Fundamentals of Convective Heat Transfer

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Module – 12
Boiling and Condensation
Lecture – 40
Boiling regimes and boiling curve

Hello everyone, till now we have studied the convective heat transfer in a single phase fluid flow. Today we will study Boiling and Condensation which is phase change process. Generally, we consider this phase change process because high heat transfer coefficient is involved in this heat transfer process.

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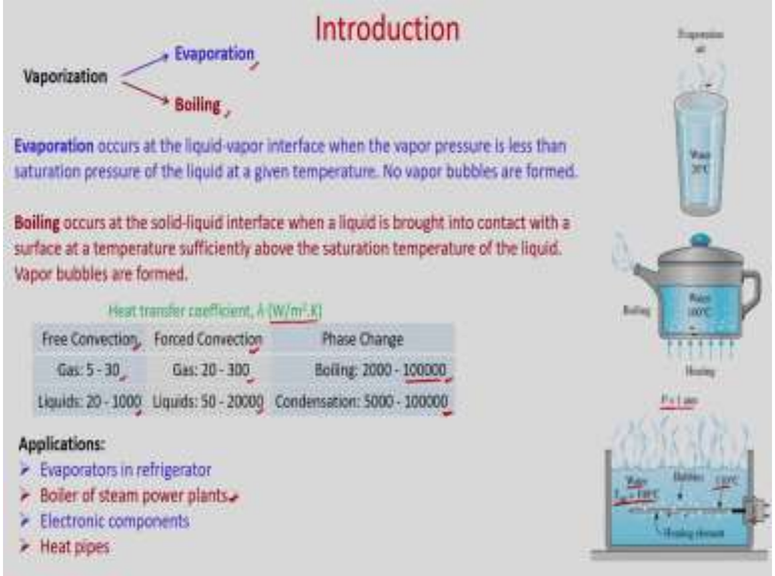

Introduction

Vaporization → Evaporation
Vaporization → Boiling

Evaporation occurs at the liquid-vapor interface when the vapor pressure is less than saturation pressure of the liquid at a given temperature. No vapor bubbles are formed.

Boiling occurs at the solid-liquid interface when a liquid is brought into contact with a surface at a temperature sufficiently above the saturation temperature of the liquid. Vapor bubbles are formed.

Heat transfer coefficient, h (W/m^2.K)

Free Convection	Forced Convection	Phase Change
Gas: 5 - 30	Gas: 20 - 300	Boiling: 2000 - 100000
Liquids: 20 - 1000	Liquids: 50 - 20000	Condensation: 5000 - 100000

Applications:

- Evaporators in refrigerator
- Boiler of steam power plants
- Electronic components
- Heat pipes

So, first we will discuss about the vaporization. Vaporization is a phase change process where phase change occurs from liquid to vapor. So, vaporization can be classified as evaporation and boiling. Evaporation is a surface phenomena and boiling is a bulk phenomena.

So, you can see here, so vaporization can be classified as evaporation and boiling. So, evaporation is a surface phenomena, so, it occurs at the liquid-vapor interface. So, you can see you have water in a glass. So, outside you have vapor. So, obviously, this process is occurring at the liquid-vapor interface.

And the vapor pressure is less than the saturation pressure of the liquid at the given temperature. And in this particular case, obviously, no bubbles are formed. And when we consider boiling, so boiling occurs at the interface of solid and liquid. So, you consider here, you are heating bottom of this pan, so, obviously the boiling takes place at the interface of the solid and the liquid .

And the temperature of this wall should be higher than the saturation temperature of the liquid at that saturation pressure. So, if you consider water as a liquid, then water saturation temperature at atmospheric pressure you know that it is 100 ^{0}C. So, if surface temperature is higher than the saturation temperature, then your boiling will takes place. In this particular case, obviously, vapor bubbles will be formed and those will go up due to buoyancy.

Let us consider the heat transfer coefficient in different modes of convective heat transfer. You can see if free convection if you consider, so, the, for gas – the heat transfer coefficient is of the range of 5 to 30 W/m^{2}K, whereas, if you consider free convection in liquids, it is 20 to 1000 W/m^{2}K. In forced convection, obviously, fluid flow is taking place by external means.

So, heat transfer coefficient increases. In this particular case, if you consider gas, then the heat transfer coefficient will be of the range of 20 to 300 W/m^{2}K; whereas, if you consider liquids, then obviously it will be much higher than this. So, it will be in the range of 50 to 20,000 W/m^{2}K.

But when you consider phase change like boiling or condensation, your latent heat is involved. So, in this particular case, heat transfer coefficient will be very very high. So, you can see here if you consider boiling phase change process, then your heat transfer coefficient may vary 2000 to 100000 W/m^{2}K. So, you can see it is a very high process; it is a very high heat transfer coefficient.

And you cannot achieve it in forced convection in a single phase fluid. If you consider condensation, the heat transfer coefficient may vary between 5000 to 100000 W/m^{2}K. So, in many application, where you need to remove high heat transfer, then this phase change process is taken as mode of heat transfer. So, you can see there are many applications of this boiling and condensation.

Mainly if you consider boiling, you can see in household application like you boil the water. So, while preparing the tea, when you boil the water, you can observe that when you put the water it is generally the temperature will be lower than the saturation temperature of the water. So, it will just start heating the liquid. After that you will see that formation of small small bubbles from the surface heating surface.

Then it will grow and it will go up due to buoyancy, and it will come to the free surface and it will bust. So, this is one example in our daily life. If you consider refrigerator, so in the evaporator, this refrigerant boiling in evaporator of refrigerator boiling of a refrigerant takes place and high heat transfer coefficient is involved in this particular case.

In electronic components if you consider, nowadays the electronic chip is becoming very smaller and smaller, so heat transfer area is becoming smaller, but you have high heat generation. So, to remove this high heat, you need to have this phase change process.

So, in many application, it is seen that on the chip micro channels are fabricated, and liquids are pass through this channels and heat is removed in phase change process. Another application of electronics cooling is heat pipe. So, heat pipe you can see in your laptop.

So, it is generally removes heat from the processor to the outside ambient by using heat pipes. So, here also phase change process occurs. Evaporator, this boiling process occurs and in condensation takes place at the condenser. And in boilers of steam power plants also you can see the boiling processes.

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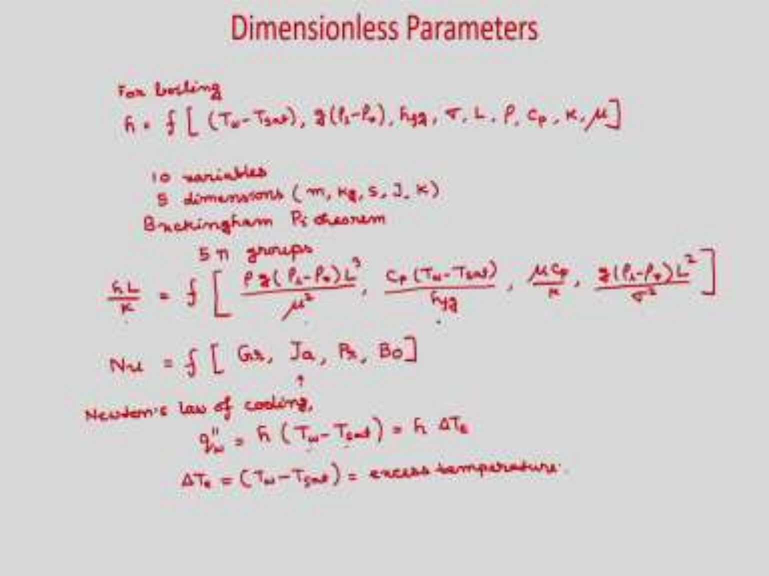

Dimensionless Parameters

For boiling

$h = f\left[(T_w - T_{sat}), g(\rho_l - \rho_v), h_{fg}, \sigma, L, \rho, c_p, K, \mu\right]$

10 variables

5 dimensions (m, kg, s, J, K)

Buckingham Pi theorem

5 π groups

$$\frac{hL}{K} = f\left[\frac{\rho g(\rho_l - \rho_v)L^3}{\mu^2}, \frac{c_p(T_w - T_{sat})}{h_{fg}}, \frac{\mu c_p}{K}, \frac{g(\rho_l - \rho_v)L^2}{\sigma}\right]$$

$$Nu = f\left[Gr, \underset{\uparrow}{Ja}, Pr, Bo\right]$$

Newton's law of cooling,

$$q''_w = h(T_w - T_{sat}) = h\,\Delta T_e$$

$\Delta T_e = (T_w - T_{sat})$ = excess temperature.

In case of phase change, this heat transfer coefficient is function of many parameters like temperature difference between the wall and the saturation temperature. Then you have the buoyancy force, you have the latent heat. And here most important another parameter we need to consider that is surface tension, because there will be liquid-vapor interface as well as it depends on the characteristic length of the geometry and also fluid properties.

So, if you see that your, for boiling, your heat transfer coefficient, $h = f\left[(T_w - T_{sat}), g(\rho_l - \rho_v), h_{fg}, \sigma, L, \rho, c_p, K, \mu\right]$. Then you have some buoyancy, because there will be density difference between the liquid and the vapor, then you have latent heat, surface tension, characteristic length, density of the liquid, specific heat, thermal conductivity and viscosity of the liquid. So, how many variables are there? You can see 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10. So, there are 10 variables are there.

And how many fundamental dimensions you have in this particular case? It is 5, because you have meter, second, kg, and two more for energy – Joule, and temperature – Kelvin. So, there are 5 fundamental dimensions, and you have 10 variables. And if you use Buckingham-Pi theorem, then you can find the 5 π non-dimensional groups. So, you can see that there are 10 variables and you have 5 dimensions, which are those you have meter, kg, second, Joule and Kelvin.

So, if you use Buckingham-Pi theorem, then you will get 5 π groups these are non-dimensional groups. And you can show that this will be $\frac{hL}{K}=f\left[\frac{\rho g(\rho_l-\rho_v)L^3}{\mu^2},\frac{C_p(T_w-T_{sat})}{h_{fg}},\frac{\mu c_p}{K},\frac{g(\rho_l-\rho_v)L^2}{\sigma^2}\right]$. So, these are all non-dimensional groups and you see you will get 5 π group, so 1, 2, 3, 4, and 5.

So, $\frac{hL}{K}=Nu$ and it is $Nu=f\left[Gr,Ja,\Pr,Bo\right]$, so this is you can define that it is the ratio of buoyancy force to the viscous force right. So, you can see that there is a density difference. Due to density difference is coming due to temperature difference, and that you can actually use Grashof number.

So, another definition in terms of the density that is similar to Grashof number is $\frac{C_p(T_w-T_{sat})}{h_{fg}}$. So, this is your in the numerator it is sensible energy absorbed by the vapor, and in the denominator it is latent energy absorbed by the vapor. So, this is your you can see that it is called Jakob number, and $\frac{\mu c_p}{K}$ you know it is Prandtl number, and this is the ratio of you can see buoyancy force to the surface tension force and this is known as Bond number .

So, bond number is the ratio of buoyancy force to the surface tension force. So, you can see we have got 5 non-dimensional numbers. So, Nusselt number in case of boiling is function of Grashof number, Jakob number, Prandtl number and Bond number.

Generally, in Jakob number when you are considering this $\frac{C_p(T_w-T_{sat})}{h_{fg}}$ is very high. So, in this many cases, you can see that Jakob number can be neglected, it will be very small and it can be neglected. So, you can see that in boiling heat transfer, obviously, your you can write from the Newton's law of cooling what is the heat flux.

So, you can see from Newton's law of cooling you can write the heat flux at the wall $q_w''=h(T_w-T_{sat})$. So, we define the heat flux based on the temperature difference of wall and the saturation temperature. And these temperature difference, generally known as excess temperature and denoted by ΔT_e. So, ΔT_e is the temperature difference between the wall and the saturation, and it is known as excess temperature.

Heat transfer in boiling is very complicated phenomena because there will be formation of bubbles, it will grow, it will collapse, and it will also rise due to buoyancy. So, first we will discuss about the boiling curve how the heat flux varies with the temperature difference that means the excess temperature. And later we will present the correlation to find the heat transfer, to find the heat transfer coefficient or the heat flux first.

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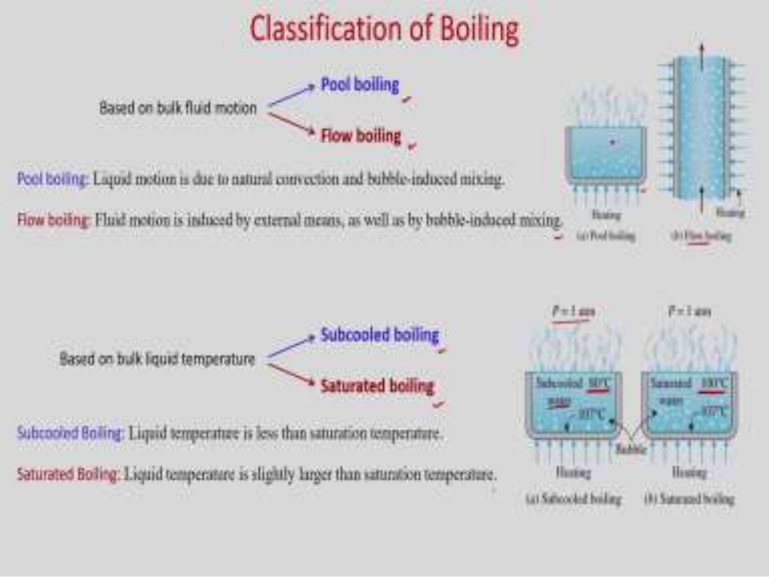

Classification of Boiling

Based on bulk fluid motion → Pool boiling / Flow boiling

Pool boiling: Liquid motion is due to natural convection and bubble-induced mixing.

Flow boiling: Fluid motion is induced by external means, as well as by bubble-induced mixing.

Based on bulk liquid temperature → Subcooled boiling / Saturated boiling

Subcooled Boiling: Liquid temperature is less than saturation temperature.

Saturated Boiling: Liquid temperature is slightly larger than saturation temperature.

Let us discuss about the classification of boiling. So, we can see based on bulk fluid motion, you can classified classify as boiling can be classified as pool boiling and flow boiling. In case of pool boiling, your liquid medium is quiescent. Once the heating starts, so there will be natural convection.

And if you increase more temperature, then there will be formation of bubbles and it will go up due to buoyancy. And due to that, naturally there will be some motion, but there will be no bulk motion in the in case of pool boiling. But when you consider flow boiling, so there will be an external bulk motion when it will pass through this heated surface.

So, there will be heat transfer between the hot surface to the liquid, and there will be formation of vapor, bubbles, and this is known as flow boiling. So, pool boiling – liquid motion is due to natural convection and bubble induced mixing; and in flow boiling – fluid motion is induced by external means as well as by bubble induced mixing.

Based on bulk liquid temperature, these boiling can be classified as sub-cooled boiling and saturated boiling. So, what is sub-cooled boiling? You can see here. So, if the liquid temperature initially it is less than the saturation temperature, then it is known as sub-cooled boiling. So, you can see water at 1 atmospheric pressure, your saturation temperature is 100 ^{0}C. So, water is at 80 ^{0}C, so it is known as sub-cooled boiling.

And when you consider saturated boiling, the liquid temperature initially will be slightly higher than the saturation temperature. In case of water you know saturation temperature is 100 ^{0}C, so the water will be just slightly higher than the saturation temperature. So, you can see sub-cooled boiling liquid temperature is less than the saturation temperature, but in saturated boiling liquid temperature is slightly larger than the saturation temperature.

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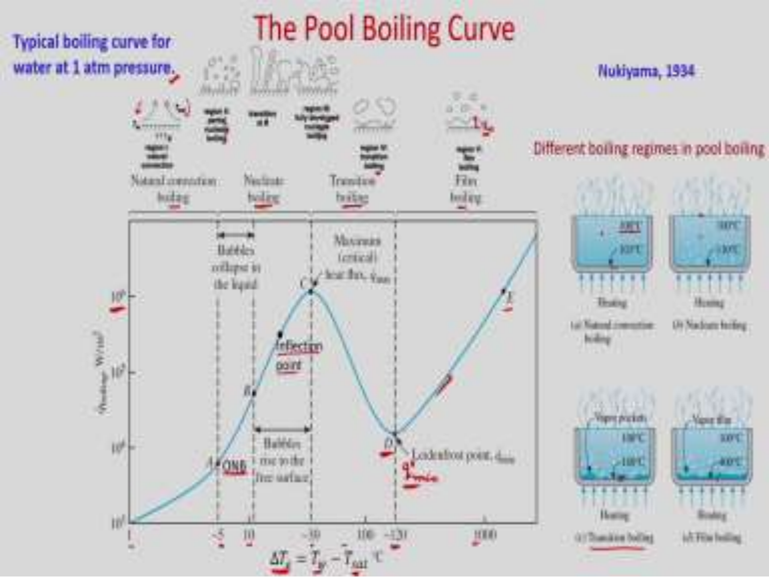

The Pool Boiling Curve

Typical boiling curve for water at 1 atm pressure.

Nukiyama, 1934

Different boiling regimes in pool boiling

So, now we will discuss about the boiling curve for the pool boiling. In this lecture, we will just consider pool boiling. And you can see that this boiling curve was first observed by scientist Nukiyama in 1934. And this typically he did the experiment for the water at 1 atmospheric pressure.

First, I will present the boiling curve what happens different regions of the boiling curve, and what happens when you increase the excess temperature. So, you see this the pool boiling curve the x-axis is your excess temperature, $\Delta T_e = \left(T_w - T_{sat}\right)$; and in the y-axis, it is the heat flux W/m^{2}K.

When you have this saturation temperature or saturated boiling you consider that means the liquid is at the saturation temperature 100^0C because we are considering the water. So, in this case, when you increase this ΔT_e, that means, essentially you are increasing T_w, because T_{sat} is constant that is for water at 1 atmospheric pressure, it is 100^0C.

So, as you increase T_w, obviously, your excess temperature will increase. So, we can see in this region up to A, where ΔT_e varies from 1 to 5^0C you will get only natural convection boiling. So, what will happen? So, you can see your temperature of the surface is increasing because ΔT_e is increasing; and the liquid is at saturation temperature 100^0C. So, the fluid near to this surface, we will have higher temperature and density will decrease. And due to that, it will go up.

And you can see here. So, this low density fluid will go up and high density liquid will come down, and that way natural convection boiling will takes place. But there will be no formation of bubbles in this region, because you have very small excess temperature. When you go from this point A to C, these are known as nucleate boiling.

So, in the nucleate boiling, you can see it is the temperature range of 5 to 30 ^{0}C – this is the excess temperature 5 to 30^0C. In this particular case, you will find that there will be formation of the bubbles from the liquid and solid surfaces and those bubbles will go up due to buoyancy. When you see between these region A to B generally bubbles collapse in the liquid, because your these super heated water will be your condense and these bubbles will disappear.

After that, if you go in the range of 10 to 30^0C, then these bubbles will go to the free surface. So, in case of delta x, the excess temperature between 5 and 10, your bubbles generally will not go to the free surface because it will be absorbed in the liquid itself. But when you go excess temperature between 10 and 30, these bubbles formation frequency will increase and it will reach to the free surface.

In this region, there are two separate regions you can see A to B, where bubble collapse in the liquid itself in the range of 5 to 10 ^{0}C ; and B to C where bubbles rise to the free surface and nucleate boiling takes place. So, you can see this point A, where the bubbles formation takes place, this is known as onset of nucleate boiling.

This point is known as ONB or onset of nucleate boiling. When temperature increases, your heat flux increases. At some point here around 20 ^{0}C you can see the curvature changes its slope. So, here the curvature of q double prime was increasing. But after this point this curvature will decrease, and this point is known as inflection point.

So, what happens here you can see from when you travel from B, generally your heat flux increases, your heat transfer coefficient will also increase. But after this inflection point your $q_w^{''}$, your heat flux is increasing, but your heat transfer coefficient will decrease because the curvature changes when you go from B to C at this point.

So, at this point – inflection point, you can see after this your heat transfer coefficient will decrease although your heat flux increases then you reach to the point C. So, C is known as maximum heat flux or critical heat flux because beyond that you cannot increase the heat flux. So, it is very important to know what is the maximum heat flux for the design of industrial equipments.

So, in this particular case, you can see if you cannot increase more than these heat maximum heat flux, and it is of the range of 10 to the power 6 W/m^{2}K. So, researchers are finding how to increase this critical heat flux. After that, so in this range A to C you can see when you are in the range of A to B, generally partial nucleate boiling takes place. So, vapor bubbles will go up, it will be it will disappear inside the liquid.

At the point of B, so there will be transition, so these bubbles actually there will be more frequency of bubble formation. And this will coalescence vertically as well as in horizontal direction. So, you can see in vertical direction, this coalescence it will form the vapor column.

And if horizontal direction it coalescence, then it will form a bigger bubble. So, in the range of B to C, you can see this is a fully developed nucleate boiling. So, these bubbles will coalescence, and there will be formation of vapor bubble column, and heat transfer will increase.

After point C to D, you can see although your excess temperature is increasing, but heat flux continuous to decrease up to point D. So, you can see, this is known as transition boiling. So, this is the regime where partial nucleate boiling and partial film boiling takes place. So, this is actually you have an unstable region where it switch to nucleate and film boiling, this is known as transition boiling.

In this particular case, you can see your discrete vapor blanket will be formed over the surface. So, you can see here, if you see here in this figure transition boiling, so in the range of 30 to 120^0C, you can see your this vapor pockets will be formed over the surface, so that means, there will be no connection between liquid and the surface.

So, as the liquid is separated from the surface by this vapor, so your heat flux will continue to decrease, because there will be one vapor blanket and discrete points over the surface. So, it will act as the resistance to heat transfer. So, your heat transfer continues to decrease although your excess temperature increases. So, this is known as transition regime. And in this particular case, generally partial nucleate boiling and film boiling will takes place.

When you come to the bottom point D, so, you will get minimum heat flux. So, this will be q double prime minimum. So, this is this point is known as latent frost point, where you have a minimum heat flux. After that what happens when you further increase the excess temperature you can see that if you go beyond 120^0C, then your heat flux again starts increasing ok. So, you can see it will continue to increase.

So, in this particular regime, what happens? Although you have a vapor blanket over the surface, but it is a continuous vapor blanket on the surface, and your temperature of the surface is also increasing because you have more excess temperature. So, as your temperature of the wall is increasing, your, you will get radioactive heat transfer mode as a dominant heat transfer mode.

So, here radiation heat transfer will take place and heat flux will start increasing. So, you can see, in this regime, there will be a vapor blanket. But as temperature of the surface T w is much much higher, so you will get the radiation mode as a dominant heat transfer mode in this particular regime.

If you see here, so you can see your temperature will be more than 120 ^{0}C and there will be vapor film over the surface. So, there will be a radiation heat transfer will takes place and your heat flux will increase. But if you go up to point E, then at this point generally most of the material will have the melting point in this region.

So, if melting point is in this region, then burn out will takes place, that means, your surface or the wall will melt. But if you use some material which is having higher melting point, then obviously, it will go up beyond the point E.

So, we can see when you considered the boiling for when you consider boiling curve for water at 1 atmospheric pressure, so we got 4 different regimes natural convection boiling which occurs between the excess temperature 1 and 5, then you get nucleate boiling in the range of 5 and 10, 5 and 30, then transition boiling between 30 and 120, and film boiling above 120.

And in the range of nucleate boiling, you can see a point is the onset of boiling, where vapor bubbles starts appearing. And at point B, you can see up to point B, there will be bubbles collapses in the liquid; but B to C, you will get bubbles rise to the free surface. And in between you will see that your this curve will change its curvature at this point that is why it is known as inflection point.

And beyond this point, your heat transfer coefficient will decrease although your heat flux increases. Once you reach at C, you will get the maximum heat flux. And the point D which is known as Leidenfrost point, so there is the minimum heat flux you will get. And after that radiation heat transfer mode will be dominant, and again heat transfer will increase.

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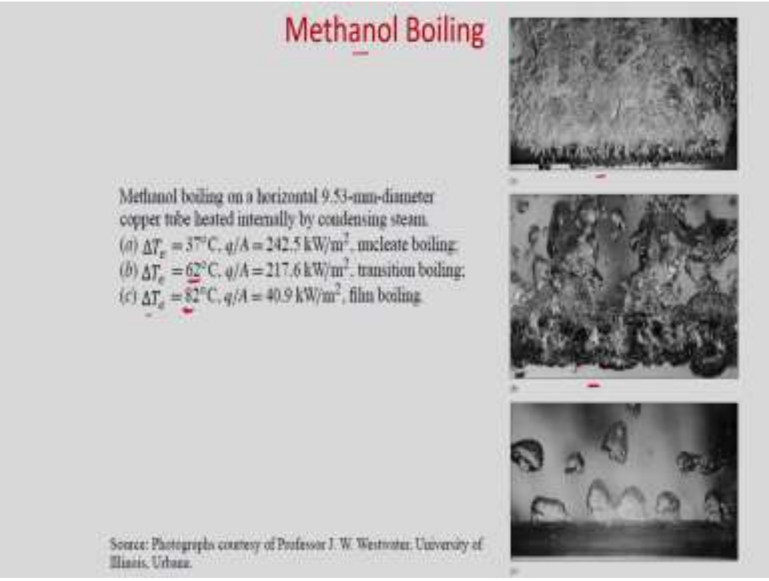

Methanol Boiling

Methanol boiling on a horizontal 9.53-mm-diameter copper tube heated internally by condensing steam.
(a) $\Delta T_e = 37°C$, $q/A = 242.5\ kW/m^2$, nucleate boiling;
(b) $\Delta T_e = 62°C$, $q/A = 217.6\ kW/m^2$, transition boiling;
(c) $\Delta T_e = 82°C$, $q/A = 40.9\ kW/m^2$, film boiling.

Source: Photographs courtesy of Professor J. W. Westwater, University of Illinois, Urbana.

Here you can see the experimental figure of methanol boiling. So, you can see that methanol boiling on a horizontal 9.53 mm diameter copper tube heated internally by condensing steam. So, when you have excess temperature of 37^0C, you can see how the nucleate boiling takes place. So, formation of bubbles, it grows, it coalescence.

And when the temperature difference as 62^0C, then transition boiling takes place, so it will be unstable region where both film boiling and the nucleate boiling will takes place. And when ΔT_e is 82^0C, you can see it is a film boiling. So, here 82 ^{0}C because we are considering methanol. So, at the 82^0C, your film boiling will takes place you can see on the surface you have a vapor blanket.

So, we discuss the pool boiling curve in general. Now, let us see what Nukiyama did the experiment. So, Nukiyama in 1934 when he did the experiment he took first nichrome wire.

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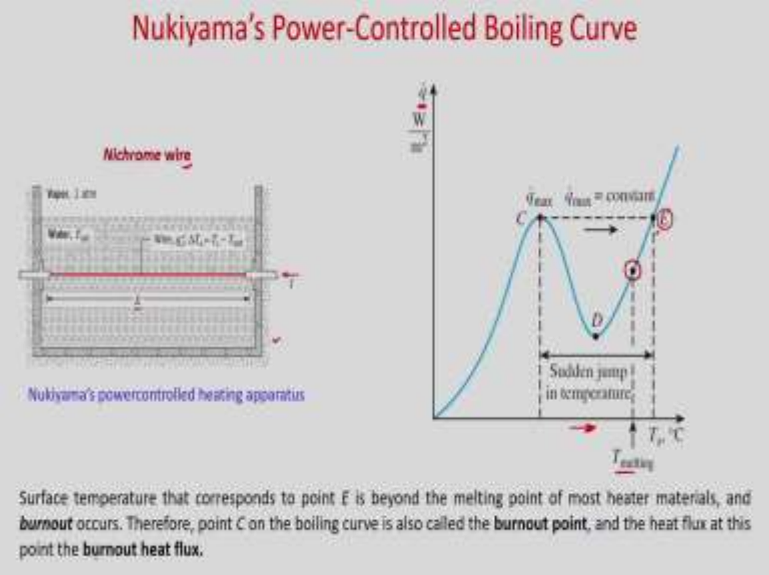

Nukiyama's Power-Controlled Boiling Curve

Nukiyama's powercontrolled heating apparatus

Surface temperature that corresponds to point E is beyond the melting point of most heater materials, and **burnout** occurs. Therefore, point C on the boiling curve is also called the **burnout point**, and the heat flux at this point the **burnout heat flux.**

So, you can see it was his experimental setup. This is a power control heating. So, you have this voltage difference and the current is passing through this nichrome wire. And he was just increasing the heat flux on this nichrome wire by controlling the current.

So, you can see this is your Nukiyama power control heating apparatus. So, when he did this experiment using nichrome wire, so we can see in the natural convection boiling nucleate boiling it goes. But when it reaches to the critical heat flux, then suddenly it jumps into the point E, where actually burn out takes place.

These region actually the temperature when you are controlling the heat flux, when you are controlling the heat flux, that means, you are increasing slowly slowly this heat flux, then what happens when you cross point C, there will be sudden jump in the temperature ok. So, suddenly your wall temperature will increase, and hence actually it will reach two point three where it will be the temperature which is higher than the melting temperature of the nichrome.

So, actually this nichrome wire, nichrome wire was burnt at this point. So, suddenly it will jump from here to here, because the melting temperature of the nichrome was lower than this point. So, your nichrome wire was burnt. So, he did not observe this curve from C to D, D to E because it suddenly goes from C to E.

So, surface temperature that corresponds to point E is beyond the melting point of most heater materials and burn out occurs. Therefore, point C on the boiling curve is also called the burnout point and the heat flux at this point the known as burn out heat flux. When this nichrome wire was burnt, then Nukiyama took platinum wire whose melting temperature is higher than the nichrome wire.

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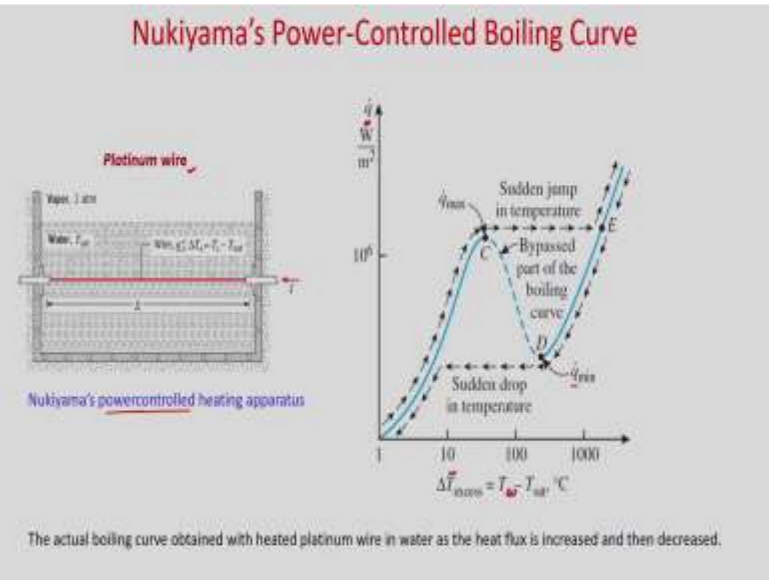

Nukiyama's Power-Controlled Boiling Curve

The actual boiling curve obtained with heated platinum wire in water as the heat flux is increased and then decreased.

So, when he used platinum wire in the same experimental setup and he was controlling the power, that means, he was increasing the heat flux then he observed that you can see here. So, when he was increasing the temperature, it was following this natural convection regime, nucleate boiling regime.

And once it comes to the critical heat flux it suddenly jumps to point E ok, so that means, there will be sudden jump in the temperature , sudden jump in the water temperature, because you are increasing the heat flux. As you are increasing the heat flux you do not have any control to over the surface temperature.

So, your surface temperature increases and this point from here, it suddenly jumps to this temperature E as your platinum wire temperature is higher than the 1000^0C. So, then you will see that your heat flux is increasing as your ΔT_e increases. And if you do the reverse, now you do the you decrease the heat flux. So, when you decrease the heat flux from this point.

So, as platinum wire is used, so burn out did not takes place. So, from that point if you decrease, the heat flux gradually decreases and it follows the path and it comes to the Leidenfrost point q_{min} at point D. But after that suddenly when you decrease the heat flux, suddenly it jumps from D to this point , then there will be sudden drop in the temperature.

So, you can see when this platinum wire was used and power controlled experiment was carried out. So, this C to D was missed because these phenomena tooks place so fast, that from C after point C suddenly there will be jump in the temperature and it will go to the point E. And once the heat flux is decreased gradually, it will follow the path up to D, but after D suddenly there will be a drop in the temperature. So, it will not follow D to C. So, this experiment was carried out by Nukiyama using power control method.

Now, somehow if you can control the temperature, how can you do that? So, you can use some phase change. Let us say condensation is taking place over the surface, so at constant temperature this phase change will occur. So, you can maintain the temperature. So, controlling the temperature, if you see the boiling curve, then you can see that it will follow whatever we have discussed.

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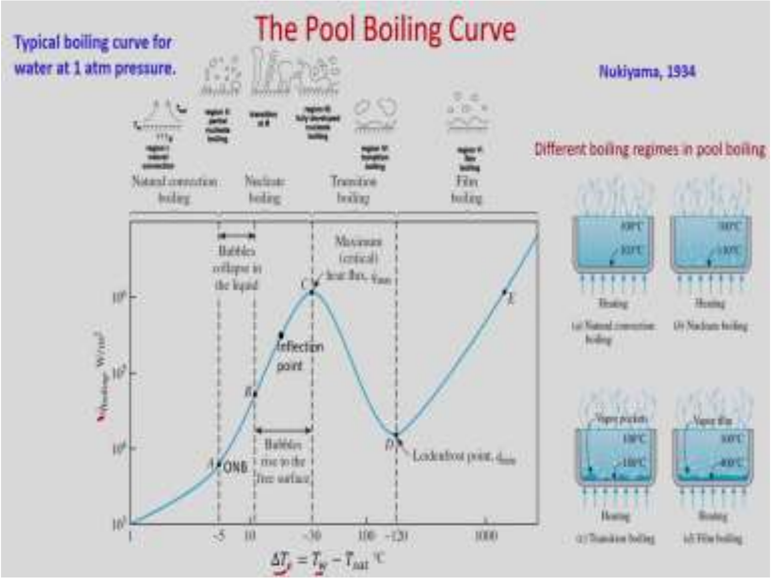

The Pool Boiling Curve

Typical boiling curve for water at 1 atm pressure.

Nukiyama, 1934

Different boiling regimes in pool boiling

So, when you use temperature controlled curve, so that means, your controlling ΔT_e, that means, T_w you are increasing slowly and you are measuring the heat flux. In a, what Nukiyama did Nukiyama, initially he was actually maintaining the heat flux. So, he was increasing the current. So, heat flux was increasing and we discuss about the boiling curve.

Now, you are controlling the temperature that means you are slowly increasing the temperature. In that particular case, you can see it will follow the curve from A to B to C and C to D is also observed because it does not take place in short time. So, it is seen in this particular case and D to E.

And if you decrease the temperature also, it will follow E to D, then D to C and C to A. So, similar way, it will also follow when temperature controlled experiment if you perform. Although these boiling curve we have discussed for water, but the other liquids also follow the similar curve. But you can see that its shape may change because the temperature range will change – the excess temperature.

As you can see that it is a very complicated phenomena as you can see that boiling is a complicated phenomena, so it is difficult to derive the heat transfer coefficient or Nusselt number analytically. So, mostly these are experimental base that means we will present now the heat flux or the Nusselt number based on the correlation. So, from the experiment whatever researchers are carried out from there generally these relations are presented and those are known as correlations.

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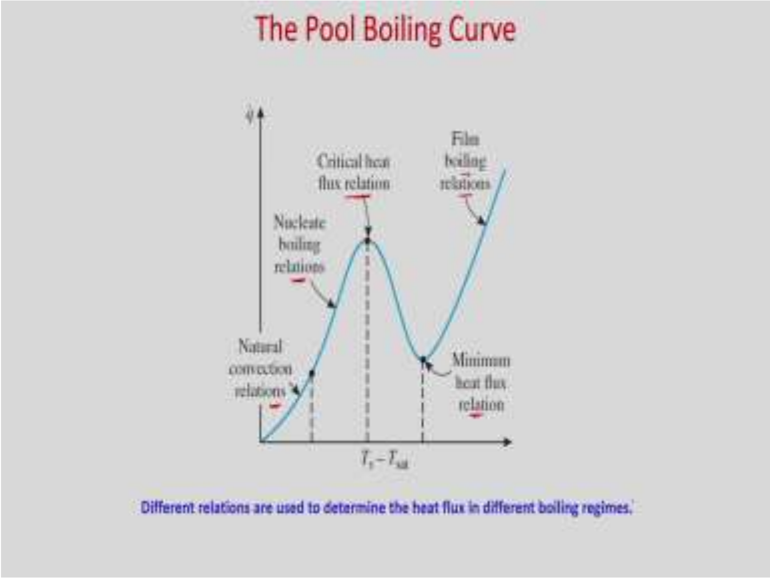

The Pool Boiling Curve

Different relations are used to determine the heat flux in different boiling regimes.

So, we can see we have natural convection relations where your natural convection takes place, then nucleate boiling relations, then critical heat flux relation where maximum heat transfer will take place, then minimum heat flux relation at the Leidenfrost point whatever heat flux you get, then film boiling relations. So, different relations are used to determine the heat flux in different boiling regimes using correlations.

Now, first regime is natural convection boiling. So, in a natural convection boiling, generally you have already studied in the natural convection. So, those relations you can use depending on the value of Rayleigh number.

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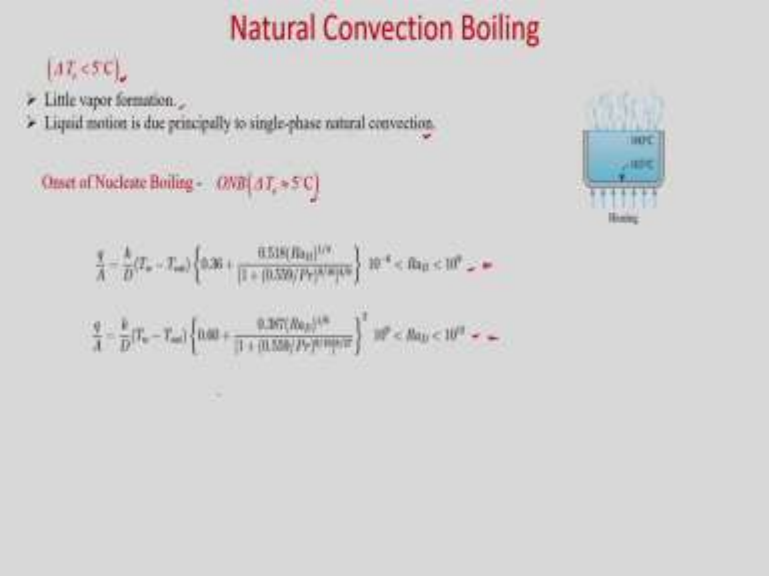

Natural Convection Boiling

$(\Delta T_e < 5^\circ C)$

- Little vapor formation.
- Liquid motion is due principally to single-phase natural convection.

Onset of Nucleate Boiling - $ONB(\Delta T_e \approx 5^\circ C)$

$$\frac{q}{A} = \frac{k}{D}(T_w - T_{sat})\left\{0.36 + \frac{0.518(Ra_D)^{1/4}}{[1+(0.559/Pr)^{9/16}]^{4/9}}\right\} \quad 10^{-6} < Ra_D < 10^{9}$$

$$\frac{q}{A} = \frac{k}{D}(T_w - T_{sat})\left\{0.60 + \frac{0.387(Ra_D)^{1/6}}{[1+(0.559/Pr)^{9/16}]^{8/27}}\right\}^2 \quad 10^{9} < Ra_D < 10^{12}$$

So, you can see this natural convection boiling takes place when your excess temperature is less than 5 ^{0}C. So, there will be little vapor formation liquid motion is due to principally due to single phase liquid motion is due principally to single phase natural convection. And onset of boiling takes place at 5 ^{0}C.

So, these are the heat flux relation you can use for different Rayleigh number regimes. So, it is 10^{-6} to 10^9, and this is 10^9 to 10^{12} that means it is in a turbulent regime. And this is you can say that Rayleigh number generally if it is less than 10^7 then it is the laminar regime. So, these relations can be used what you have studied in the natural convection.

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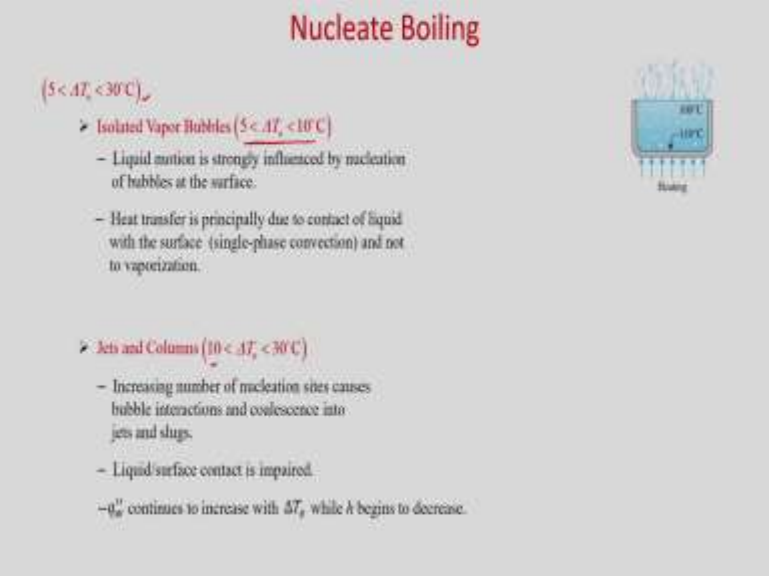

Nucleate Boiling

$(5 < \Delta T_e < 30^{\circ}C)$

- Isolated Vapor Bubbles $(5 < \Delta T_e < 10^{\circ}C)$
  - Liquid motion is strongly influenced by nucleation of bubbles at the surface.
  - Heat transfer is principally due to contact of liquid with the surface (single-phase convection) and not to vaporization.
- Jets and Columns $(10 < \Delta T_e < 30^{\circ}C)$
  - Increasing number of nucleation sites causes bubble interactions and coalescence into jets and slugs.
  - Liquid/surface contact is impaired.
  - q''_s continues to increase with ΔT_e while h begins to decrease.

Next nucleate boiling. So, in the nucleate boiling takes place between excess temperature 5 degree centigrade and 30^0C, so you can see there will be isolated vapor bubbles. Liquid motion is strongly influenced by nucleation of bubbles at the surface, and heat transfer is principally due to contact of liquid with the surface. So, single phase convection and not to vaporization between 5 to 10^0C.

So, in the first regime of this nucleate boiling and when you go beyond 10 ^{0}C, so between 10 to 30^0C, there will be coalescence of the bubbles in the vertical direction and horizontal directions you will get jets and columns and increasing number of nucleation sites causes bubble interactions, and coalescence into jets and slugs.

Liquid and surface contact is impaired, and your heat flux continues to increase with ΔT_e with while h begins to decrease. So, you can see that their after the inflection point, your h begins to decrease.

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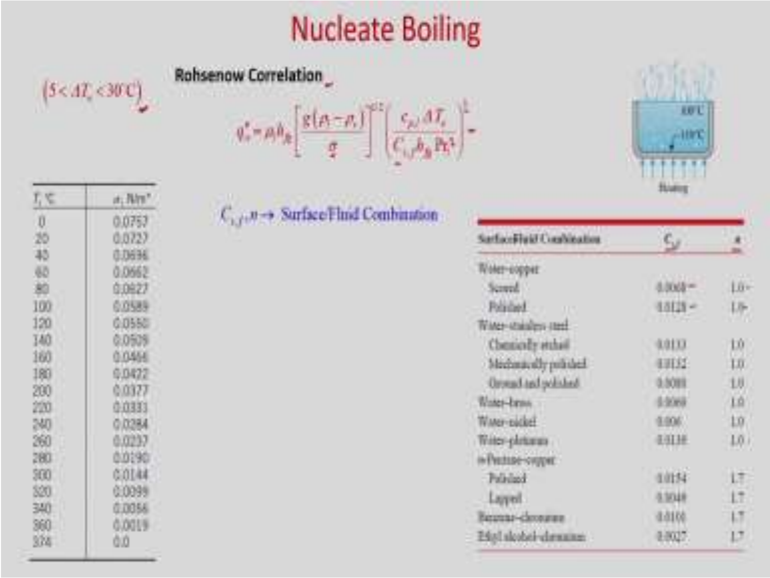

Nucleate Boiling

$(5 < \Delta T_e < 30^\circ C)$

Rohsenow Correlation

$$q''_s = \mu_l h_{fg}\left[\frac{g(\rho_l-\rho_v)}{\sigma}\right]^{1/2}\left(\frac{c_{p,l}\Delta T_e}{C_{s,f}h_{fg}\mathrm{Pr}_l^n}\right)^3$$

$C_{s,f}, n \rightarrow$ Surface/Fluid Combination

T, °C	σ, N/m
0	0.0757
20	0.0727
40	0.0696
60	0.0662
80	0.0627
100	0.0589
120	0.0550
140	0.0509
160	0.0466
180	0.0422
200	0.0377
220	0.0331
240	0.0284
260	0.0237
280	0.0190
300	0.0144
320	0.0099
340	0.0056
360	0.0019
374	0.0

Surface/Fluid Combination	$C_{s,f}$	n
Water–copper		
Scored	0.0068	1.0
Polished	0.0128	1.0
Water–stainless steel		
Chemically etched	0.0133	1.0
Mechanically polished	0.0132	1.0
Ground and polished	0.0080	1.0
Water–brass	0.0060	1.0
Water–nickel	0.006	1.0
Water–platinum	0.0130	1.0
n-Pentane–copper		
Polished	0.0154	1.7
Lapped	0.0049	1.7
Benzene–chromium	0.0101	1.7
Ethyl alcohol–chromium	0.0027	1.7

So, in the nucleate boiling generally these correlation is used that is known as Rohsenow correlation. So, you can use this correlation in the nucleate boiling regime. So, here you can see, $q''_w = \mu_l h_{fg}\left[\frac{g(\rho_l-\rho_v)}{\sigma}\right]^{1/2}\left(\frac{c_{p,l}\Delta T_e}{C_{s,f}h_{fg}\mathrm{Pr}_l^n}\right)^3$.

So, here you can see there are two constants, these are experimental constant. So, $C_{s,f}$ depends on the surface, and n depends on the fluid. So, you can see different surface fluid combination what are the values of this $C_{s,f}$ and n. So, if you consider water copper combination, so water is your fluid and copper is your surface.

So, there are scored and polished surfaces depending on that you will get different $C_{s,f}$ and n values is 1 for water. And for water mostly these value n value is 1. But if you take different liquid like pentane, benzene, ethyl alcohol, then it is 1.7. And $C_{s,f}$ also varies accordingly.

Here you can see your surface tension. So, surface tension is also depends on the temperature. So, at different temperature, you can see in this table the surface tension value in N/m.

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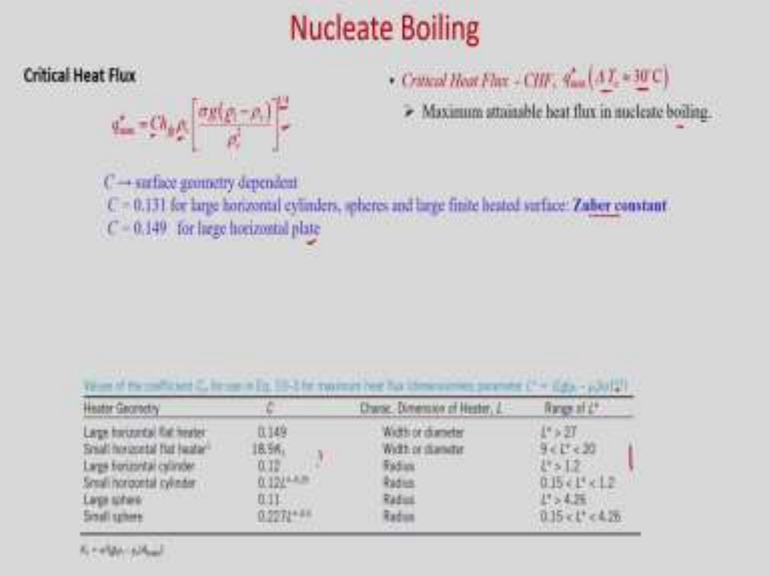

Nucleate Boiling

Critical Heat Flux

$$q''_{max} = Ch_{fg}\rho_v\left[\frac{\sigma g(\rho_l-\rho_v)}{\rho_v^2}\right]^{1/4}$$

- Critical Heat Flux - CHF, q''_{max} ($\Delta T_e \approx 30^0C$)
  - Maximum attainable heat flux in nucleate boiling.

$C \rightarrow$ surface geometry dependent
$C = 0.131$ for large horizontal cylinders, spheres and large finite heated surface: **Zuber constant**
$C = 0.149$ for large horizontal plate

Values of the coefficient C, for use in Eq. [illegible] for maximum heat flux (dimensionless parameter $L^* = L[g(\rho_l - \rho_v)/\sigma]^{1/2}$)

Heater Geometry	C	Charac. Dimension of Heater, L	Range of L*
Large horizontal flat heater	0.149	Width or diameter	$L^* > 27$
Small horizontal flat heater[a]	$18.9K_1$	Width or diameter	$9 < L^* < 20$
Large horizontal cylinder	0.12	Radius	$L^* > 1.2$
Small horizontal cylinder	$0.12L^{*-0.25}$	Radius	$0.15 < L^* < 1.2$
Large sphere	0.11	Radius	$L^* > 4.26$
Small sphere	$0.227L^{*-0.5}$	Radius	$0.15 < L^* < 4.26$

[a] $K_1 = \sigma/[g(\rho_l - \rho_v)A_{heater}]$

So, as a temperature increases, you can see surface tension decreases. Then at the in the nucleate boiling, you will get the critical heat flux. So, this critical heat flux you will get when your excess temperature is of the order of 30 ^{0}C. So, this is the maximum attainable heat flux in nucleate boiling.

So, this critical heat flux correlation is given by this relation $q''_{max} = Ch_{fg}\rho_v\left[\frac{\sigma g(\rho_l-\rho_v)}{\rho_v^2}\right]^{1/4}$.

So, here ρ_v is your vapor density, and ρ_l is your liquid density. And this is the constant and it depends on surface geometry.

So, C is 0.131 for large horizontal cylinders, spheres and large finite heated surface. And this C is known as Zuber constant, and C is 0.149 for large horizontal plate. So, you can see here this C value for different surface geometry, these are the value of C in the range of L*, where $L^* = L\left[\frac{g(\rho_l-\rho_v)}{\sigma}\right]^{1/2}$. So, this is the L*. So, different L* regime, you will get different value of C.

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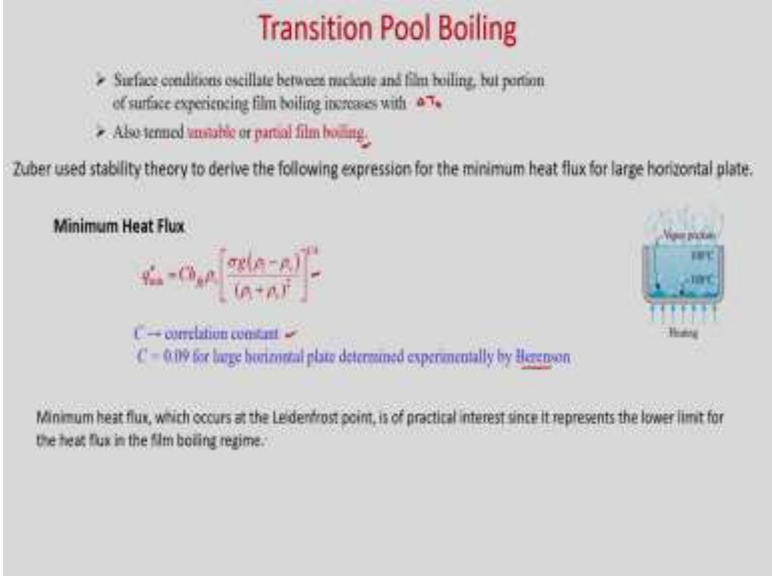

Transition Pool Boiling

- Surface conditions oscillate between nucleate and film boiling, but portion of surface experiencing film boiling increases with ΔT_e
- Also termed unstable or partial film boiling.

Zuber used stability theory to derive the following expression for the minimum heat flux for large horizontal plate.

Minimum Heat Flux

$$q''_{min} = Ch_{fg}\rho_v\left[\frac{\sigma g(\rho_l-\rho_v)}{(\rho_l+\rho_v)^2}\right]^{1/4}$$

$C \rightarrow$ correlation constant

$C = 0.09$ for large horizontal plate determined experimentally by Berenson

Minimum heat flux, which occurs at the Leidenfrost point, is of practical interest since it represents the lower limit for the heat flux in the film boiling regime.

Now, if you go beyond that regime, then you will get transition pool boiling. So, in a transition boiling, what happens it shifts between nucleate boiling and film boiling. So, surface condition oscillates between nucleate and film boiling, but portion of surface experiencing film boiling increases with your ΔT_e, also termed unstable or partial film boiling.

So, Zuber used stability theory to derive the following expression for the minimum heat flux for large horizontal plate, and this minimum heat flux which actually happens in the Leidenfrost point, so that is $q''_{\min} = Ch_{fg}\rho_v\left[\frac{\sigma g(\rho_l-\rho_v)}{(\rho_l+\rho_v)^2}\right]^{1/4}$. So, here C is your correlation constant it is generally 0.09.

For large horizontal plate determined experimentally by Berenson. So, maximum heat flux minimum heat flux which occurs at the Leidenfrost point is of practical interest since it represent the lower limit for the heat flux in the film boiling regime. So, in the pool boiling, we have seen when the vapor bubbles are formed those bubbles goes up due to buoyancy, and goes to the free surface.

But when we consider the flow boiling where fluid flow is there due to the external means like a pump then there will be no free surface to remove these bubbles. So, let us consider a vertical pipe where fluid flow is taking place from bottom to top, and the surface of the tube is maintained at a constant heat flux. So, you can see this is your vertical pipe.

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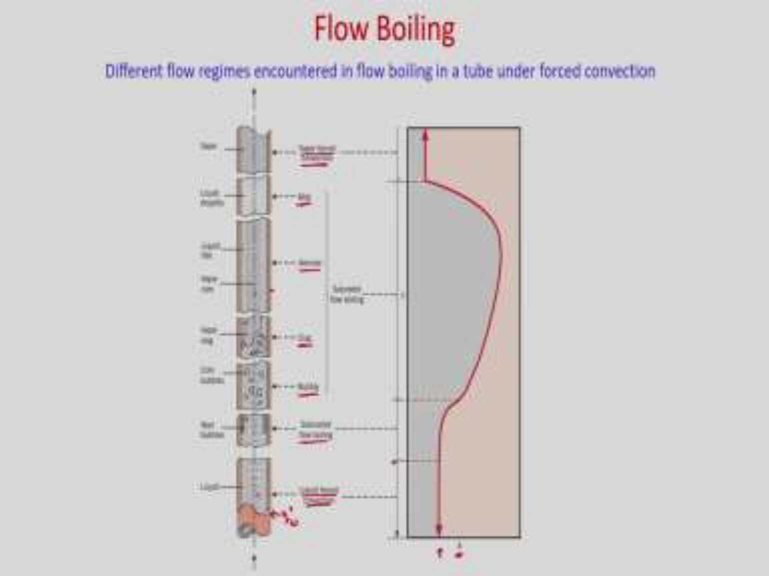

Flow Boiling

Different flow regimes encountered in flow boiling in a tube under forced convection

So, water, subcooled water is entering here. Now, the surface of the tube is maintained at constant wall heat flux. So, when this liquid flows through this tube, there are different regimes are seen. You can see that when subcooled liquid enters here, so obviously, the there will be forced convection because the temperature of the liquid will get heated. Once you go up, then you will see that there will be subcooled flow boiling will takes place.

So, some vapor bubbles will be formed from the surfaces. And these vapor bubbles will come near to the central region, and it will form bubbles. And those region is known as bubbly region. If we go further, more heat transfer will take place. And these vapor bubbles will coleus each other and it will grow in size forming the slug region. So, vapor slug will be formed. If you go further, then this vapor slug will form a vapor core in the central region.

And liquid will be flowing between this vapor core, and the surface in the annular region of this vapor core and the tube surface. So, vapor liquid film will be just in contact with the heated surface, and vapor core will move in the central region. After that, if we go further these liquid film, there will be generation of small small vapor bubbles and it will form liquid droplets and homogeneous mixture will be formed, and that is known as mist.

If you go further, then due to heat transfer from the tube surface, these liquid droplets will convert into vapor, and pure vapor region you will get where only vapor forced convention will takes place. So, you can see when you are going from bottom to top, in the bottom you have liquid forced convection because it is a sub-cooled liquid is coming.

So, here single phase heat transfer takes place in this region. Then in between phase change occurs from liquid to vapor following the different regimes. Then at the end, you can see the liquid will be fully converted to vapor, and again you will get a vapor forced convection which is your single phase heat transfer will takes place.

If you see the heat transfer coefficient how it varies, so it is shown in this picture. So, this is your heat transfer coefficient along the length, and x is the liquid mass fraction. So, you can see when you go from this liquid forced convection – single phase heat transfer takes place, there will be not much increase in the heat transfer. When subcooled flow boiling, this will takes place there is will start increasing in bubbly and slug flow it will start increasing, you will get maximum heat transfer coefficient in the annular region.

So, you can see that, when it will come in the annular region you will get maximum heat transfer. Once you go to the mist, so slowly your heat transfer coefficient will decrease. And in the vapor core convection, you can see that there will be formation of hotspot because there is no liquid, so obviously, your low heat transfer will takes place. So, it will become minimum in this region.

So, you can see your liquid mass fraction will be 1 when it is entering; and when it is going to the vapor forced convection region, then obviously this will become 0 because it has become fully vapor. So, you can see this is a very complicated process goes through the different regimes, and different researchers proposed different correlation in different regimes. But those discussions is out of scope of this lecture.

So, you can see only in the sub-cooled region as well as in your vapor convection region, you can use a single phase heat transfer correlations, you can use heat transfer coefficient correlations. And in between you can use because it is a exhibits the combined effect of pool boiling and the forced convection. So, different correlations are proposed in this region considering the effect of pool boiling as well as the pure single phase convection.

So, today we discussed about the pool boiling curve. In pool boiling curve, first we considered the water at 1 atmosphere. With increase of excess temperature we have found four discrete regime; one is nucleate boiling, then first is natural convection boiling, then nucleate boiling regime, then transition boiling and film boiling. So, the point at which your first vapor bubble formation takes place, so that is known as onset of nucleate boiling. Then you will get the inflection point.

In the nucleate boiling regime, if you go beyond the inflection point, then your heat transfer coefficient decreases with increase of heat flux. Then you reach at the maximum heat flux which is known as critical heat flux. After that as you increase the ΔT_e , your heat flux starts decreasing because of formation of vapor blanket over the surface which acts as a resistance to the heat transfer.

Once you come to the Leidenfrost point which is your where you will get the minimum heat flux, after that regime your heat flux starts increasing with the increase of ΔT_e. Because in this particular regime, you will get which is your film boiling, you will get radiation as a major mode of heat transfer.

Due to that, there will be increase in the heat flux as you increase the excess temperature. As boiling phenomena is a very complicated phenomena. So, to calculate the heat flux or the heat transfer coefficient, generally correlations are used from different experiments. So, today we have presented the expression for heat flux in different regimes from where you will be able to calculate the heat transfer coefficient.

Thank you.