Two Phase Flow and Heat Transfer

Dr. Arup Kumar Das
Department of Mechanical and Industrial Engineering
Indian Institute of Technology, Roorkee

Lecture No: 17
Boiling Heat Transfer

Hello, welcome to the course Two Phase Flow and Heat Transfer. Today we will be going for seventeenth lecture and the topic of our lecture today is Boiling Heat Transfer. At the end of today's lecture, we will be understanding the differences between pool boiling and flow boiling. We will be also understanding different regimes of pool boiling heat transfer along with its boiling curve.

We will be also finding out that how departure radius of a bubble varies with degree of superheat. We will be also seen that how heat flux can be evaluated when the bubble is growing in pool boiling situation.

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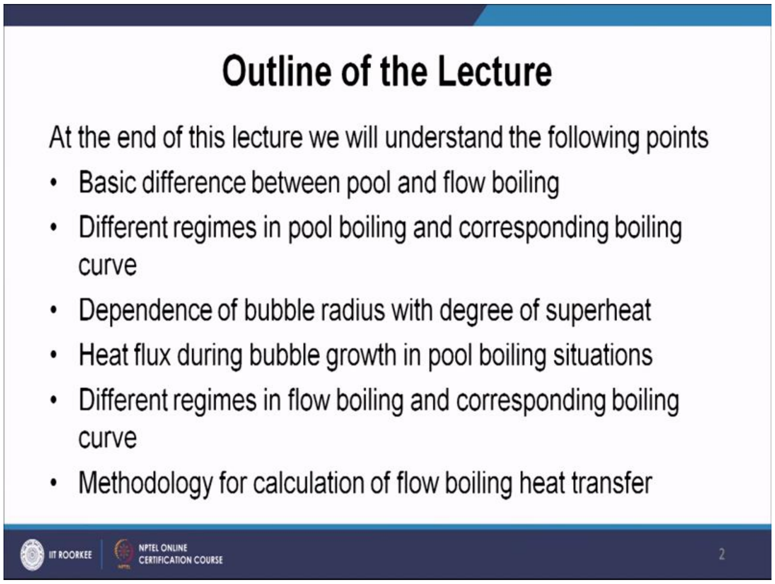

Outline of the Lecture

At the end of this lecture we will understand the following points

- Basic difference between pool and flow boiling
- Different regimes in pool boiling and corresponding boiling curve
- Dependence of bubble radius with degree of superheat
- Heat flux during bubble growth in pool boiling situations
- Different regimes in flow boiling and corresponding boiling curve
- Methodology for calculation of flow boiling heat transfer

We will be seeing how flow boiling and how flow boiling occurs in side a pipe and its corresponding boiling curve. We will be finding out the methodologies for calculation of flow boiling heart transfer. Let us quickly see what is boiling heat transfer. Actually boiling describes the process in which you will be finding out addition of heat is causing change of phase from liquid to gas okay.

Now boiling, if we try to define or categorize then will be finding out it can be divided into 2 broad classifications, those are pool boiling and flow boiling. Pool boiling is associated inside a stagnant pool, where liquid flow is not predominant okay.

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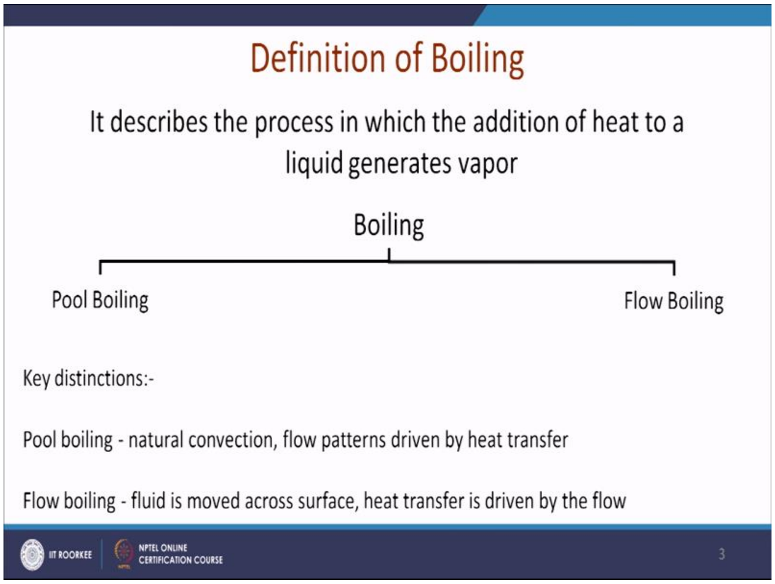

Definition of Boiling

It describes the process in which the addition of heat to a liquid generates vapor

Boiling

Pool Boiling

Flow Boiling

Key distinctions:-

Pool boiling - natural convection, flow patterns driven by heat transfer

Flow boiling - fluid is moved across surface, heat transfer is driven by the flow

So mainly we will find out flow is causing due to natural convection and whatever flow pattern is causing there is driven by heat transfer. On the other hand if you see flow boiling, the flow boiling will be guided by the fluid movement inside the pipe. You will be having the movement of the fluid and that velocity of the fluid will be defining what flow regime will be occurring inside.

Obviously heat transfer will be taking major role in the flow pattern inside flow boiling also. So let us see, next that what are the common mistakes we do while we define boiling heat transfer. So basically boiling is actually phase change and which can be talked as a vaporization process. So, vaporization is nothing but conversion of liquid into vapor by applying heat. Now if this vaporization is occurring only at the surface of the liquid, we will be calling that as evaporation okay.

And if we find out that boiling or vaporization is happening throughout the pool okay inside the bulk of the pool also liquid pool we are happening the phase change then we will be calling that 1 as boiling okay.

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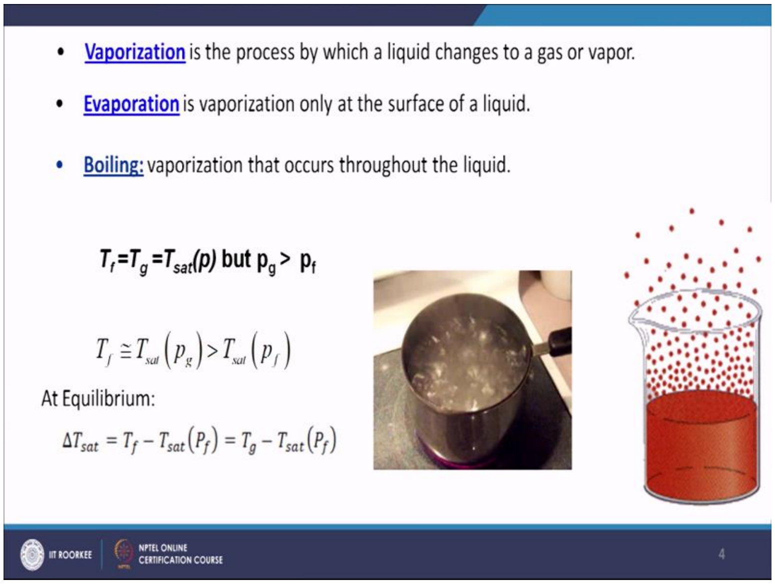

- **Vaporization** is the process by which a liquid changes to a gas or vapor.
- **Evaporation** is vaporization only at the surface of a liquid.
- **Boiling:** vaporization that occurs throughout the liquid.

$T_f = T_g = T_{sat}(p)$ but $p_g > p_f$

$$T_f \cong T_{sat}(p_g) > T_{sat}(p_f)$$

At Equilibrium:

$$\Delta T_{sat} = T_f - T_{sat}(P_f) = T_g - T_{sat}(P_f)$$

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There is basic difference between evaporation and boiling if the phase change occurs only at the surface, free surface that is called evaporation and if it is volumetric phenomenon then it is called boiling heat transfer. Okay here I have shown typical examples for boiling heart transfers. So this is macroscopic analysis you can find out the water is boiling in a pictorial view and here I have given you some sort particulate understanding.

So here inside we had close compaction of the molecules in the form of liquid and once you add heat, you will be finding out some molecules will be becoming widely pact and you will be finding out those are coming in the vapor form okay. Now our common understanding about boiling heat transfer is that whenever the temperature of the fluid and gas will be coming equivalent to the saturation temperature of pressure that will be the limit from here boiling will be starting okay.

But eventually we will find out that due to this molecular compaction difference the pressure of the vapor will be higher compared to the pressure of the liquid. So you can find out pg which is the vapor pressure is higher than the pf which is the liquid pressure right. As the pressures are different, we will be finding out that liquid temperature and vapor temperature they are not similar you will find out that liquid temperature is more or less equivalent to the saturation temperature corresponding to the vapor pressure okay.

Now what is the saturation temperature corresponding to this vapor pressure? We have already understood in thermodynamics. So you can find out for any substances even for water also. What is the saturation temperature corresponding to this given pressure? And we know that temperature is actually saturation, temperature is actually proportional to your pressure.

So you will be finding out as vapor pressure is higher than the liquid pressure, saturation temperature corresponding to vapor pressure will be higher than the saturation temperature corresponding to a liquid pressure okay. So if you think about equilibrium when boiling is happening and once again you know pool is coming into equilibrium position then you can write down that saturation temperature Tsat okay. del Tsat = Tf -Tsat pf.

So this Tf is nothing but the fluid temperature and Tsat pf is saturation temperature corresponding to the fluid pressure will be equals to Tg- Tsat * pf. So basically these differences between the saturation temperature and liquid temperature for both the liquid and vapor phases will be equal and that will be calling as delta t saturation right. Next let us see that how pool boiling heat transfer occurs will be starting with the first regime which is pool boiling heat transfer.

So at the beginning you will find out inside the pool we will be having only natural convection okay. We have already understood what is heat transfer. So we know what is natural convection will be finding out that as the surface over which the boiling is occurring that is hot.
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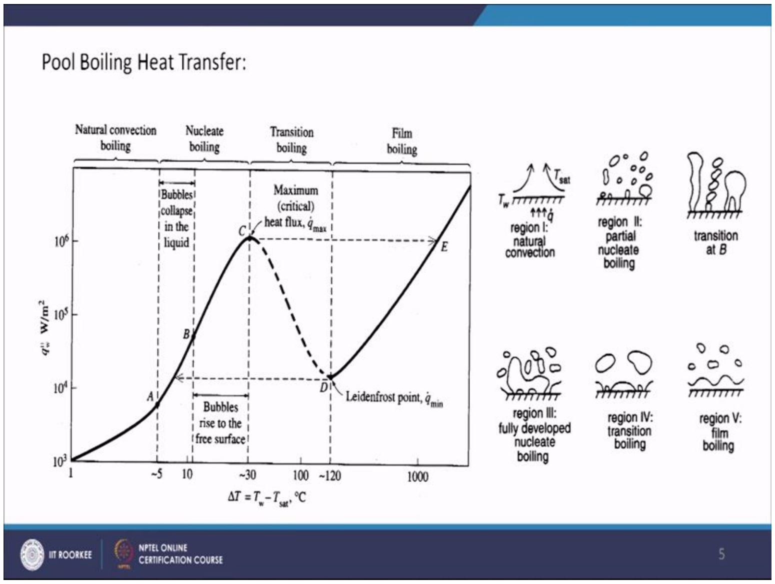

Pool Boiling Heat Transfer:

Then we will find out that the liquid will be having some circulation cells like this okay. Heavier liquid is coming down taking the heat and once again moving up okay. So there will be circulation cells inside. Now very soon you will be finding out that over the surface, when the temperature increases, you will be finding out that small sized bubbles are being generated at the nucleation sides.

So this is actually you can call this one as secondary region and you call this one as partial nucleate boiling. So this you can say that this is the initiation of nucleate boiling. In this zone you will be finding out lots of smaller bubbles are over the surface and you will be finding out that those bubbles are actually departing from the surface whenever it gets a finite amount of size. What will be the size depending on the degree of superheat, I will be discussing soon.

Next you will be finding out a zone, where you know lots of bubbles are being generated from a surface from a nucleation side and you will find out those bubbles are generated so fast that they are forming a bubble train. Here I have shown one example of bubble train you see and if the bubble train is very closely spaced that means fast bubbles are being released from the surface, you can find out there is a vertical merging and a long film also can be protruded from the nucleation side.

Now soon as we increase the heat transfer and as we increase the degree of superheat of the surface then you will be finding out this films are being merged with each other or it can be starting from this region 2. Also bubble will be forming more in number over the surface because nucleation sides will be becoming activated more and more in number and you will find out those bubbles are merging with each other. And they are forming a horizontal film okay.

So in this transition b you will be finding out vertical film and here you will be finding out horizontal film okay. Then at some position you will be finding out that there is no more scope of fresh liquid to come inside the coming contact with the solid surface. And you will be finding out that more over the surface is occupied by the gaseous phase. So this we call as transition boiling okay.

And at the end you will be finding out that whenever this vapor films are also merging with each other in the horizontal direction the whole surface is occupied by the film, and you will be finding out a zone which is called film boiling. Now let us try to see the boiling curve. Boiling curve means how heat flux varies with degree of superheat. Here I have shown a typical curve you can find out in the first zone which is called a natural convection zone.

You can find out as we increase the degree of superheat, heat flux increases but in this zone essentially you will not find out any formation of bubble. Then after that a to b is actually our region 2, where you will be finding out smaller bubbles are being generated from the surface and you know with degrees of superheat heat flux will be also increasing. Later on from b to c, you will be finding out that we are having horizontal merging of the bubbles and formation of you know this kind of horizontal film bigger bubbles in the horizontal direction you can find out.

At point c you will be finding out maximum heat flux has been reached and you will be getting from this point. There will be sudden shift of temperature in case of heat flux controlled experiment okay. Because you will be finding out after reaching at point c the whole surface is actually covered by film and suddenly the temperature of the surface will be increasing. So this point is actually very, very critical from here, the temperature suddenly shoots up.

So this is actually called critical heat flux point okay. So after that we will be getting at the same heat flux will be having a huge change of you know degree of superheat suddenly. And finally you will be finding out after point t we are having overall film over the surface which is region 5. And you know due to your gaseous convection, you will be finding out as degree of superheat increases heat flux will be also increasing over here.

So this curve is always increasing in nature okay. So in case of heat flux controlled experiment, you will be finding out this sudden jump of the temperature okay. While you are increasing the heat flux and if you do the reverse that means if you reduce the heat flux continuously then you will be finding out it will be starting from the film boiling. It will reduce like this come over here at the minimum point which is called actually little level cross point okay.

In this level cross point, you will be finding out film is actually breaking into smaller, smaller you know small bubbles, horizontally small bubbles and at this point you will be finding out that there is a sudden drop of the temperature and you know film is forming smaller bubbles over the surface and then once again a small zone of nucleate boiling and finally your convection continues okay. But in case of your temperature controlled experiment this type of sudden jump or drop will not be observed.

You will be finding out that for a particular temperature you are having a particular heat flux okay right. Next let us discuss about nucleate boiling heat transfer under pool boiling section. So here I have shown a typical nucleation side. So typically nucleation cell sides are surface roughness. So you will be finding out though were very, very irregular but to standardized what we do we take a nucleation side like this one here. I have shown you v grouped surface. So you see this is your nucleation side you know.
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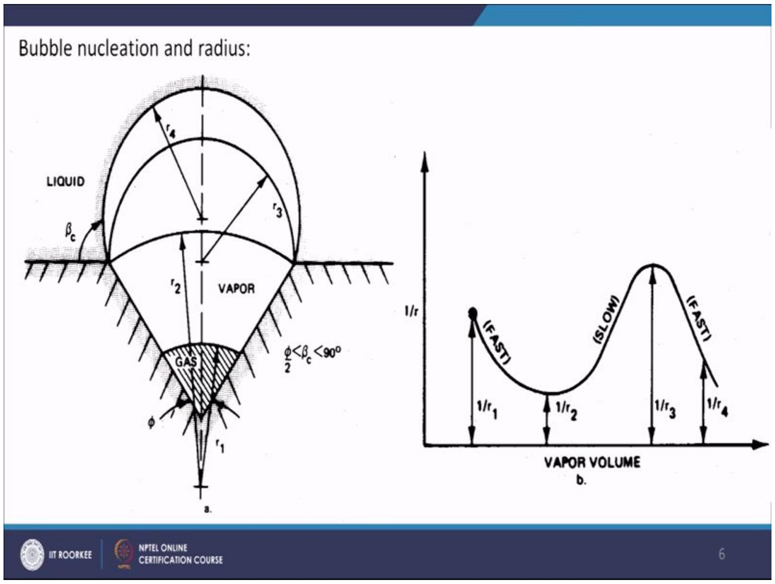

Bubble nucleation and radius:

So here at the beginning whenever bubble is forming, you will be finding out that the lowest position of the nucleation side is acting at the as the centroid of the vapor. So you can find out here, you see if at the beginning this is the gas liquid interface. So you can finding out its centroid is somewhere over here okay, this ark is somewhere over here okay. So you can find out this is below the domain of you know nucleation side. As it increases volume you can find out this interface will be moving in the outward direction and after sometime you see it comes to a limiting zone.

When the interface corners has touched the free surface, the free surface means solid surface okay the Xe the outer periphery of the solid surface. So you see this is the point where the outer plane surface is actually coming into picture with the nucleation surface okay. Nucleation side you see this is the critical position. So over here also you can find out it is making some radius with the same center, which is far below than the nucleation side okay.

But after that immediately you will be finding out when the vapor liquid interface has protruded outside, the surface you will be finding out that it is getting more and more space to grow circumferentially in a spherical manner. And you will find out that this growth is unconstant in the pool and you will be finding out that the center of mass or you can say the center of curvature for this interface will be slowly, slowly coming up.

And you will be finding out at some point of time it will come up even above the solid surface. So here I have given typical example r4, you can see which is out above the horizontal surface. Now if one tries to plot that this variation of the curvature 1 / r with respect to the vapor volume, he will be finding out or she will be finding out that at the beginning phase there will be a fast reduction of the curvature from 1/ r1 to 1 / r2.

Here r1 and r2 both I have shown. So bubble will be actually increasing but you know bubble will be increasing the volume but you will be finding out that this radius will be also increasing okay. As a result 1/r will be decreasing okay. Then after a critical point, you will be finding out there is once again slow raise. So this slow raise is due to from 1 /r2 to 1 /r3. You can finding out over here r2 is higher compared to r3.

So, obviously 1 /r3 will be higher okay. And you will be finding out a raise in the curvature but this raise will be slower compared to the fall of 1 / r2 to 1 / r1. Then after once again rating a critical point, it will once again fall very fast which is nothing but between 1 /r3 to 1 /r4. The important thing is here 1 / r3 to 1 /r4 is this one that at this domain the center of the curvature is actually center of the interfacial periphery will be actually coming out of the surface okay.

And it happens very fast okay. So this is the typical bubble growth behavior and it is a center of curvature radius of curvature. You can plot with respect to volume okay. Then let us see that how this radius of curvature or you can say the radius of a bubble varies with respect to your degree of superheat okay.
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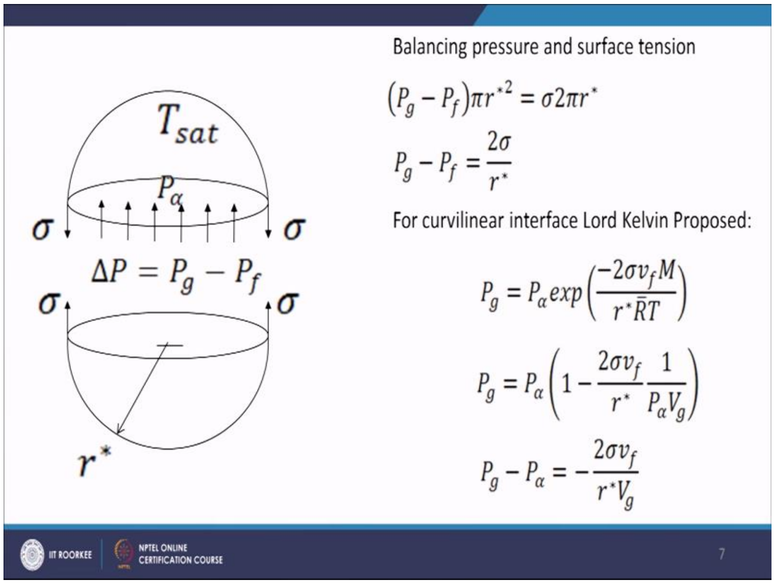

Balancing pressure and surface tension

$$(P_g - P_f)\pi r^{*2} = \sigma 2\pi r^*$$

$$P_g - P_f = \frac{2\sigma}{r^*}$$

For curvilinear interface Lord Kelvin Proposed:

$$P_g = P_\alpha exp\left(\frac{-2\sigma v_f M}{r^* \bar{R} T}\right)$$

$$P_g = P_\alpha\left(1 - \frac{2\sigma v_f}{r^*}\frac{1}{P_\alpha V_g}\right)$$

$$P_g - P_\alpha = -\frac{2\sigma v_f}{r^* V_g}$$

So to give the idea of that we will be taking a bubble let us say this is bubble, which we have caught form the middle plane and you can find out that we are having 2 different forces over here applicable. First 1 obviously the pressure force because the gaseous pressure will not be equivalent to the liquid pressure already we have explained in the previous slide and we will be also finding out that surface tension plays a major role okay to make the circumferential periphery. So we will be trying to balance the pressure force and the surface tension force.

So if you do so, you will be finding out pg – pf, which is the pressure drop between across the surface * pi r square. And this is equivalent to pi *2 pi r. So pi *2 pi r will be actually sigma*2 pi r and sigma is surface tension and 2 pi r will be this perimeter of the circle along which the surface tension will be acting. So if we balance this 2 then you will be finding out pg-pf becomes 2 sigma /r okay then let us take the help of famous relationship given by lord Kelvin from his Kelvin Helmholtz instability.

He proposed that if we are having some curvilinear interface, he proposes that pg can be written as p infinity, where p infinity is the pressures of the you know bulk okay. So that will be the bulk pressure in the liquid. So, p infinity *e to the power - 2 sigma vfM. M is the molecular weight okay. For the gaseous phase / r*, r* is nothing but your radius of the bubble and then r bar is the universal gas constant *t okay. So from here, if we try to replace this M / RT with your pressure and volume using PV equals to M RT for the gaseous phase then I can write down Pg = P infinity (1 -2 sigma vf /r *1 /p alpha p infinity * vg

By the way here, we have already taken the assumption e to the power x is actually equals to 1 + x plus some higher term, which we can neglects. So we have neglected the higher terms over here okay. So here we are having e to the power – x. So this (1 – x) comes into picture. Now, from here we can get the pg -p infinity = - 2 sigma vf / r * * Vg. So now here you see we are having 2 pressure differences. This is the pressure difference between the gaseous phase and the liquid phase. And this is the pressure difference between the gaseous phase and the bulk.

So you can find out this we can easily use and we can find out the relationship between the bulk pressure and the immediate near liquid pressure of the interface. So we get, if we subtract those equations whatever I have shown you in the previous slide, we will be getting 2 sigma /r * into 1 + Vf /Vg okay. Next let us see, how we can simplify it further. We will be taking the help of famous Clausius Clapeyron equation. So we know that Clausius Clapeyron equation says (del P/ del T) at sat = hfg /Tsat * Vg - Vf right.

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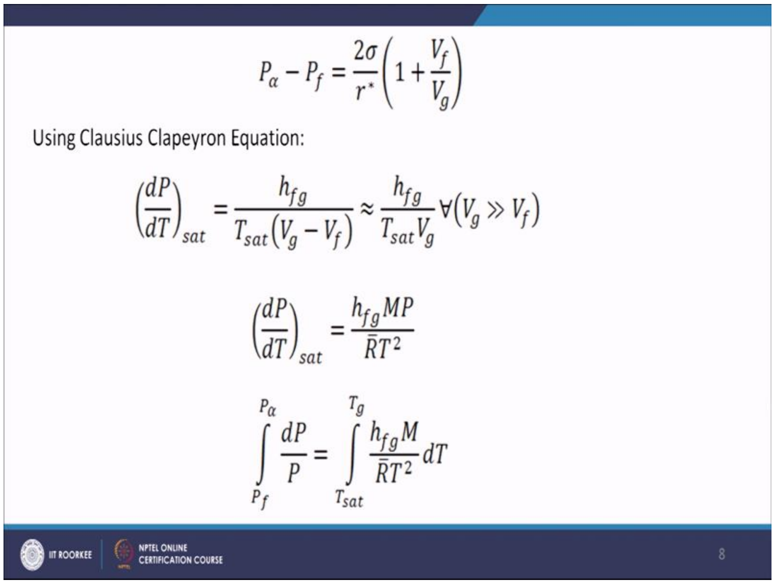

$$P_\alpha - P_f = \frac{2\sigma}{r^*}\left(1+\frac{V_f}{V_g}\right)$$

Using Clausius Clapeyron Equation:

$$\left(\frac{dP}{dT}\right)_{sat} = \frac{h_{fg}}{T_{sat}\left(V_g - V_f\right)} \approx \frac{h_{fg}}{T_{sat}V_g} \forall\left(V_g \gg V_f\right)$$

$$\left(\frac{dP}{dT}\right)_{sat} = \frac{h_{fg}MP}{\bar{R}T^2}$$

$$\int_{P_f}^{P_\alpha} \frac{dP}{P} = \int_{T_{sat}}^{T_g} \frac{h_{fg}M}{\bar{R}T^2}\,dT$$

So here I will be considering that your vapor specific volume is very, very high compared to liquid specific volume that means we are talking about a fluid, where density ratio is very high, perfect example is water okay. Here I will be considering the vg is higher compared to Vf. So what we can do, we can neglect this vg and we can write down Vg - Vf = Vg. So we get subsequently this (del P/ del T)sat is nothing but hfg /Tsat * Vg okay. So if you continue further like this then you will be finding out that (del p /del T) sat = hfg/ Tsat and then you know this Vg I can convert using pv = MRT formula once again.

Then I will be getting that hfg * MPR and 2 temperatures will be multiplied now. 1 was already there in the form of T sat another 1 will be coming due to your Vg. So you will be getting t square over here. So now here you see in the left hand side we are having dP and dT. Here we are having a function, which is pressure and dependant on pressure and temperature. So we can start integration procedure. So we have integrated over here. dP to dP /P and the limits will be Pf *p infinity and here in the right hand side we have integrated with respect to t and the limits will be T sat to Tg.

Once you go for this integration then you will be finding out that LMP infinity / Pf = - of hfg m /r *1 /Tg -1 / Tsat okay. Further simplification, if you do then you will be getting this kind of equation. Now from here I can get what is Tg – Tsat. So Tg – Tsat. So obviously that will be this multiplier will be going in the other side and we will be getting this is R Tg Tsat / hfgm ln of this term okay. This term once again see there was ln p alpha /pf. So p alpha/ pf already we have shown you in the slide over here what is P alpha/ Pf P alpha /Pf. If you see over here that will be 1 plus of this term okay. So that we have put over here 1 + 2 sigma Pf r * into 1 + vf /vg okay.
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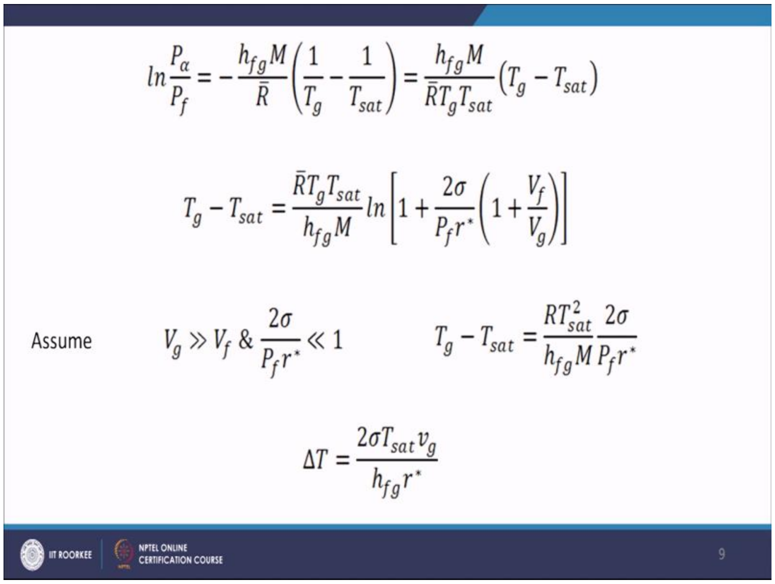

$$\ln\frac{P_\alpha}{P_f} = -\frac{h_{fg}M}{\bar{R}}\left(\frac{1}{T_g}-\frac{1}{T_{sat}}\right) = \frac{h_{fg}M}{\bar{R}T_gT_{sat}}\left(T_g - T_{sat}\right)$$

$$T_g - T_{sat} = \frac{\bar{R}T_gT_{sat}}{h_{fg}M}\ln\left[1+\frac{2\sigma}{P_f r^*}\left(1+\frac{V_f}{V_g}\right)\right]$$

Assume $V_g \gg V_f$ & $\frac{2\sigma}{P_f r^*} \ll 1$ $\quad T_g - T_{sat} = \frac{RT_{sat}^2}{h_{fg}M}\frac{2\sigma}{P_f r^*}$

$$\Delta T = \frac{2\sigma T_{sat} v_g}{h_{fg} r^*}$$

Lets us take further assumption to make it simpler. Once again the same assumption that vg is higher, higher than vf and let us consider that 2 sigma / pf *r star is very small okay. So if this is very small okay and this is actually vf is lower compared to very, very lower compared to vg then we will find out Tg - Tsat simplifies to this equation okay. (R Tsat) whole square / hfg M* 2 sigma /Pf r *okay. Further simplification of this 1 gives us delta T = 2 sigma T sat vg / hfg r *. So you can see over here that delta t is actually having inverse relationship with r *. So this gives you some sort of idea that what will be your bubble radius whenever we are having variable degree of super heat okay.

So this equation is very, very important for finding out the departure radius of a bubble okay. Next let us try to see when the bubble is growing in that situation what happens in case of nucleate boiling okay. Now bubble growth in nucleate boiling can be classified into 2 portions dependent on the time. So first portion is actually called initial growth period okay. In the initial growth period you will be finding out that all will is below the bubble will be having a thin liquid layer wedge shaped liquid layer on the other hand after a initial growth period Tg.

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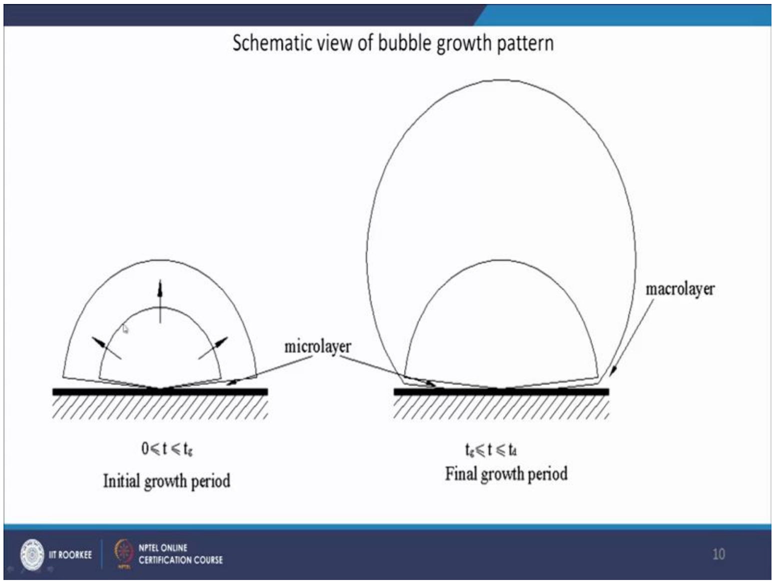

Schematic view of bubble growth pattern

$0 \leq t \leq t_g$

Initial growth period

$t_g \leq t \leq t_d$

Final growth period

You will be finding we have final growth period, where you will be finding out that we are having 2 layers okay. The first layer was actually termed as micro layer and in case of a second growth period, you will be finding out apart from micro layer we are having another portion which is called macro layer okay. So here you can find out this was micro layer and over there here we are having macro layer at the junction of macro layer and micro layer there will be change of radius of curvature. So the curvature will not be continue as at the junction of macro layer and micro layer.

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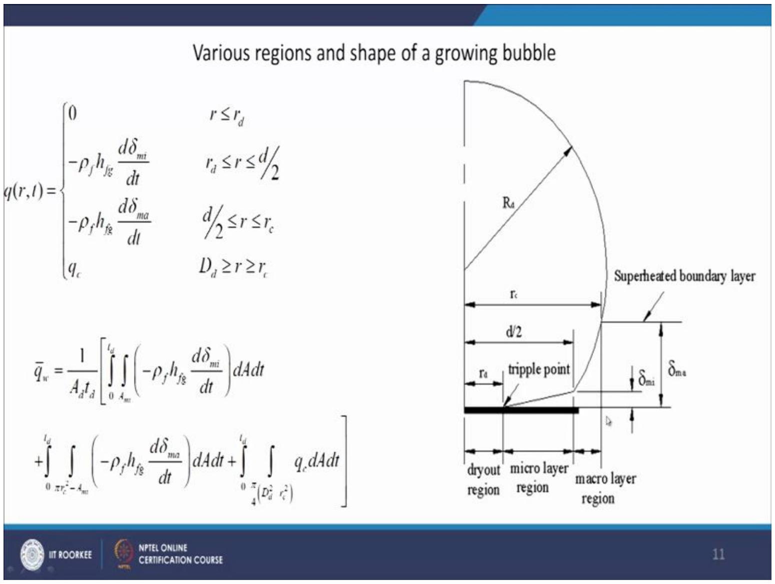

Various regions and shape of a growing bubble

$$q(r,t)=\begin{cases} 0 & r \leq r_d \\ -\rho_f h_{fg}\dfrac{d\delta_{mi}}{dt} & r_d \leq r \leq d/2 \\ -\rho_f h_{fg}\dfrac{d\delta_{ma}}{dt} & d/2 \leq r \leq r_c \\ q_c & D_d \geq r \geq r_c \end{cases}$$

$$\bar{q}_w = \frac{1}{A_d t_d}\left[\int_0^{t_d}\int_{A_{mi}}\left(-\rho_f h_{fg}\frac{d\delta_{mi}}{dt}\right)dA\,dt + \int_0^{t_d}\int_{\pi r_c^2 - A_{mi}}\left(-\rho_f h_{fg}\frac{d\delta_{ma}}{dt}\right)dA\,dt + \int_0^{t_d}\int_{\frac{\pi}{4}\left(D_d^2 - r_c^2\right)} q_c\,dA\,dt\right]$$

Okay now if we try to figure out that what will be heat flux during this bubble growth period? So lets us take this figure for example, here I have shown you this domain is actually liquid layer which is called micro layer. Here we are having macro layer apart from that we have also consider a region which is called a dry out region where liquid is not in contact with the solid heated. So if you consider all these 3 regions apart from the outer periphery also of the bubble into consideration. Then we will getting that heat flux will be becoming 0 for the dry out region because there is direct contact between the gas and a solid surface.

And in the macro layer and micro layer region we can find out – Rho f hfg *d delta /dt and you know micro layer thickness and macro layer thickness will be coming into picture over there okay. Because mass loss will be directly proportional to the thickness of the layer loss okay. So here this will be varying from different radiuses using this rd was actually the dry out region d / 2 is actually is your extreme limit of the micro layer rc is your extreme limit of the macro layer and finally your this capital rd was the bubble diameter okay. Now here I have shown you what will be happening whenever we integrate this 1 over the limits of this 1.

Here it was zonal base heat flux I have shown instantaneous and at a particular position. If you integrate then you will be getting this equation for the first and second we will not be getting anything so here we have written 0. Sorry, for the first we will not be getting anything but here we have to integrate depending on the area that we have done okay. Next lets us see that in case of nucleate boiling what type of correlations are available. So the best known correlation for nucleate boiling heat transfer is Rohsenow correlation. So in case of Rohsenow correlation you will be finding out that we are having lots of empirical constants also over here okay.

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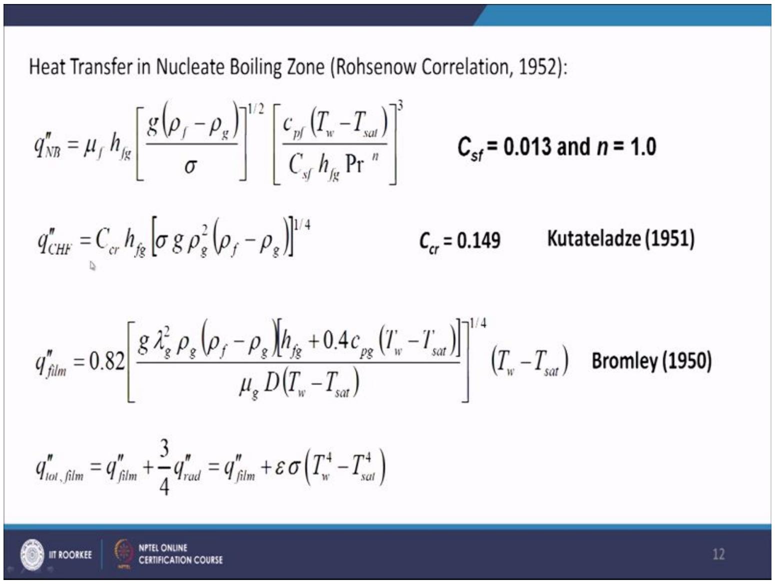

Heat Transfer in Nucleate Boiling Zone (Rohsenow Correlation, 1952):

$$q''_{NB} = \mu_f\, h_{fg}\left[\frac{g\left(\rho_f-\rho_g\right)}{\sigma}\right]^{1/2}\left[\frac{c_{pf}\left(T_w-T_{sat}\right)}{C_{sf}\, h_{fg}\, \Pr^{\,n}}\right]^3$$

C_{sf} = 0.013 and n = 1.0

$$q''_{CHF} = C_{cr}\, h_{fg}\left[\sigma\, g\, \rho_g^2\left(\rho_f-\rho_g\right)\right]^{1/4}$$

C_{cr} = 0.149 **Kutateladze (1951)**

$$q''_{film} = 0.82\left[\frac{g\,\lambda_g^2\,\rho_g\left(\rho_f-\rho_g\right)\left[h_{fg}+0.4c_{pg}\left(T_w-T_{sat}\right)\right]}{\mu_g\, D\left(T_w-T_{sat}\right)}\right]^{1/4}\left(T_w-T_{sat}\right)$$

Bromley (1950)

$$q''_{tot,film} = q''_{film}+\frac{3}{4}q''_{rad} = q''_{film}+\varepsilon\sigma\left(T_w^4-T_{sat}^4\right)$$

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So you see Rohsenow correlation is qnb, which is the heat flux in the nucleate boiling zone and it actually connected with this del tw - Tsat which is nothing but your surface temperature. So here other properties are fluid properties, which you can find out from the specific fluid combinations but csf and n these 2 are the empirical constant and Rohsenow, he has given a wide variety of fluids and he has mentioned that what will be constant values. For water 1 can use csf = 0. 013 and n = 1 okay. Similarly it is also very important to predict the critical heat flux just like your nucleate boiling heat transfer. So critical heat flux will be ccr *hfg okay.

[sigma* g* Rho g square (Rho f – Rho) g to the power 1 / 4] and this correlation has been given by Kutateladze okay. In 1951 here ccr is the empirical constant and he has proposed empirical constant can be taken as 0.149. Similarly, for film boiling region we are having lots of correlation the famous 1 is Bromley correlation in 1950. He has given this correlation. Here also you see we get film boiling heat flux as a function of (Tw – Tsat), which is your surface superheat. So all other properties are actually fluid properties. So you can find out fluid combination properties you can find out

And total heat flux in case of film boiling can be written as q film over here +3 / 4 q radiation because in case of film boiling surface temperature will be very high, so radiation cannot be neglected. So radiation heat transfer also we need to calculate in this fashion, I have shown this is very common to all of us how radiation can heat flux can be considered okay. Next lets us see something about flow boiling. In case of flow boiling we know this figure is known to you already I have shown you in the first lecture. So that if we start heating a pipe okay in which water is or some liquid is going on then you will be finding out at the beginning.

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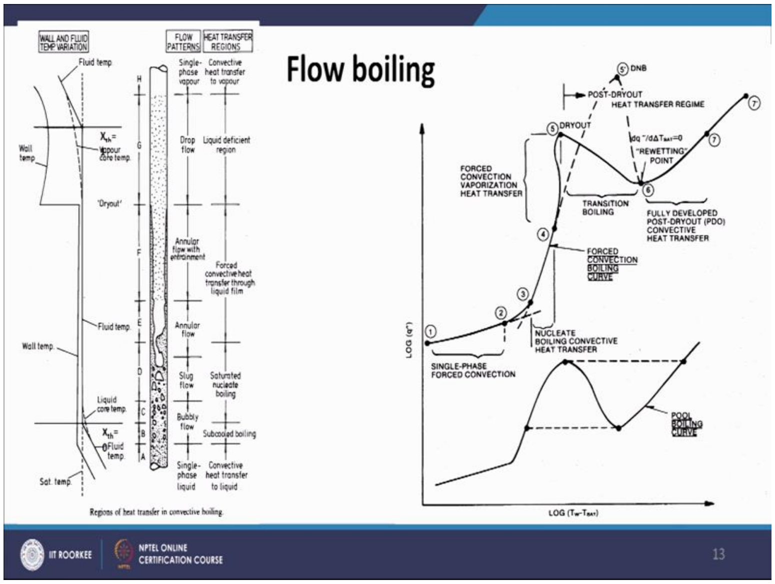

Flow boiling

Regions of heat transfer in convective boiling.

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We are having bubbly flow small bubbles are being generated and then all those bubbles will be merging and forming a slug bubble. Then you will be finding out annular film over here okay. So in the wall, you will be finding out inside the tube in the wall .You will be finding out liquid and then we will be finding out annular flow with entrainment. This also we have discussed in detail and finally we will be having droplet flow, which is more or less similar to this bubbly flow but in reverse manner okay. At the end you will be finding out once again a single phase flow few important things we need to notice over here.

It is that at some point of time you will be finding out the dry out of the pipe okay. So this is the point, where you will be finding out the pipe is not in contact with the liquid. So you will be having a dry out at this point and at this point you will be finding out that wall temperature is suddenly increasing. So you see up to this we are having a constant temperature almost constant temperature and whenever dry out of there will suddenly increase of temperature okay for that tube wall. So this is very typical feature for your flow boiling condition.

Now flow boiling curve if we want to plot that means q verses delta T sat plot, if you want to do for flow boiling then you will be finding out the curve looks like more or less having the natural convection nucleate boiling and then finally critical heat flux and then film boiling. But obviously due to the flow whatever you are having heat transfer coefficient will be increasing and you can find out that flow volume curve will be in the higher side in comparison than to the nucleate boiling or pool boiling curve okay.

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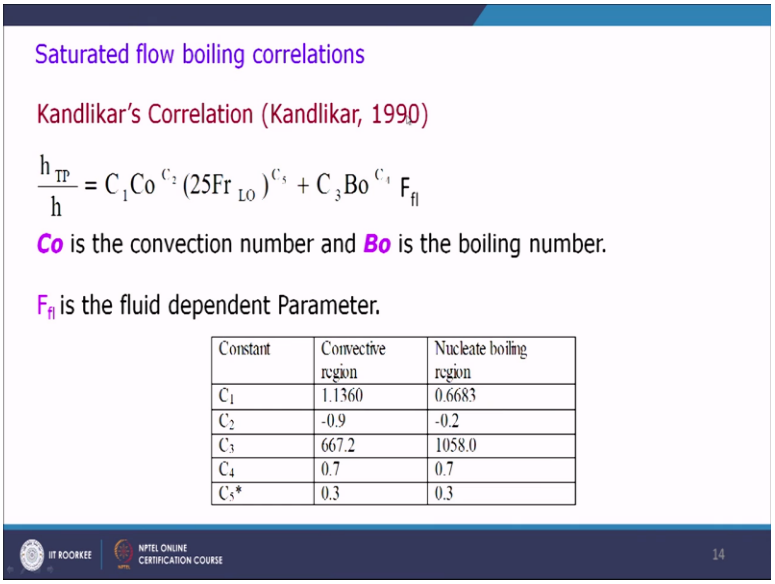

Saturated flow boiling correlations

Kandlikar's Correlation (Kandlikar, 1990)

$$\frac{h_{TP}}{h} = C_1 Co^{C_2} (25Fr_{LO})^{C_5} + C_3 Bo^{C_4} F_{fl}$$

Co is the convection number and **Bo** is the boiling number.

F_{fl} is the fluid dependent Parameter.

Constant	Convective region	Nucleate boiling region
C_1	1.1360	0.6683
C_2	-0.9	-0.2
C_3	667.2	1058.0
C_4	0.7	0.7
C_5*	0.3	0.3

So here also you can see the single phase conviction the nucleation then transition. Finally this is your dry out or critical heat flux and then we are having a part we are having film boiling that I have discussed earlier. Next let us see in case of a flow boiling. How we can find out the heat transfer coefficient. There are few correlation the famous 1 is called Kandlikars correlation, who has given the correlation in 1990. So he has mentioned that 2 phase flow, flow boiling correlation h heat transfer coefficient h TP can be found out as h * C1 Co to the power C2 * 25 Froude number Lo liquid only to the power C5 + C3 and this is boiling number.

So boiling number to the power c4 and f fl okay. So here see Co is actually convection number because you know in flow boiling convection important parameter and Bo is the boiling number which is important for boiling heat transfer. F fl is the fluid dependent parameter. So what Kandilikar has proposed, he has proposed all these empirical constant C1, C2, C3, C4, C5 all these empirical constant he has proposed for convective region and nucleate region like this. So you can pick up these values and always find out what is the 2 phase flow heat transfer coefficient.

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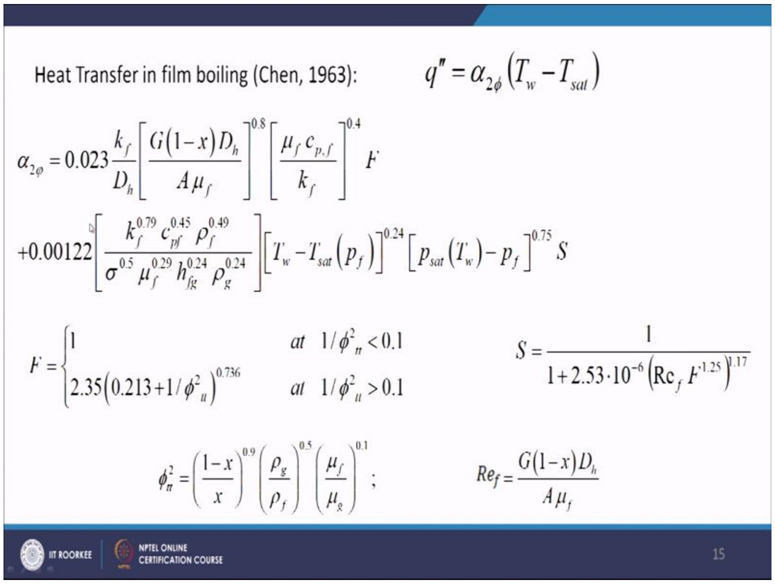

Heat Transfer in film boiling (Chen, 1963): $q'' = \alpha_{2\phi}\left(T_w - T_{sat}\right)$

$$\alpha_{2\varphi} = 0.023\frac{k_f}{D_h}\left[\frac{G(1-x)D_h}{A\mu_f}\right]^{0.8}\left[\frac{\mu_f c_{p,f}}{k_f}\right]^{0.4}F$$

$$+0.00122\left[\frac{k_f^{0.79}\, c_{pf}^{0.45}\, \rho_f^{0.49}}{\sigma^{0.5}\, \mu_f^{0.29}\, h_{fg}^{0.24}\, \rho_g^{0.24}}\right]\left[T_w - T_{sat}\left(p_f\right)\right]^{0.24}\left[p_{sat}\left(T_w\right) - p_f\right]^{0.75}S$$

$$F = \begin{cases} 1 & at \quad 1/\phi_{tt}^2 < 0.1 \\ 2.35\left(0.213 + 1/\phi_{tt}^2\right)^{0.736} & at \quad 1/\phi_{tt}^2 > 0.1 \end{cases} \qquad S = \frac{1}{1 + 2.53\cdot 10^{-6}\left(\mathrm{Re}_f\, F^{1.25}\right)^{1.17}}$$

$$\phi_{tt}^2 = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_f}\right)^{0.5}\left(\frac{\mu_f}{\mu_g}\right)^{0.1}; \qquad Re_f = \frac{G(1-x)D_h}{A\mu_f}$$

Similarly, in case of a film boiling, in flow boiling situation 1 can find out the heat transfer coefficient in this fashion. So heat transfer coefficient q w` will be alpha 2 phi (Tw-Tsat) and this alpha 2 phi can be found out in this fashion all these things are actually fluid dependent parameters apart from g. So once we know the value of the flow rate, you can find out the value of g. All these here you can find out our fluid dependent parameter only this (Tw – Tsat) is actually your degree of super heat. Here we are having empirical constant also this f and s.

So f and s can be find out in this fashion. f is 1 for this limit whenever it is very higher value of 2 phase friction factor and if for lower value you will be finding out this 1 okay. S can be found out in this fashion, where it is once again dependent on f and the film Reynolds number. Film Reynolds number can be defined in this fashion okay. He has Chen, he has defined this 2 phase multiplier in different. So he has defined this 1 with some power over here. Earlier we have seen this is (1-x) / x Rho f / Rho g and Mu f / Mu g but he has given some power over here 0.9, 0.5 and 0.1. So this Chen’s correlation will be very, very important for finding out of the heat transfer coefficient in film boiling.

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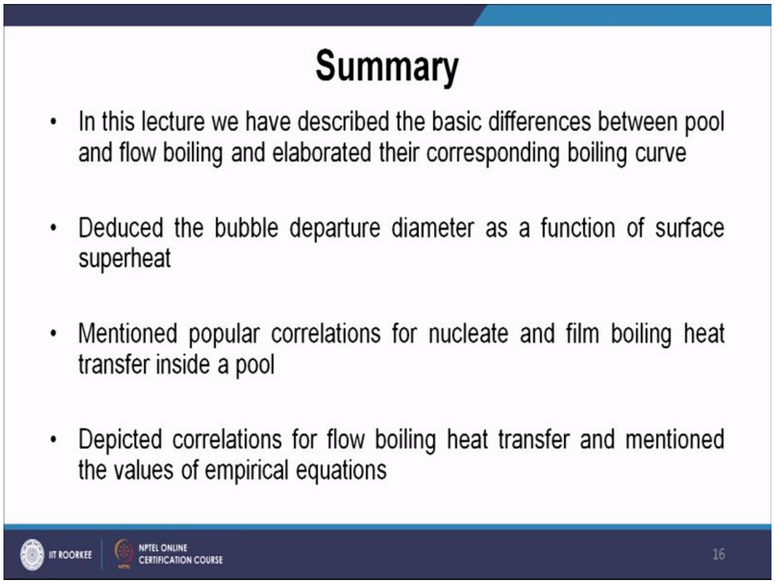

Summary

- In this lecture we have described the basic differences between pool and flow boiling and elaborated their corresponding boiling curve
- Deduced the bubble departure diameter as a function of surface superheat
- Mentioned popular correlations for nucleate and film boiling heat transfer inside a pool
- Depicted correlations for flow boiling heat transfer and mentioned the values of empirical equations

Let us summarize this lecture. So in this lecture what we have done. We have discussed about pool boiling and flow boiling situations .We have found out the departure diameter for a bubble. Whenever we are having different degree of super heat, we have found out popular correlations in case of nucleate boiling and film boiling. And finally we have find out that what will be the flow boiling empirically constant in case of your Chen and Kandlikar equations okay. Let us test your understanding at the end of this lecture.

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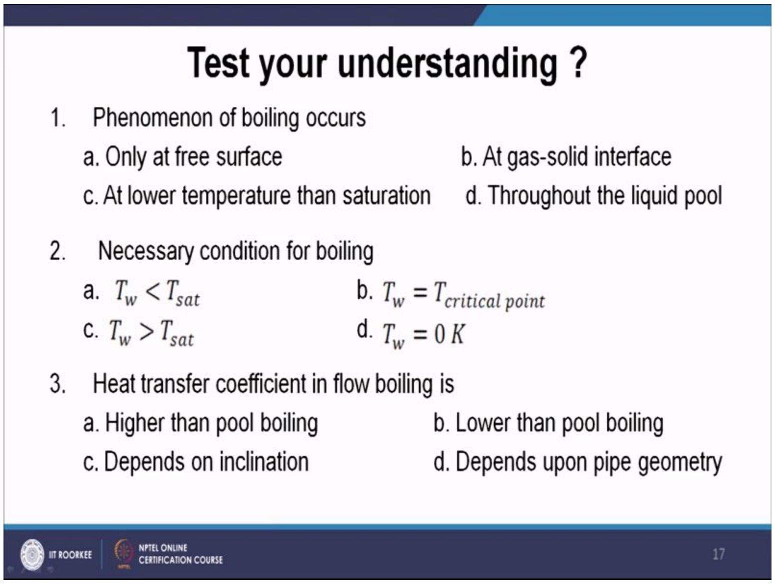

Test your understanding ?

1. Phenomenon of boiling occurs
   a. Only at free surface
   b. At gas-solid interface
   c. At lower temperature than saturation
   d. Throughout the liquid pool
2. Necessary condition for boiling
   a. $T_w < T_{sat}$
   b. $T_w = T_{critical\ point}$
   c. $T_w > T_{sat}$
   d. $T_w = 0\ K$
3. Heat transfer coefficient in flow boiling is
   a. Higher than pool boiling
   b. Lower than pool boiling
   c. Depends on inclination
   d. Depends upon pipe geometry

So here we are having 3 questions. Phenomenon of boiling occurs; we are having 4 answers .Only at free surface, at gas-solid interface, at lower temperature than saturation and throughout the liquid pool. So these we have mention in third slide of this lecture. So answer is throughout the liquid pool okay. So if it is only at the free surface then that will be your evaporation okay. Next question necessary condition for boiling. So we are having 4 answers. Tw < T sat, T w = T critical point, Tw > Tsat and Tw = 0 kelvin okay. So I think all of you know the answer. So answer is Tw > Tsat okay.

Third question heat transfer coefficient in flow boiling is. Higher than pool boiling, lower than pool boiling, depends on inclination and depends on pipe geometry okay. Already we have compared using a graph how the heat transfer coefficient is actually dependent on in pool boiling and flow volume situations. So obviously the answer is higher than pool boiling okay. So with this I will be ending this lecture, thank you.