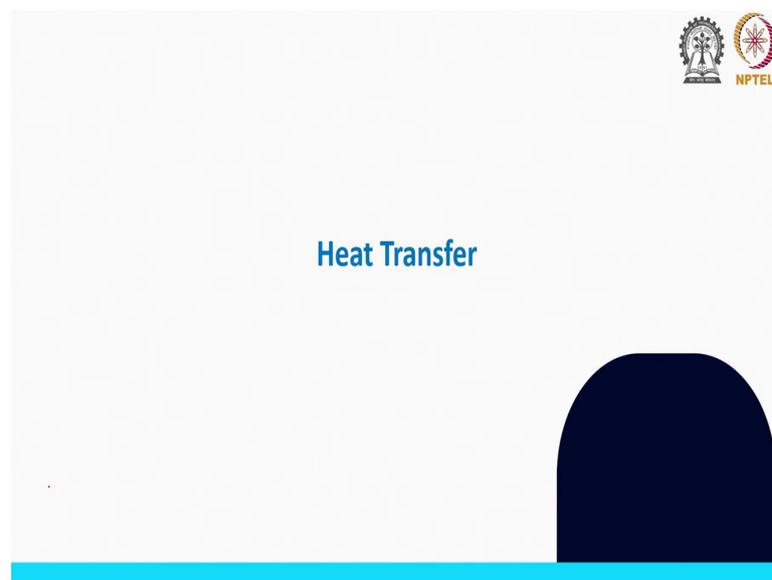


Chemical Engineering Fluid Dynamics and Heat Transfer
Prof. Arnab Atta
Department of Chemical Engineering
Indian Institute of Technology, Kharagpur

Lecture - 57
Natural Convection (Contd.)

Hello, everyone. Welcome back once again with another lecture on Natural Convection in Chemical Engineering Fluid Dynamics and Heat Transfer.

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We were discussing in the last class the mechanism of natural convection and the importance of Grashof number. The impact of Grashof number in natural convection is that of the Reynolds number in forced convection. It helps us to determine the flow regime and once we determine the flow regime, we can choose appropriate correlation for Nusselt number calculation.

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$$Nu = \frac{hL_c}{k} = C(Gr.Pr)^n = C(Re_L)^n$$

$$Re_L = Gr_L.Pr = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2} Pr$$

$$T_f = \frac{T_s + T_\infty}{2}$$

$$\dot{Q} = hA_s(T_s - T_\infty)$$

$n = \frac{1}{4}$ Laminar flow
 $n = \frac{1}{3}$ Turbulent flow
 $C < 1$

$Re_L \rightarrow 10^5 - 10^9$
 $Nu = 0.59 Re_L^{1/4}$
 $Re_L \rightarrow 10^8 - 10^{10}$
 $Nu = 0.1 Re_L^{1/3}$

So, in case of natural convection it has been seen that the Nusselt number:

$$Nu = \frac{hL_c}{k} = C(Gr.Pr)^n = C(Re_L)^n$$

$$Re_L = Gr_L.Pr = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2} Pr$$

Now, this value of C and n in this cases C and n depends on the geometry of the surface that we are looking into and the flow regime. Now, which is again characterized by or categorized by the Rayleigh number calculation the range of Rayleigh number. Usually, the value of n is 1/4 for laminar flow is equals to 1/3 for turbulent flow and constant C is usually less than 1.

Now, the parameter of while considering from the reference book or the table like we did in the previous cases that at which temperature we should choose the fluid properties that is similar to the previous understanding is that it is calculated at the film temperature,

$$T_f = \frac{(T_s + T_\infty)}{2}$$

T_s is the surface temperature for the vertical plate this is the T_s and this is the T_∞ outside the boundary layer.

So, all the fluid properties should be taken at the film temperature when the average Nusselt number and subsequently this average heat transfer coefficient is known. Then the rate of heat transfer like we calculated earlier can be calculated simply from this relation:

$$\dot{Q} = hA_s(T_s - T_\infty)$$

where, A_s is the surface area across which this natural convection is happening and h is the average heat transfer coefficient.

So, strategy remains similar it is just now the correlations changes. So, now depending on as I mentioned the orientation the shape of the geometry there are several correlations available. Let's say you here a couple we will not going to the further details because those increases the number I mean as we go changing the domain size or the domain shape or the orientation several type of correlations appear.

So, for example, as in the case of vertical plate as we mentioned here in this case say for example, this vertical plate if the Rayleigh number ranges from 10^4 to 10^9 . Then the Nusselt number takes a form Rayleigh number to the power $1/4^{\text{th}}$ i.e.

$$Nu = 0.59Ra^{\frac{1}{4}}$$

In case this range changes from 10^9 to 10^{13} Nusselt number takes a form Rayleigh number to the power $1/3^{\text{rd}}$.

$$Nu = 0.1Ra^{\frac{1}{3}}$$

So, several researchers came up with several such correlations that is the best fit for their range of operation. Again, some researchers have tried to come up with more generic expression or for the entire range of the flow of this Rayleigh number is sometimes more complex in nature, but is more accurate and it is pointless to try to remember those relations because as I mentioned earlier repeatedly that these relations should be chosen from the reference book or the textbook whenever it is needed for design calculations.

So, similar to that instead of vertical plate if there is a cylinder again a new correlation is there. This cylinder is oriented instead of vertically it is horizontally depending on the Rayleigh number again a new correlations is given. So, those can be seen from the textbook will not go into every details of it.

So, as I mentioned several geometries several orientations different correlations comes up. So, in all the cases the strategy of solving a problem is exactly identical that we have seen in the previous section that at first what we do we classify the problem whether it is laminar or turbulent.

Now, here instead of Reynolds number in force convection based on the Grashof number of the Rayleigh number we classify it. Once it is done, we choose appropriate correlation for laminar certain set of correlations are available for turbulent another set of correlations are available. We have to now look into the domain shape orientation etc and we have to choose the nearest kind that is available in the literature.

Now, the point is the combination of force and natural convection can there be scenarios for that yes of course, like we had the hybrid cases of certain portion laminar and then fully turbulent. So, in the presence of temperature gradient in the fluid in gravity there always be a natural convection. So, that means, heat transfer by natural convection would be imminent. So, forced convection is always accompanied by natural convection.

In gravitational field whenever there is a temperature gradient in fluid there will be natural circulation. So, natural convection is inevitable even in the case of forced convection, but now comes here the relative magnitude of it the dominance of it. Forced convection is so dominant that calculation of natural convections in those respect are meaningless.

However, there is a parameter that defines or that demarcates a certain line that when we can neglect and when we cannot the contribution of natural convection. So, natural convection eventually there can be scenarios, which assist the heat transfer in case of forced convection as well. In other case it can contradict there it can actually oppose it tries to diminish the influence of or the heat transfer enhancement by forced convection.

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$$Nu_{comb} = [Nu_{fg}^m + Nu_{fm}^m]^{1/m} \quad m=3.69$$

$$Q = hA \Delta T \quad h \propto T_s$$

$\frac{Gr}{Re^2} < 0.1$ negligible natural convection
 $\frac{Gr}{Re^2} > 10$ negligible forced convection
 $0.1 < \frac{Gr}{Re^2} < 10$ mixed convection

Assisting flow
 Opposing flow

For example, there is a vertical plate a fluid is flowing over it now this is done by forced convection a forced flow. Now, since we have considered the flow the plate directions in vertical manner. So, eventually the flow is happening like this as well as externally there will be flow.

So, inside this boundary layer there is natural convections like we have seen. Now, eventually here the direction of natural convection and because here the buoyant flow is happening upward, whichever fluid is coming in contact with the water surface it goes upward by natural current. At the same time there is a forced flow of fluid from this bottom to top, which means this natural current is assisting the forced convection.

So, in this case we can call this is as assisting flow. In the other case consider there is a flat plate now the liquid is flowing from top to bottom by natural convection, but then still the forced flow is in this direction. So, there is some liquid is being poured over it on a flat surface due to gravity it would come down. Now, as it comes in contact with the hotter surface the fluid will have a natural tendency here, but due to gravity it is pulling it down the buoyant flows would be in this direction the buoyant flow.

And it is in opposition with the forced convection flow that is we are flowing from bottom to top. And this happens in case for example, if this is a cold plate if this is a cold plate and some hot fluid is poured over it. As the hotter fluid comes in contact with this cold surface what will happen the density of the fluid immediately goes higher. And if it is goes

higher, it will come down, but in its opposite we have a forced flow that it pulling it upward.

So, in this case it is the opposing flow. In other case what can happen is the transverse flow. For example, here in this object there is a natural current like it goes in this direction and your fan position is somewhere in the transverse direction. So, in this case what will happen in the transverse direction buoyant motion is perpendicular to the forced motion. So, transverse flow eventually would enhance fluid mixing and eventually enhance heat transfer.

In opposing flow buoyant motion is in opposite to the forced direction. So, natural convection would try to resist forced convection and it decreases heat transfer. In assisting flow buoyant motion is in same direction as that of the force flow it enhances heat transfer. So, the point is in certain cases Nusselt number combined would be eventually be calculated based on Nusselt number forced plus Nusselt number natural convection correlations.

$$Nu_{combined} = [Nu_{forced}^n + Nu_{natural}^n]^{\frac{1}{n}}$$

Where, Nusselt number forced is determined from the correlations for pure forced and this is for the pure natural convection plus sign or minus sign depending on whether it is assisting flow or whether it is opposing flow depending on that the value of this the signs plus or minus would be determined.

The value of n this exponent n typically varies between 3 or 4 depending on the geometry that is observed. So, it has been seen when n is 3 it works better for the vertical surfaces. This is simply the experimental observation and the empirical correlations. So, the question that typically comes that cooling of a heat generating equipment any electronic component that you can consider is whether to use a fan or to use its natural convection or forced convection cooling equipment.

The answer actually depends on the allowable temperature that it can operate because we know that Q convection is essentially $(hA\Delta T)$, h is the heat transfer coefficient, A is the surface area. So, for a fixed value of power dissipation if we know that this amount of energy that needs to be dissipated and the surface area is fixed. Then what we have h and ΔT or the surface temperature because ambient temperature is also fixed.

The surface temperature and h are inversely proportional. So, the device that you under consideration will operate at higher temperature when h is low, if that is the condition then natural convection is fine because that is the typical value of natural convection.

Because h would be definitely smaller in natural convection. If your device can operate at higher temperature and that is within the allowable temperature with the minimum h you can operate with the extra without any extra space for the application of fan or position of fan.

If that is not the case you have to increase the h in order to reduce the T_s the object temperature or the surface temperature and so, you have to use forced convection. Now, the point that I was talking about earlier that when to consider the combination or when not; that means, what is the demarcation between whether I should consider natural convection along with the we should consider forced convection along with natural convection or simply just forced convection because natural convection is so negligible.

Now, that is determined by the calculation of a number or a parameter which is again the Grashof number and Reynolds number relation. So, $\left(\frac{Gr}{Ra^2}\right)$; parameter this tells us the relative importance of natural and forced convection. Grashof number represents the natural convection part Reynolds number represents the forced convection part. The natural convection is negligible when $\left(\frac{Gr}{Ra^2} < 0.1\right)$. Forced convection is negligible when $\left(\frac{Gr}{Ra^2} > 10\right)$.

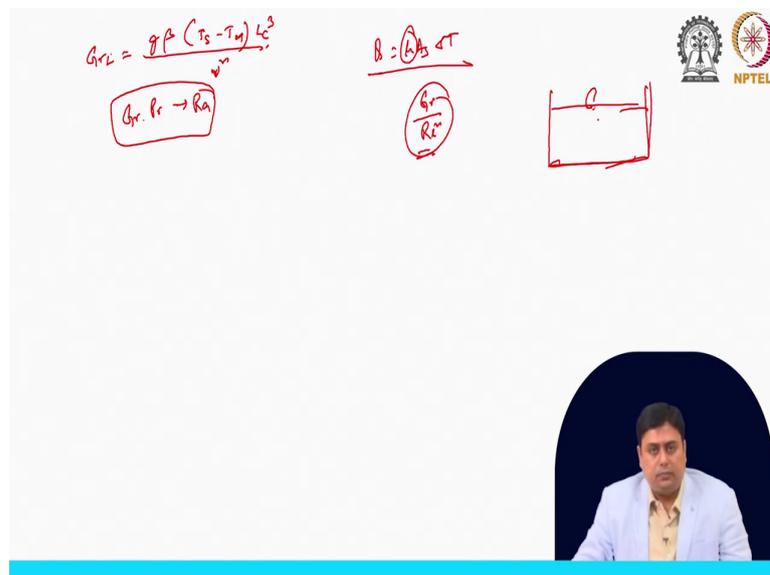
So, in this case it is negligible natural convection in this case we have negligible forced convection. Now, this is a rare case that forced convection is negligible, but there is dominant natural convection. But the situations may arise and neither one is we can neglect when this comes in between this value anything in between we have to consider both component and; that means, this combination of Nusselt number.

So, I hope this natural convection in a Nutshell a very briefly is clear to you. So, what happens here is that as I mentioned we cannot go beyond a certain value as there is change in sensible temperature. Now, the point is that for high power output devices where the higher energy changes are necessary the forced convection is also sometimes is not sufficient to keep the surface temperature at a desired level.

Now, in those cases we have to look beyond the change in sensible temperature and we have to include the consideration of phase changes and that happens in boiling and condensation. This is a complicated extension of natural convection because in boiling and in condensation without the sensible temperature change the phase change occurs from liquid to vapour and from vapour to liquid in case of condensation.

So, before going into that or a very brief overview of boiling and condensation that we will see in the next class what we have done here in a summary if we look at it what we have understood the concept of Grashof number.

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The Grashof number is:

$$Gr = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2}$$

So, this tells us or this classifies the problem in laminar or turbulent region. Here the characteristic length for a circular pipe or a circular cross section the characteristic length is diameter of the cylinder or a pipe. Now, the point is that this Grashof number multiplied by Prandtl number gives us the Rayleigh number ($Gr.Pr = Ra$).

Based on the Rayleigh number or the Grashof number we classify the problem to be either laminar or turbulent and when we classify it then we actually look into the appropriate correlations that are available for that particular geometry or the domain whether its

vertical, its horizontal, its slanted based on several orientation and the laminar or turbulent this subset there are several correlations available for Nusselt number.

Once we find the Nusselt number which means we find the average heat transfer coefficient. Once we have this, we use the simple Newton's law of cooling that we have understood very clearly that it is: $Q = hA_s\Delta T$. We know ΔT , we find the amount of heat transfer or the rate of heat transfer that is happening the heat flux or the heat transfer rate.

And then we have also seen the demarcation line between the dominance of forced and natural convection whether we should have the combination of natural convection and forced convection or one of those because, forced convection automatically comes with natural convection.

But as I mentioned its importance or its contribution is so, mild that usually in the calculations that are those are not included. But the calculation of $\left(\frac{Gr}{Ra^2}\right)$ will give us an idea whether this parameter this dominance of natural convection or dominance of forced convection can be neglected or not; If $\left(\frac{Gr}{Ra^2} < 0.1\right)$ we can neglect the contribution of natural convection because in that case; that means, denominator is very high which means the Reynolds number impact as in forced convection is very high. However, $\left(\frac{Gr}{Ra^2} > 10\right)$ then we consider only natural convection; that means, in that case the importance of Grashof number is huge.

And we cannot neglect the consideration of or the contribution of natural convection in between these two values anything we have to consider both of their contribution. But as I said that sometimes this sensible heat transfer or the heat change is not sufficient in certain cases the change in sensible temperatures.

And we have to consider the cases where phase change occur and that also happens by natural convection because when you boil a pool of water. When you boil a pool of water what happens there is no bulk movement of the liquid it is the stagnant liquid pool.

So, it is not forced convection, but it is a classification of natural convection where the phase change occurs at the surfaces and we will see that brief overview of those different types of regimes in boiling as well as in condensation in the next class. Till then I wish that you go through all these materials that has been covered because we will briefly

overview this boiling and condensation without going into much details of it. And then we will finish this course by discussing the basics of radiation.

Till then thank you for your attention.