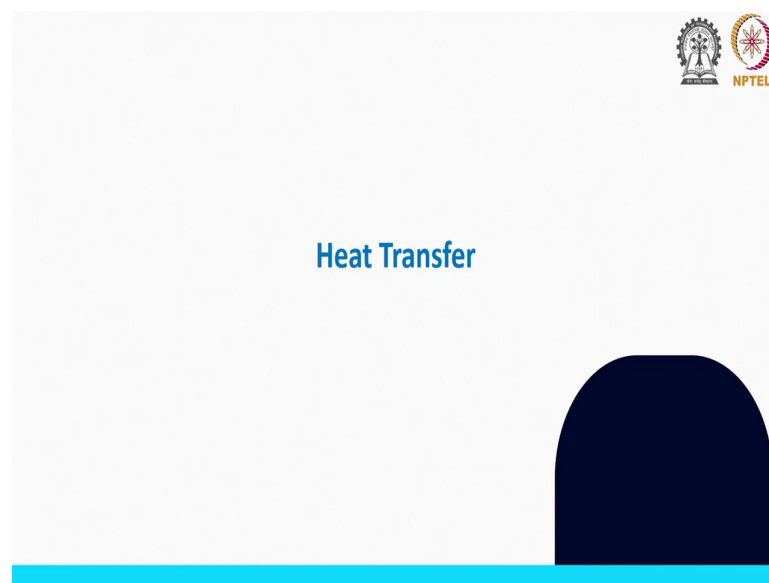


Chemical Engineering Fluid Dynamics and Heat Transfer
Prof. Arnab Atta
Department of Chemical Engineering
Indian Institute of Technology, Kharagpur

Lecture - 58
Boiling and Condensation

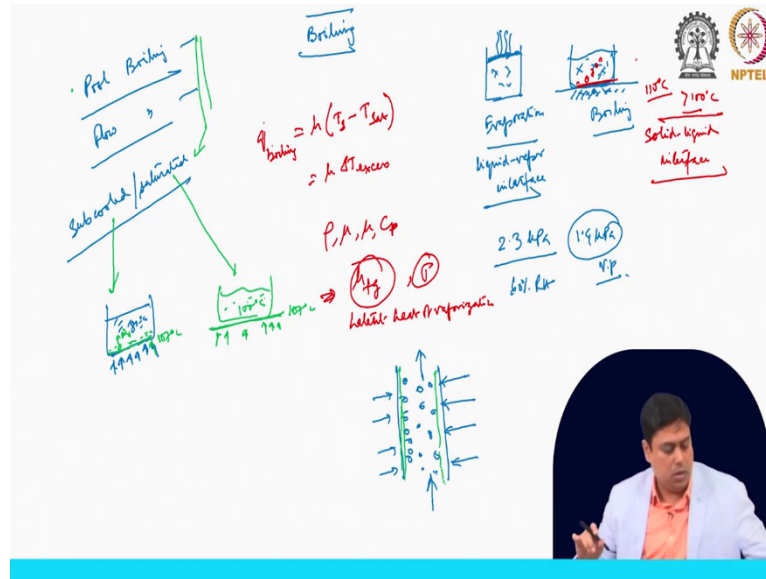
Hello everyone, welcome back once again with another lecture in Chemical Engineering Fluid Dynamics and Heat Transfer.

(Refer Slide Time: 00:39)



We are in heat transfer segment where we are specifically discussing convection, conduction and radiation mode of heat transfer. We have covered conduction and convection most of it the convection.

(Refer Slide Time: 01:16)



Today we will discuss briefly an overview of Boiling and Condensation which is an extension of natural convection to start with boiling. There are several examples that we find in our day to day application and most of the times we mix or confuse with the two situations one is the boiling the other one is the evaporation.

So, what happens is that when you place a glass of hot water in a pan you place it on a electric heater with a pool of liquid. Now, when this glass of water hot glass of water is there placed naturally on cooler environment. What will happen this at the interface or this liquid will try to cool down and you see a vapor that is coming out from that hot cup of water or hot glass of water.

The other scenario is that you have a stagnant pool of liquid in a pan and you start heating that and then after a certain time you see some steam on top of the pool of liquid or that is coming out from the heating pan. Now, one case is evaporation the other one is the boiling. So, the first case is that we see is essentially evaporation and the second case is boiling.

So, boiling is a liquid to vapor phase change process in this case when the liquid temperature goes above its saturation temperature then it start forming vapors. So, liquid to vapor phase change just like evaporation in this case the similar thing is happening, but there are technical differences and one of the significant difference is that the evaporation takes place from the liquid vapor interface.

When the vapor pressure is less than the saturation pressure of the liquid then it will evaporate. For example, water if we take at 20 °C, will evaporate to air at 20 °C if we have the pressure above 2.3 kPa. Now, say if the relative say for example, here as I mentioned that water at 20 °C will evaporate to air at 20 °C depending on what is the relative humidity as well.

So, say if it is there is 60 % relative humidity. Because at that condition the vapor pressure of water is 1.4 kPa. So, when this happens the evaporation takes place from the liquid vapor interface; that means, this is the liquid vapor interface from the top. However, in case of boiling it occurs at the solid liquid interface. That means it starts at the solid liquid interface.

So, when a liquid that you brought into contact with a surface that is maintained at a temperature sufficiently above its saturation temperature because that is what this heater does. It brings a temperature significantly higher or at least higher than its saturation temperature and then the boiling starts. There also the phase change occurs from the liquid phase to the vapor phase.

So, at 1 atmosphere liquid water in contact with a solid surface that is at 110 °C will boil because, at that temperature at that pressure that at atmospheric pressure the saturation temperature of water is 100 °C, which is greater than that currently.

So, the boiling process will be characterized by the rapid formation of vapor bubbles at the solid liquid interface and will start to detach from the solid liquid interface and will go upward. It will start to rise on the top. So, this is the complicated process boiling because what happens a large number of variable is involved in this process and the complex fluid motion further complicates the whole understanding.

But since this is a form of convective heat transfer the boiling heat flux which is eventually our goal is to calculate the \dot{Q} , if it is boiling. In the same form like in the other cases that we have done what we can write is:

$$q_{boiling} = h(T_s - T_{sat})$$

Which is in fact called the excess temperature that is this is the excess temperature this temperature difference between the surface temperature and it is the fluid saturation

temperature is called the excess temperature. That represents the excess temperature of the surface that is working above its saturation temperature.

So, in this case along with this ρ, μ, k, c_p all the terms are there the Prandtl number everything would be there as well as since this is a phase change process that is happening that is from the liquid to vapor. There is an important or critical parameter a properties that we must be aware is called the latent heat of vaporization. It is called the latent heat of vaporization as well as it involves surface tension force or the parameter surface tension the value of surface tension because the bubbles are forming.

So, this latent heat of vaporization it actually represents the energy that is absorbed per unit mass of the liquid that vaporizes at a specified temperature or pressure and it is a primary quantity for energy that is transferred during the boiling heat transfer. Now, the value of this property or this parameter are usually given and mostly available in as the appendix or in table of various or all the text books that are there.

Now, the bubble forms because of the surface tension or particularly at the liquid vapor interface what happens? The liquid molecules they have their own attraction force on the molecules and the interface towards the liquid phase is tries to retain its shape with this attractive forces.

Now, this surface tension decreases as we increase the temperature and becomes 0 at critical temperature and that is why there is no bubble formation at the super critical pressure and temperatures. So, the boiling process does not happen at equilibrium.

And this is not a thermodynamically equilibrium process the boiling process and the temperature and pressure of the bubble is different than the bulk fluid temperature and depending on this temperature and pressure difference either the bubble collapses or grows or it ruptures.

So, when the liquid is at higher temperature than the bubble the heat will be transferred from the liquid to the bubble. And that causes the bubble to grow and it would rise to the top due to this density difference and the buoyancy force, which is the characteristics of the natural convection and that is why it is an extension of the natural convections because initially there is no bulk motion of the fluid.

This temperature difference this density difference and the phase this density difference mostly appears because of the phase change and that leads to a significant natural current generation inside the liquid pool. Now, depending on the presence of the bulk motion along with this the boiling it is classified the boiling is further classified in several segments or several categories.

So, boiling is called pool boiling in absence of any bulk liquid flow. The thing that we are mentioning here where there is initially no bulk motion of the flow or any time there is no bulk motion of the flow, we call that as the pool boiling and when forced convection is associate with the boiling, we call that as the flow boiling.

So, this is the natural convection boiling in other words and this is forced convection boiling. So, in pool boiling liquid is stationary and any motion in the fluid is due to the natural convection current and motion of the bubble that is under the influence of gravity or buoyancy in other words.

Now, the point is the pool boiling in the flow boiling the fluid is forced to move from one place to other. For example, in a pipe the flow is happening along with that the side walls are at higher temperature the heating is happening of this pipe and along with that there is a bulk motion of the flow.

So, in such case when the fluid is forced to move through a heated pipe or say over a flat plate by some external means such as pump in that case, it is always accompanied by other convection methods. That it is now not only the pure natural convection because natural convection always comes with a forced convection that we discussed in the last class.

Sometimes its magnitude is lesser, but when it is dominant, we cannot neglect it. Now, the point is that this pool and flow boiling these are further classified in different regime. And those are called sub cooled or saturated boiling depending on the bulk liquid temperature this sub cooled or saturated boiling can take place.

So, the boiling would be called sub cooled when the temperature of the liquid is equals to the saturation temperature that is the bulk liquid is saturated. So, when you have a pan of liquid that is being heated and in this case the liquid temperature is exact at $80\text{ }^{\circ}\text{C}$ and this is at $107\text{ }^{\circ}\text{C}$.

So, the point is that when the temperature of the main body of the liquid is below the saturation temperature it is the sub cooled boiling and when it is exactly at the saturation temperature say this bulk fluid temperature at 100 °C and this is 107 °C as like before this we called the saturated boiling.

At the early stage of boiling what happens bubbles are confined within a narrow region near the hot surface at the bottom surface of the plate or of the pan. This is because this liquid adjacent to this hot surface vaporizes as a result of direct being in contact with the surface that is at above the saturation temperature. Once it comes in immediately heat transfer takes place and it vaporizes in that local region.

But the, but this bubbles actually disappears as soon as they move away from the hot surface because the heat transfer also takes place from the bubbles to the cold liquid places. So, once a single bubble is formed and it goes upward this bubble loses its identity because of the heat transfer that takes place between the bulk liquid and that bubble.

So, this disappears at the early stages because the bulk fluid has still not reached the saturation temperature. So, it is not vaporizing at the same time. Now, these bubbles serve as the energy pockets that is being moved or energy movers from one place to the other. So, once this happening this is happening that then what happens this it is confined within a region that is the locality of the hot surface and we call that as the local or sub cooled boiling.

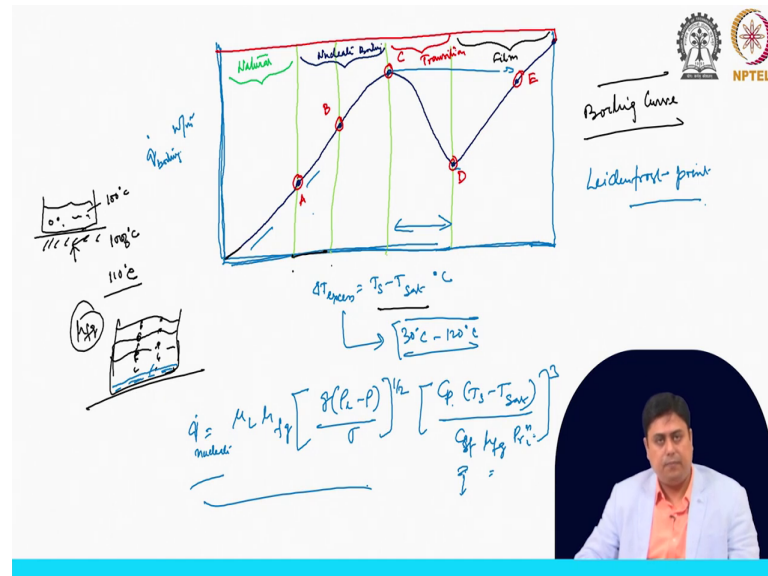
Although the nearby part or the nearby region of the heated surface achieve the surface saturation temperature bulk of the fluid has not reached it. So, this is the sub cooled boiling in that case. Now, once the process continues what happens this heat transfer is taken place throughout the bulk and eventually everywhere in the pool or in the pool of liquid it reaches the saturation temperature after a certain time and then we call that situation as the saturated boiling or the bulk boiling of the liquid.

Now, within this pool boiling that is I mean this category pool boiling and flow boiling both have these two scenarios that is the sub cooled or the saturated and this explanation is analogous for the flow boiling as well.

That initially near this surface the heated surface the bubbles would appear and then those diminishes or disappears in the case of sub cooled when it is saturated you see in all

positions the bubble formations. Now, the point is along with this, two classification there is a nice formation of different regimes and that we can elaborate with the boiling curve.

(Refer Slide Time: 21:22)



So, here we plot $\Delta T_{excess} = T_s - T_{sat}$ in $^\circ\text{C}$ and here the $q_{boiling}$ that is W/m^2 the energy requirement and then we have several regimes. So, so, what happens here is that if we start a pool boiling process, this is essentially we called as the boiling curve. So, four different boiling regimes are observed when we start heating a pool of a pan of liquid.

So, as soon as it reaches this saturation temperature say this is water so, 103°C . So, as soon as it crosses this saturation temperature there is or until then we have the natural boiling part. Then it goes for the nucleate boiling and further at the end it is film boiling in between we have transition regime.

Now, all these things this shape of this boiling curve depend on the type of the fluid or the kind of the fluid or for specific fluid this curve changes. And this is the case of, but the point is that all the four regimes are seen in those cases, but with a different proposition or different width of these ranges.

So, now the point is when we have till point A the boiling curve we have the natural convection boiling. So, here the liquid is slightly superheated and it starts to evaporates as from its free surface. The fluid motion in this mode is governed by the natural convection that the density difference between the two phases that is the vapor and the liquid phases.

In case or in between point A to C the first bubble that forms at point A of the boiling curve what happens? It rises it increases the bubble form at this rate there is a increasing number of nucleation site because the first bubble where it forms we call that is the nucleation site.

Now, in this range the number of nucleation sites increases rapidly as well as say in this case as I mentioned that say the this temperature is now consistently increased and goes to say 110 °C, but this liquid temperature remain that 100 °C, but with phase change. Now, here you are supplying more and more latent heat of vaporization and that is why the sensible temperature is not changing and it is evaporating faster than the natural boiling part.

So, in the region that is B to C we start seeing a columns of bubbles that is forming regularly that we see. If you start boiling a fluid water at home you would see that there is a now column of bubbles that are rising continuously from the bottom that is the rapid formation of the bubbles. And it is released at when it comes at the vapor liquid interface; that means, it is vaporizing it is evaporation.

Now, in the transition part what happens as we further increase this value that surface temperature as if we still keep on increasing it from 103 to 100 °C; that means, the 3 °C and it is now 10 °C this is the change. So, this is 3 this is 10 like this for water.

As the heated temperature increases or this excess temperature increases and it goes passed C then the heat flux actually decreases. This is because the large fraction of the heater surface is then covered by a film of vapor that, whichever is comes in contact with this it is then there is a vapor film that resist the heat transfer or the heat flux that is imparted from the heating surface to the bulk liquid.

So, the heat transfer or the heat flux significantly drops and in this transition boiling regime what happens both nucleate and film boiling partially occurs. And that is why this is the unstable part of the boiling that means so our conventional understanding that as we increase the heated temperature possibly the heating would be faster, but there is a certain stage where that does not help and it is the unstable state. It can quickly come across it when this film disappears and then it rapidly increases.

So, for water this transition happens in the temperature excess temperature range remember this is the term excess temperature range between 30 to 120 °C. Now, in the film boiling till the at point D what happens the heat flux again reaches the I mean D at where the it reaches the minimum.

Now, that point is also called the Leidenfrost point after the scientist. The point D where the heat flux reaches minimum is called the Leidenfrost point. Now, at that point liquid droplets on a very hot surface actually jumps around and slowly boils away and that is why when if you instead of putting water or oil before you start heating the pan.

After heating the pan to a significantly higher temperature once you drop a certain amount of oil or water on top of it you see those droplets are jumping and making some crazy noises.

So, the point is that the presence of vapor film between the heated surface and the liquid is responsible for that low heat transfer rate in the film boiling regime. And the heat transfer rate increases with increasing excess temperature as a result of heat transfer from heated surface to the liquid through the vapor film by radiation, which becomes significantly high at higher temperature.

And in certain cases what can happen that from this stage it may jump to the point E with the risk of bursting the whole scenario. So, the point is that the burnout phenomena can happen in such case if this point C quickly moves to point E. So, the point here that we are trying to make is that each fluid goes through each of these phases or each of this regime when we try to boil it.

And interestingly the things that I am not written here, but I can give you an example that the amount of heat transfer that is happening for each and every regime has been proposed by several expression. For example, in the nucleate boiling regime the expression is something very difficult to remember, but it appears like in this kind of a form. And that is why we are not going into the details of these expressions because of the same regime.

$$q_{nucleate} = \mu_L h_{fg} \left[\frac{g(\rho_L - \rho)}{\sigma} \right]^{\frac{1}{2}} \left[\frac{c_p(T_s - T_{sat})}{c_{sf} h_{fg} Pr^n} \right]^3$$

Prandtl number to the power n to the power cube where, all the expressions we know h_{fg} is the enthalpy of vaporization. C_p is the specific heat of the liquid C_{sf} is essentially a experimental constant that depends on the surface liquid combination whatever the surface by which you are heating the liquid and n is the experimental constant that depends on the fluid and rest or other parameters we know.

So, each and every regime would come with such kind of heat flux expression and from there. So, these empirical relations we need to again look into in our reference books or the text books whenever we find such scenario or in order to calculate the amount of heat being transferred.

The essence of showing this boiling the boiling curve is that it happens similarly for all the fluids. And for condensation as well which we will not go now in the details, but the similar thing happens now it is in the reverse order or it is in a different manner. Because now the phase change happens from the liquid phase from the vapor phase to the liquid phase through again several regimes.

So, those regimes can be drop wise condensation film wise condensation that you see a drop wise condensation when you put say a cold drink in a glass and put it outside in the ambient temperature. During summer you see due to the presence of high relative humidity the drop wise condensations of the atmospheric vapor is happening on the glass of it.

Similarly, a film wise condensation can happen that you can see on a car wind shield that is kept outside during the summer. So, again in the condensation part as well based on the regimes the condensation regime like we have the boiling regime we have difference or several expressions empirical relations for the amount of heat that is transfer or the heat transfer rate correlations are available.

So, with this understanding I will stop here for the convection part. All the details or the other details if necessary or whenever it is needed that would be needed for the advanced heat transfer cases. In the next class we will start with radiation the overview of radiation till then.

Thank you for your attention.