Chemical Engineering Fluid Dynamics and Heat Transfer
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Lecture - 56
Natural Convection

Hello, everyone. And welcome to the another section of Chemical Engineering, Fluid Dynamics and Heat Transfer. Today, we will discuss a brief overview on Natural Convection. Over the last few classes, we have talked about forced convection in external flow, also internal flow.

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Now, we move to natural convection and we will see a briefly its mechanism and the kind of correlations that are available in order to find out the convection coefficient. Because from the beginning, it is clear that in heat transfer, we are looking into particularly the amount of heat that is being transferred or the rate of heat transfer.

And at the same time, in order to do that, we find out what is the heat transfer coefficient. In conduction, it was the conductivity values. In case of convection, it is the convection coefficient and in radiation, the similar parameter that we will look into, but a few lectures later.

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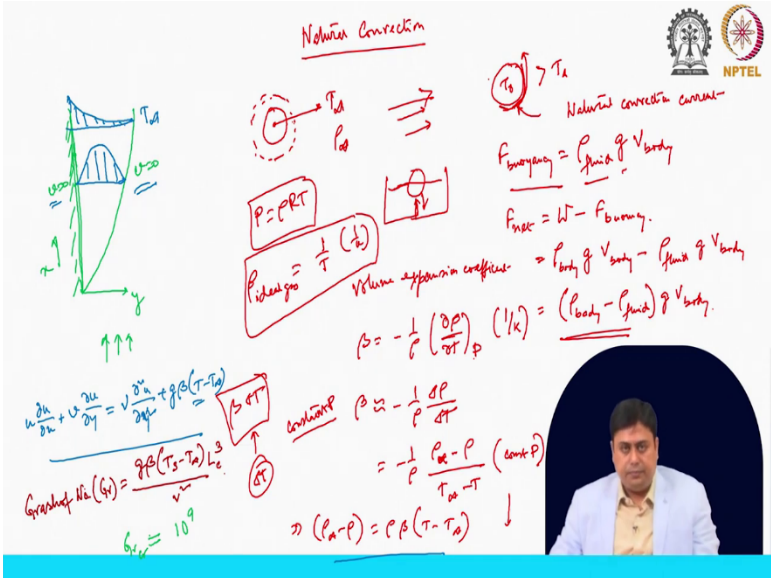

Now, in this case, In natural convection, in natural convection, what happens? There is no bulk motion of the flow, but then how the convection is happening. So, for example, you have a hot object that you place in a stagnant air, the room that is no bulk motion of the air; it is a kind of a peaceful room. And there, if you leave that object, if this object has a temperature T_o, which is greater than the ambient temperature, along with radiation, there will be the convection.

Now, what will happen? Immediately, once you place this hot object or hot object in a in atmospheric temperature, where the temperature is lower than the object, what will happen? The outer surface, the solid surface that comes in contact with the air, that from that surface, the heat conduction will happen and immediately, the nearest layer around this surface will be covered by a layer of hot air.

Now, the point is that initially, immediately once it is just in instant of time, once it is wrapped by a layer of air, then the point is that the transfer rate, the heat transfer rate will decay slowly. But eventually, the energy transfer will continue until it reaches a steady state.

So, once the air comes in contact, which is at a relatively cooler temperature, then the object, once it comes in contact with the object, what will happen? That air temperature will go up, at the same time, its density will be lower. So, there will be lighter, air and it is surrounded by heavier. The density of the gaseous phase drastically changes with temperature.

Now, based on that fact, what will happen? That immediately, once this nearby region of the surface, the air which is now having a higher temperature than the surrounding temperature, this density due to the buoyancy effect, it would go upward. And that position, that why that it creates will be filled by the surrounding cooler here.

And then, this circulation of air will continue, even though there is no bulk motion of the air, that this room is not filled or not regularly pumped or blown with some air. It will happen inside the room itself and without any visible effect of circulation.

The temperature will slowly go down, but at infinite state, it will come at a steady state with the room temperature. So, which means there will be a natural convection current. And this mode of heat transfer is called the natural convection heat transfer. Now, the point is that this convection, natural convection is as effective heating a surface or cooling a surface in a warmer or a cold environment.

Now, in a gravitational field, what happens if there is a density difference between two fluids? What happens, The lighter fluid goes upward and the heavier fluid settles down. It is the similar phenomena that happens here as well. That as a fluid comes in contact with the hotter surface or the hot object its density changes. Once the density changes or becomes lighter, it goes it generates a natural current of flow.

So, the point is that we know the buoyancy effect. The buoyancy effect that we are aware in the cases we what we can write about the buoyancy effect? The buoyancy force is essentially density of the fluid that is being displaced, g and the volume of the portion of the body that displaces fluid or emerged in a fluid i.e.

$$F_{buoyancy} = \rho_{fluid} g V_{body}$$

We know Archimedes principle. So, it is essentially on the same principle where we calculate the buoyancy force.

Now, what happens in the buoyancy force? This ρ_{fluid} we have to remember that this is this density of the fluid not of the solid object. The fluid the amount of fluid it displaces that fluids density, g is the gravitational force and v body is the volume of the body or the portion of the volume of that body that is emerged in a fluid the amount of fluid it displaces.

So, in absence of any other forces when you drop a object say in a pool of liquid the object will be emerged or it will float depends on the net force that acts on this body. So, there is upward buoyancy force and its weight that drags it down inside the pool of the liquid. So, the F_{net} force is essentially:

$$F_{net} = W - F_{buoyancy}$$

$$F_{net} = \rho_{body} g V_{body} - \rho_{fluid} g V_{body}$$

So, eventually the net force that acts on this body is:

$$F_{net} = (\rho_{body} - \rho_{fluid}) g V_{body}$$

So, the amount of weight loss this object feels is this density difference between the fluids in which it is emerging or it is floating. This is essentially the Archimedes principle that we knew.

Now, the point is that when a object is having a higher density average density greater than the density of the fluid then it drops or it is completely emerged. Now, when it is exactly same as that of the fluid the density are matched. It is kind of a emerged or some emerged sub emerged condition.

That is it is actually inside the liquid pool not touching the bottom, but it is floating somewhere in the middle. So, and the other case when this is higher or this is lower this body floats when the density average density of the body is lower than that of the fluid it floats on the surface.

So, the point is that the same principle actually is responsible for this natural convection that when this air gets lighter because of the higher temperature region as it enters the higher temperature region, it gets lighter, it floats it goes upward or it goes from that positions to upward and those void positions are then filled by again a fresh or the cooler air, which is the and this process continues until a steady state is reached. So, eventually this natural convection process is unsteady in nature.

Now, the point is that in heat transfer studies the primary variable that we consider or we try to find out is the temperature or the temperature change. So, the point is that this density now we have to write in terms of temperature and then we can find some relation. That , we understand that there is density difference between the body and the fluid and what would be the buoyancy force, but then where this temperature comes into play.

Now, the variation of density of a fluid with temperature at constant pressure this knowledge we have to now translate here and the property that provides that knowledge we call that as the volume expansion coefficient, β. So, β is defined as:

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p$$

It has a unit of (1/K).

So, this expansion coefficient now the point is that the condition of fluid when it is sufficiently in this case a object there is a nearby region where the temperature changes are effective or are failed, but at a significantly far away from this object the that impact is not understandable. So, the temperature in this cases we is that T_∞ far away from the object.

Now, the volume expansion coefficient that we can write by instead of this with a help of differential quantities is that:

$$\beta \approx -\frac{1}{\rho}\frac{\Delta \rho}{\Delta T}$$

$$\approx -\frac{1}{\rho}\frac{\rho_\infty - \rho}{T_\infty - T}\ (constant\ p)$$

$$\rightarrow (\rho_\infty - \rho) = \rho\beta(T - T_\infty)$$

Where ρ_∞ is the density of the fluid that is far away from this object, or the quiescent fluid. T_∞ is the temperature of the quiescent fluid that is far away from the surface where, this natural convection is taking place. Now, for ideal gas:

$$P = \rho RT$$

$$\beta_{ideal\ gas} = \frac{1}{T}(1/K)$$

where T is the absolute temperature. So, the large value of β for a fluid means large change of volume or density last, I mean a significant change in density with temperature. And the expression ($\beta\Delta T$) this parameter presents the fraction of volume change of a fluid that corresponds to the ΔT at a constant pressure.

So, if we change the temperature ΔT this corresponds to change in volume at constant pressure. Now, the buoyancy force is proportional to the difference of density at constant pressure. So, the larger the temperature difference the larger would be the buoyancy force. Buoyancy force is essentially is proportional to the density difference.

As the temperature difference is larger the density difference should be larger and accordingly there will be the enhancement or significant impact of natural convection would be failed. So, there will be more circulation natural circulation or natural convection currents.

So, as the density difference is larger what we have is the at constant pressure the temperature difference resulting in the larger buoyancy force and stronger the natural convection current. So, the heat transfer rate would be higher. Now, the magnitude of natural convection heat transfer between the surface and fluid is directly related to the flow rate of the fluid.

Now, here again the flow rate means the natural circulation of the flow that is happening and higher the flow rate higher the heat transfer rate. So, at a very high flow rate; that means, the heat transfer coefficient increases by the order of magnitude and that is why in case of forced convection the rate of heat transfer is much higher than this natural convection.

But then why natural convection we are studying or why it is important to understand? Because there are several scenarios practical as well as design problems that where there is no space or no option to provide some external force in order to flow the fluid. For example, nowadays the compact laptops the ultra books, the notebooks etcetera. Where, the placement of fan itself takes some place, but the chips need to be cooled. Now, those cases these air vents and all these designs are there that actually does this work of natural convection.

Now, as the surface area increases as in case of fins say for example, we augment fins as we have seen in case of conduction in order to increase the surface area. So, that the contact between the gas the liquid and or the solid phase or the gas or the liquid solid phase the contact surface increases, which enhances the heat transfer rate.

But the in case of natural convection what happens there is a competing medium as you increase the surface area it increases the frictional forces between the fluids and the solid surface. And as that happens as the frictional forces increases the relative movement of the fluid and the surface decreases. If it decreases the natural convection rate decreases. So, that is why all these things are important to understand at the same time in order to design an equipment carefully and optimize its operation.

The other thing that must be prominent from here or you should be clear in mind that in absence of gravity there would be no natural convection. If there is no gravitational force there would be no convection and that is why in space if the spacecraft where the gravity force is not there is no natural convection. The heat transfer mode in such case in absence of any external flow is by conduction.

So, based on this understanding now if we look at the governing equations of the flow of the because once this natural convection is there for example, here to feel the effect of gravity let us consider there is a vertical plate some liquid or air is flowing from bottom to top upward. Now, this direction say we y and this direction we x the flow direction we consider x and normal to it is y-direction.

Now, once it flows over it there is also the development of boundary layer and like forced convection on an external surface here also the boundary layer grows infinitely as the along the direction of the flow.

Now, the point is that the difference here is that here the velocity is 0, no slip boundary condition we consider. In case of forced convection here outside there was free stream velocity outside the boundary layer, but here in natural convection the free here there is no free stream velocity the air is supposedly stagnant. So, here also the velocity is 0 of the fluid.

So, which means the velocity profile in this case is expected to be something like this that it would reach a maxima somewhere at the middle and again it drops to 0. The temperature profile, if this plate is hotter if this is a hot plate, which is suddenly being cooled by or placed in air vertically in order to be cooled. So, then this boundary layer develops and the temperature profile becomes something like this it becomes the temperature profile.

So, again elemental differential elemental analysis. So, here as like the forced convection the continuity momentum equations etc. can be derived the with the only difference that I mentioned here is the boundary conditions that at a far distance or outside the boundary layer the velocity would be 0. And T is T_∞ here that we consider the infinity is far away from the plate or the surface where there is no influence of this temperature change or the coefficient fluid.

Now, in those cases what we see is that the momentum equation on the right hand side we see there is a change unlike the forced convection where we see that. So, based on this directions that we are considering a governing equations the equations that governs the motion of the flow in the boundary layer:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \vartheta\frac{\partial^2 u}{\partial y^2} + g\beta(T - T_\infty)$$

This parameters this temperature difference comes in place of the density. The density as I mentioned here is replaced by the volume expansion coefficient values. And then in this respect once we non dimensionalize this equation what we find a non dimensional number, which is extremely important in case of natural convection is called the Grashof number:

$$Grashof\ No., Gr = \frac{g\beta(T_s - T_\infty)L_c^3}{\vartheta^2}$$

This tells the impact of Grashof number in natural convection is analogous to the impact of Reynolds number in force convection.

This Grashof number if we look at this expression carefully what it tells it tells the ratio of buoyancy force to the viscous force. The physical significance is that this is the ratio of buoyancy force and the viscous force it tells which one is dominant and accordingly it defines the flow regime.

So, here similar to that in case of this flow over say flat plate I mean here there is no as such bulk flow, but when a flat plate this natural convection boundary layer is considered what has been seen that the critical Grashof number is about 10^9. Grashof critical is around 10 to the power 9 a flow regime on a vertical plate becomes turbulent at Grashof number, $Gr > 10^9$ this is the significance and below it we consider this as laminar flow.

Now, the point is this critical Reynolds number varies with the orientation of the plate or for different geometry that we have seen in previous cases. So, as I mentioned its impact as that of the Reynolds number in case of forced convection. So, what happens? That once we calculate Grashof number for such problem or for natural convection.

We classify the problem as either laminar or turbulent and then there are correlations or empirical relations that are proposed in order to calculate the Nusselt number exactly the process that we did in the previous classes. So, with this I will stop here today and we will be back in the next class to show you a few relations that are available in natural convections to calculate Nusselt number based on this Grashof number.

Till then thank you for your attention.