow. So, let me summarize those names, you have to go through it. So, one is viscous flow & inviscid flow, it is either viscous flow or inviscid flow that is we consider in case of simplification. There is internal flow and external flow.

So, internal flow when the flow is enclosed. For example, flow is happening inside a pipe or a tube. External flow for example, when it is happening with some surface open say open drain flow, flow over a flat surface that is external flow. Then, we have compressible and incompressible flow. This all the flows by now you are aware of it.

One of the popular classification is laminar and turbulent and then we have understood natural versus forced flow, natural circulation and forced circulation. Then, also there is steady and unsteady flow; that means, the flow parameter changes with time, unsteady flow not changing with time steady flow. And of course, we have 1D, 2D and 3D flows. This is as the mathematical simplification of the flows that we consider. We have also gone through the velocity boundary layer and its concept.

We know what is surface shear stress. Surface shear stress is we write as:

$$\tau_S = \mu \left.\frac{\partial u}{\partial y}\right|_{y=0}$$

considering the fact that the flow is happening over a flat surface. There is a 0 velocity at this surface that is the no slip boundary condition exists, and this is the y and this is x direction where μ , we say the dynamic viscosity of the fluid.

Now, the fluids that obey the linear this kind of relationship, we call that as the Newtonian fluid. And in our discussions, we mostly restrict our discussion on this Newtonian flow. And there is a term ϑ which is called the kinematic viscosity, this term also you are aware by now which is $\frac{\mu}{\rho}$, dynamic viscosity by the density. The common unit is m^2/s or Stoke.

$$1\, Stoke = 1\frac{cm^2}{s} = 0.0001\frac{m^2}{s}$$

Now, to determine the surface stress we require this velocity profile. Now, the other approach in external flows that we relate this τ_S with the upstream velocity, if this is my V. What we write there:

$$\tau_S = C_f \frac{\rho V^2}{2}$$

C_f is the dimensionless friction coefficient whose value in most of the cases are determined experimentally and are typically given in a problem.

Now, this friction coefficient generally will vary with the location along the surface. So, once we have an average friction coefficient over a given surface, then that we can determine the complete the friction force over the entire plate is by:

$$F_f = C_f A_s \frac{\rho V^2}{2}$$

This friction coefficient is very important parameter in heat transfer also because it is directly related with the heat transfer coefficient and the pumping power requirement. Because eventually friction force determines how much energy you have to spend to pump or to flow that fluid over the surface. And in convection, this flow over fluid over a surface is vital or is essential. So, friction factor, the friction coefficient is also important in heat transfer study.

Now, the thing that I was mentioning about the thermal boundary layer, we will understand that in the next lecture. But before that I want you to go through once again with the various types of flow that we have mentioned here and again just refresh your memory about the velocity boundary layer because that is eminent again here in the case of convection.

With this, I stop here today. And we will see you in the next class with the Thermal Boundary Layer.

Thank you.