Chemical Engineering Fluid Dynamics and Heat Transfer
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Lecture - 32
Fundamentals and Mechanism of Heat Transfer (Contd.)

Hello everyone. Welcome back to the another class of Chemical Engineering Fluid Dynamics and Heat Transfer. In the last class, we started understanding the Fundamentals of Heat Transfer and its various Mechanisms.

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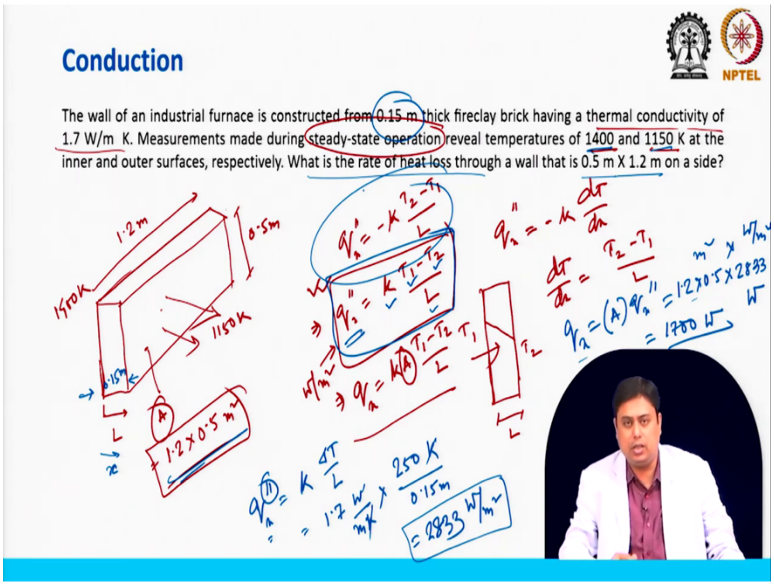

We continue on that particularly on the conduction part. So, in the conduction what we have seen is that, when we apply Fourier's law or say the basic equation of heat conduction to estimate the heat transfer rate or the heat flux particularly the heat flux when we have seen say:

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

in particular say x direction.

And when our temperature profile was linear inside this slab having two sides of two different temperature, what we did was that we approximated this as considering this as my width or the length of the slab the distance between the sides. And what happened after that? That q the heat flux became:

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

Or,

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

it becomes a positive value.

Now, based on this idea if we try to implement it or if you try to see its utilizations or application, we further have seen that this is the heat flux that is unit we have watt per meter square. If we try to understand that what is the overall heat transfer rate, then what we do? We multiply this with the area through which the heat transfer is happening the and this area is perpendicular to the direction of heat transfer.

Now, if we try to see its application these equations through this example that we have that the wall of an industrial furnace is constructed from 0.15m thick fireclay brick having a thermal conductivity of 1.7 W/mK. Measurements made during steady state operation reveal temperatures of 1400 and 1150 kelvin at the inner and outer surfaces respectively. So, the question is, what is the rate of heat loss through a wall that is of say 0.5 m × 1.2 m on a side.

So, if we think of a this slab the schematic of the problem this would look like that, we have slab that is of 1.2 m this is say the L that we have, the heat transfer on this the side that are happening is say this side we have a temperature which is of 1400 K and this side we have 1150 K the height of this slab say, if I this like. So, this is the schematic. So, this is the wall area that say is having a cross section this area that is A and this is this A is 1.2 × 0.5 m^2.

So, the question is that on the one side we have 1400 K, the other side we have 1150 K temperature. So, what is the rate of heat loss through a wall that is having a area of this much. So, the assumptions that we are making here or in fact, it is implicit here the first point that is mentioned is the steady state operation. Then we consider that this is an one dimensional phenomena that the one dimensional heat transfer is happening only through in one direction that is in this direction.

And this brick that has a thermal conduct with this fireclay brick that has a thermal conductivity of 1.7 W/mK. This thermal conductivity does not vary with temperature or in space it is uniform throughout the domain. Now, since the heat transfer is through the wall that is here, we are considering only by conduction. So, the heat flux that is happening we can estimate by this relation by this relation that we are looking into where we know the value of T_1, know the value of T_2.

Now, this is the value that we are looking into this k it is also given the L width is known to us that is of 0.15 m thickness. So, this is 0.15 m thickness we have to calculate simply what is the heat flux. So very simple problem, but the point is the reason I am showing this is that this is the fundamentals of the basic calculation that we start doing in conduction to estimate the heat flux and to apply this Fourier's law.

So, that means, here the x denotes that it is happening say only in the x direction if we consider this as x in one direction heat flux. So, it is basically

$$q_x'' = k\frac{\Delta T}{L}$$

that are happening. So, here the value of

$$1.7\frac{W}{mK} \times \frac{250\ K}{0.15\ m}$$

So, what we get here? The value that we get would have a unit that is of W/m^2 this K cancels out and we have W/m^2. This numerical calculation its trivial that you can do and it would have a numerical value close to this one 2833 W/m^2.

So, this is the heat flux that is happening for this problem. But the question is what is the rate of heat loss through the wall through a wall of this much cross section? So, the total heat loss that would we will have is basically this heat flux multiplied by the area through which it is happening which means, the q_x heat loss. Now, look at the difference we are not calculating heat flux which was designated by this double prime.

So, the heat loss is basically what we have? This

$$q_x = (A)\, q_x''.$$

That means :

$$= 1.2 \times 0.5 \times 2833\ W$$

And the value would be around 1700 W, so this is the simple problem that we have started with the solution the example. Now, the point here that we must understand that the heat flux has a direction and it’s a vector quantity, but the rate of heat loss the rate of heat transfer is not.

So, this is a simple problem, this is how we apply Fourier's law which we will see this in detail in when we take steady state conduction as the next lecture.

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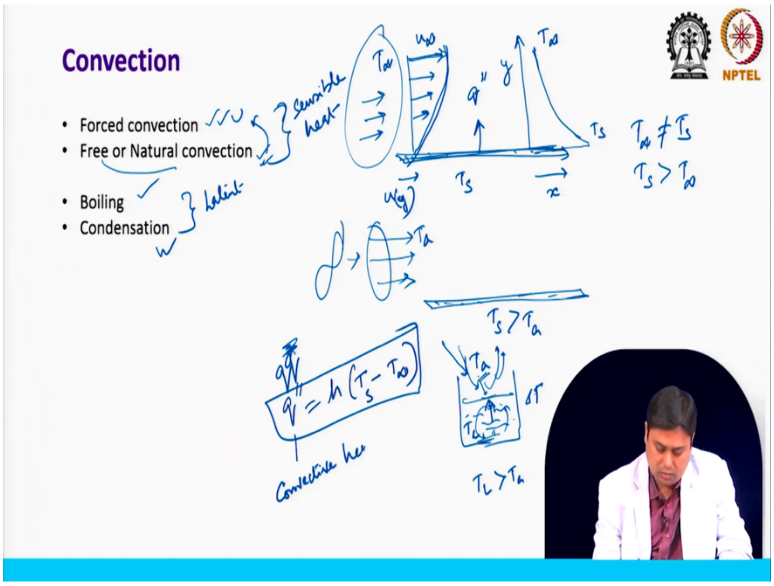

Now, again coming back to the fundamentals of convection, that I described in the last class is that typically that you see the similar thing when it happens there is a flow of liquid over a plate and the fluid temperature is at a different temperature than the this plate or the surface temperature.

We know that bulk motion is necessary for convection to happen and we also understood that there is the development of boundary layer whenever such situation occurs. And if our $T_s > T_\infty$, we also have a temperature profile that looks like this. The heat transfer direction the direction of heat flux is in this direction also. This is our velocity distribution, we call this as the free stream velocity when it is in the fully developed region U(y) we can write in this case.

So, now the point that we already discussed that there will be the development of hydrodynamic boundary layer as well as the thermal boundary layer. Now, along with this understanding. So, when we talk about convection there are two broad categories that we can define or we can characterize convection one is the forced convection, the other one is the natural convection.

So, this movement of the fluid when this happens by an external force, the bulk motion of the fluid when it is driven by an external force that is the forced convection. For example, there is a flat hot plate there is some air is blown by some external means either by fan or some anything else.

Now, this we are forcing the air to flow over this flat plate in order to cool it say for example, if this is the ambient temperature, T_a here and this is the surface temperature, T_s of the plate, $T_s > T_\infty$ then we are forcing the plate to cool down. Now, this movement by external force comes under the forced convection category. In other case, say we have a hot cup of tea or coffee.

Now, we leave it this is the ambient temperature, T_a and this is the tea liquid, T_L; $T_L > T_a$. Now, say we put this inside a room where there is no air flow, there is no bulk motion of the air and after sometime you would see that this liquid temperature or the tea temperature or the coffee temperature would eventually cool down and it goes near to the atmospheric temperature or the ambient temperature.

This happens by natural convection which means, once this air comes in the interface of this hot liquid surface and the air interface what happens, this density of this fluid the gas is reduced or decreases and then it goes upward due to the buoyancy force and the fresh air comes that is having a different temperature once it attains again as temperature that is similar to T_L, it also moves upward because it is now lighter, the density reduces.

So, at the same time due to this transfer the liquid temperature is also going down because the temperature of the air ambient air and the liquid temperature due to this difference in ΔT, there is heat transfer that is happening from liquid to air and this liquid is also cooling down and as it cools down it also inside this liquid pool its density varies with temperature.

And once this happens we know that once it is cooled it becomes heavier and it goes downward and the hotter liquid that is of having lighter density comes upward. So, there is a natural circulation that happens and that comes under the category the free or natural convection. So, either we sometimes call free convection or natural convection is naturally occurring.

It is enhanced this convection process is enhanced if we blow some air that we typically do when we get a hot cup of coffee or tea in order to cool it immediately, we blow some air over it through our mouth that enhances this heat transfer process and it becomes the free or natural convection, it becomes forced convection from natural to forced convection.

Now, these two convections forced and free convection, this reduces or increases temperature that we sense or in other words, this deals with the sensible temperature change or the sensible heat. Now, we know that there is other component which is called the latent heat where the temperature remains same, but the phase change occurs.

So, when that happens, so these two mechanism where we have the sensible heat transfer that is happening, but when the apparent temperature the temperature remains same, but the phase change occurs that is the latent heat transfer it becomes in a different category the convection is then categorized differently that is or two other special categories we call boiling and condensation.

So, boiling the example that you can immediately relate to is that when water is at 100ºC in liquid form, you still heat it, it goes to steam at 100ºC. This phase change when it occurs, we call that as the boiling. Similarly, from 100ºC steam to 100ºC of water droplet formation the first water that droplet that forms when you reduce the temperature or the heat source the first drop of water when it appears we say that it is now condensing.

So, that is the condensation. So, all these aspects we will discuss in details when we talk about convection. But regardless of how it is happening forced free boiling condensation typically or say I would say conventionally, this heat transfer process we typically write or we quantify by a simple equation which is again what is happening. So, this is the case that we usually consider for this convection process and we call this as the Newton's law of cooling.

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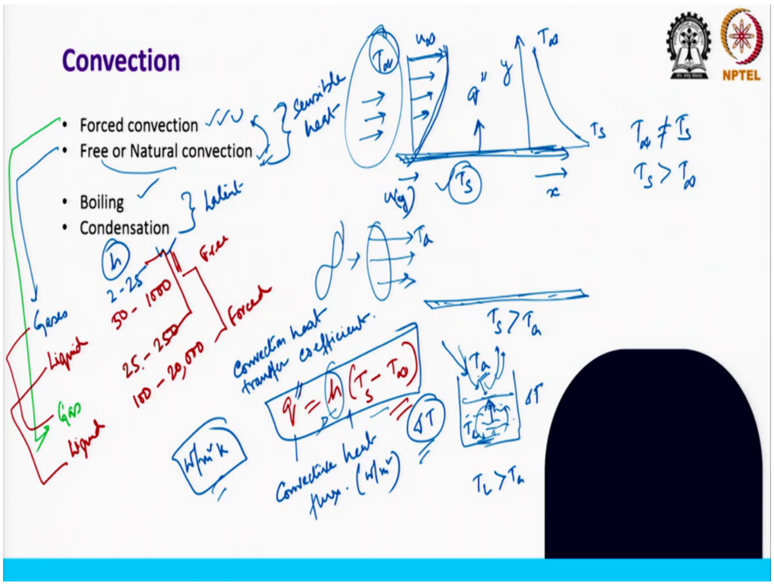

So, here again q_x'' is the convective heat flux in W/m^2. It is proportional to the difference between the surface and the fluid temperature. So, again h is a proportionality constant. So, q_x'', the heat flux is proportional to the temperature difference, ΔT of the solid and the fluid and this proportionality constant we call this as convective heat transfer coefficient that h we say that the convection heat transfer coefficient that has a unit of W/m^{2}K.

Now, this convection part when we will talk about, we will see that everything eventually would lead to that how we find out the value of h for different scenario. That is the overall objective or the goal of those studies would be that somehow, we have to find out what is the value or how do we estimate this convection heat transfer coefficient in order to calculate the amount of heat transfer that is happening by convection and that is complicated several scenarios because there are several situations, we will see are non-trivial and it requires some improvisation.

Now, let me just tell you a some of the usual values, then you would understand that a several processes say for example, forced convection, free convection and the value of h how it is enhanced or how a forced convection actually helps in cooling or heating a material more rapidly than the natural convection. Because now here from this equation you should be able to understand that the heat transfer rate or the heat flux is actually proportional to the value of ΔT as well as the value of h.

So, as h increases for a particular ΔT, temperature difference our heat flux increases and the magnitude it increases it increases on the similar way. So, for example, in free convection in gases say free convection in case of gases, the value of h is usually in between 2 to 25 the unit is W/m^2K. This is for free convection, for free convection if the fluid is liquid then this value of h varies between 500 to 1000.

So, by just changing the medium we see that for free convection how the heat flux or the heat transfer rate can be enhanced for a particular ΔT or the driving force which is the temperature difference of the surface as well as the fluid. If we talk about forced convection, so for forced convection again for the gases the value typically varies between 25 to 250, whereas that for the liquid changes somewhere in between 100 to 20,000.

Now, the reason of giving this magnitude you can quickly compare either between gas and liquid when the fluids is changed or the mode of convection when we change from forced to free to forced even for a particular fluid if this is the set of fluid that we consider.

So, it is significantly higher in the order of magnitude for the liquid for different liquid and from changing it from free to forced and the same for the gases as well. So, this gives us an idea that why or when forced or free convection to choose and the selection of medium in a design process.

So, I will stop here today on this with the fundamentals of convection, we have covered the fundamentals of conduction. In the next class I will just start with the brief introduction to radiation and we will now move to for the details on conduction, with this.

Thank you.