Heat Transfer And Combustion in Multiphase Systems

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Lecture 40

Boiling-II (Bubble dynamics and critical heat flux)

So, welcome to the final lecture of this particular series. Now we are going to study bubble detachment today.

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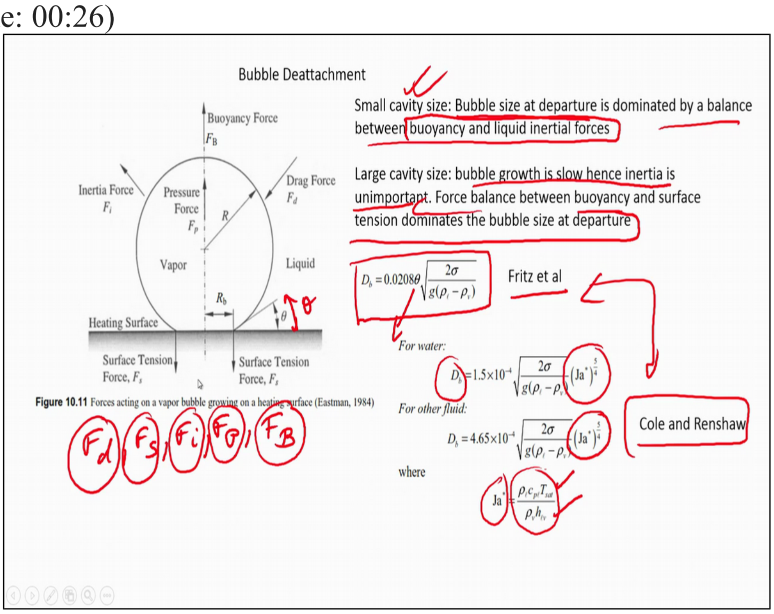

Bubble Deattachment

Small cavity size: Bubble size at departure is dominated by a balance between buoyancy and liquid inertial forces

Large cavity size: bubble growth is slow hence inertia is unimportant. Force balance between buoyancy and surface tension dominates the bubble size at departure

$$D_b = 0.0208\theta\sqrt{\frac{2\sigma}{g(\rho_l - \rho_v)}}$$

Fritz et al

For water:

$$D_b = 1.5\times10^{-4}\sqrt{\frac{2\sigma}{g(\rho_l - \rho_v)}}\left(\text{Ja}^*\right)^{\frac{5}{4}}$$

For other fluid:

$$D_b = 4.65\times10^{-4}\sqrt{\frac{2\sigma}{g(\rho_l - \rho_v)}}\left(\text{Ja}^*\right)^{\frac{5}{4}}$$

Cole and Renshaw

where

$$\text{Ja}^* = \frac{\rho_l c_{pl} T_{sat}}{\rho_v h_{lv}}$$

Figure 10.11 Forces acting on a vapor bubble growing on a heating surface (Eastman, 1984)

So, if you take a look at the slide you will find that a bubble as we say it first forms those nice hemispherical caps and then it slowly grows and at one point of time it detaches right. So, bubble size at departure is dominated by a balance between buoyancy and the liquid inertial forces particularly when a cavity size is small okay.

If the cavity size is large then the bubble growth is slow and inertia is unimportant. Then the force balance between buoyancy and surface tension is what determines the bubble size at departure. So, for example Fritz at al found that the bubble sizes departure is given by this particular relationship where this theta is basically nothing but this contact angle.

Now for water okay and for other fluids okay Cole and Renshaw found that the droplet size of the point of departure is also a function of the Jacob number. But this is a different definition of Jacob number as you can see but its essence is the same this is like the sensible enthalpy divided by the latent heat.

So, it is also dependent on the Jacob number as well. So, this was like two different studies but more both the studies actually show that the bubble size at departure is usually buoyancy inertia dominated or buoyancy surface tension dominated depending on the size and a multitude of other factors okay.

Now if we look at now this particular diagram over here okay you will find that there are many forces which are acting on a bubble at the point of departure right. So, these forces are basically Fd, Fs, Fi, Fp and FB. So, basically Fd is the drag force, Fs is basically the force due to surface tension.

Fi is inertial related force, Fp is the pressure force and FB is a buoyancy related force okay. Now the bubble would actually departure depart if one of these forces I mean the sum total of these forces somehow becomes imbalanced.

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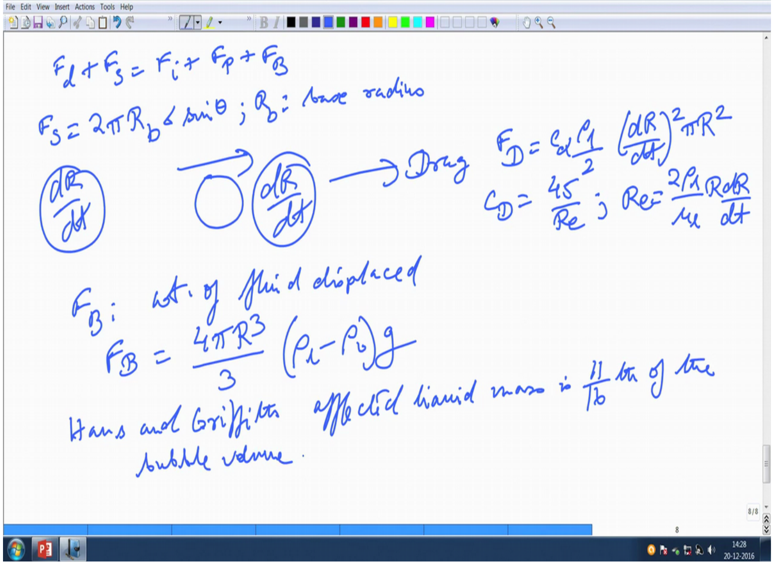

$F_d + F_s = F_i + F_p + F_B$

$F_s = 2\pi R_b \sigma \sin\theta$; R_b: base radius

Drag $F_D = C_d \frac{\rho_l}{2} \left(\frac{dR}{dt}\right)^2 \pi R^2$

$C_D = \frac{45}{Re}$; $Re = \frac{2\rho_l}{\mu_l} R \frac{dR}{dt}$

F_B: wt. of fluid displaced

$F_B = \frac{4\pi R^3}{3} (\rho_l - \rho_v) g$

Hans and Griffith affected liquid mass is $\frac{11}{16}$th of the bubble volume.

So, let us go back to our little journal item over here and there we will show that from the forces that are acting on the bubble Fd + Fs = Fi+ Fp+ FB right okay. So, Fs is very straightforward it is 2Pi Rb into sigma into sine theta right where theta we know it is a contact angle Rb is equal to the base radius.

This we already saw from that little figure that we had over here so this is your basic on your RB okay. So, you should consult the two notes. So, as the bubble grows the drag force will act on the bubble right, if the bubble is spherical and translates with a velocity of dr by dt. So, this is equivalent to saying that this is a bubble which is translating at a velocity dr by dt there will be an equivalent drag force that will be created on the bubble okay.

So, that drag force is given by Fd and that is the drag force that we say is actually what is acting on the bubble which is anchored onto the substrate right. So, this drag force is given by

Cd Rho l by 2 dr by dt square Pi R square where Cd is basically equal to 45 by Re, Re is basically given by 2 Rho l by Mu l R into dR by dt okay.

Now for a spherical bubble submerged in a stagnant fluid the buoyancy force is equal to the weight of the fluid displaced right. Buoyancy force Archimedes principle is equal to the weight of fluid displaced right. So, that FB is therefore given as 4 Pi R cube by 3 Rho l - Rho v into g. Now in most of the cases that vapour inertia is negligible right. The inertia of the vapour phase within the bubble is negligible.

But the inertia of the liquid surrounding the bubble is not negligible okay. So, what Han's Griffith found is that the affected liquid mass is 11 by 16 that is a strange number of the bubble volume okay.

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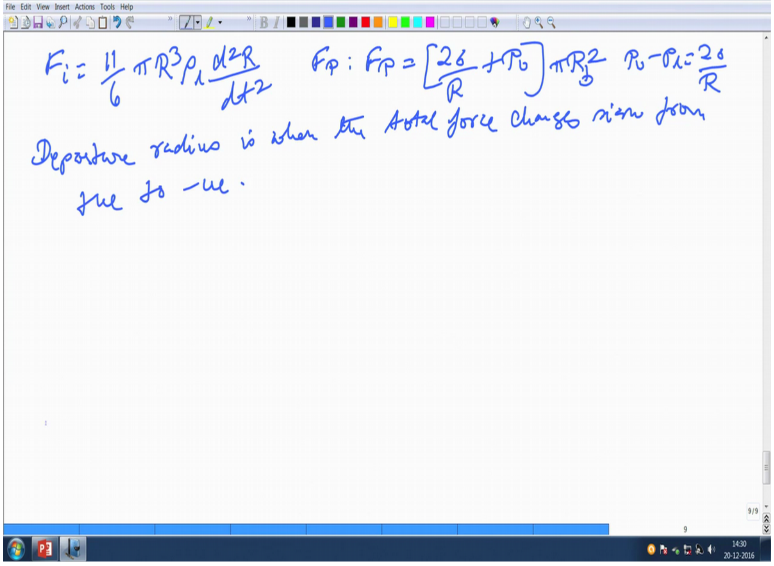

$F_i = \frac{11}{6}\pi R^3 \rho_l \frac{d^2R}{dt^2}$ $F_P : F_P = \left[\frac{2\sigma}{R} + P_v\right]\pi R_b^2$ $P_v - P_l = \frac{2\sigma}{R}$

Departure radius is when the total force changes sign from +ve to -ve.

So, your Fi basically is given as 11 by 6 Pi R cube Rho l d square R by dt square okay. Now Fp which is the pressure force is basically nothing but see if you understand it 2 sigma by r + Pv into PI Rb square okay where Pv -Pl = 2 sigma by R. So, it is basically the excess vapour pressure and capillary pressure that is what it is okay.

So, the departure radius departure radius R the radius at which the bubble depart is when the total force okay change is sign from positive to negative okay. So, when the total force changes time to change a sign from positive to negative okay.

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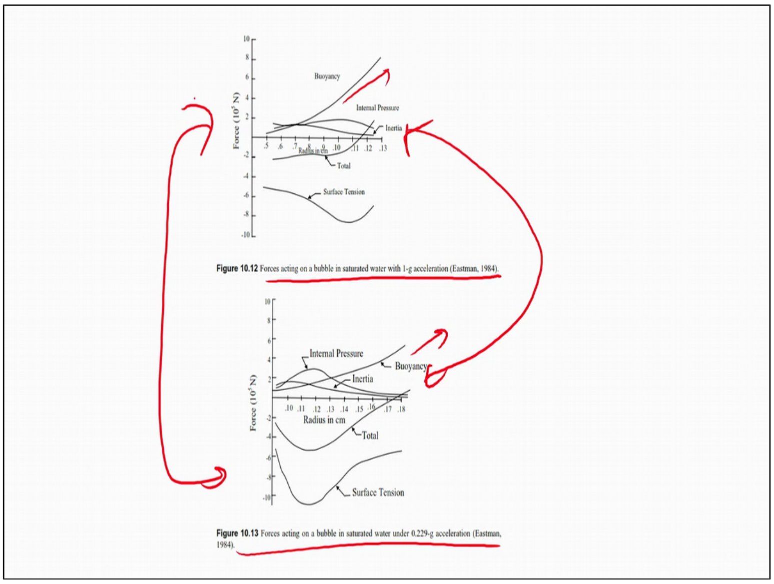

Figure 10.12 Forces acting on a bubble in saturated water with 1-g acceleration (Eastman, 1984).

Figure 10.13 Forces acting on a bubble in saturated water under 0.229-g acceleration (Eastman, 1984).

So, if you look at it you will find that okay these are the distribution of the forces basically. So, for example forces are actually this is 1g acceleration this is .29 g acceleration, so when the bubble is accelerating, so these are the forces as you can see couple of observations the buoyancy moves up like that okay.

The inertia is more or less unaffected it does not change no matter what acceleration you are bringing to the table okay. So, the buoyancy is directly related basically to the gravitational acceleration. So, these are the forces profiles that you see for the bubble at the point of departure okay.

So, this is what is with respect to bubble detachment right. So, these are the forces, these are the nature of the forces, the force changes will sign okay. And when it does that the bubble actually departs.

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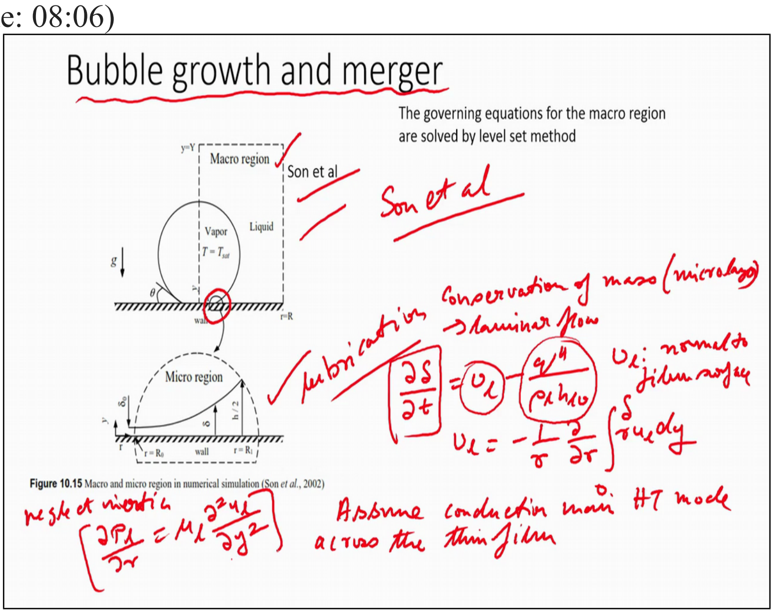

Bubble growth and merger

The governing equations for the macro region are solved by level set method

Son et al

Figure 10.15 Macro and micro region in numerical simulation (Son et al., 2002)

Son et al

Conservation of mass (microlayer)

→ laminar flow

lubrication

$$\boxed{\frac{\partial \delta}{\partial t}} = v_l - \frac{q''}{\rho_l h_{lv}}$$

v_l: normal to film surface

$$v_l = -\frac{1}{r}\frac{\partial}{\partial r}\int_0^\delta r u_l dy$$

neglect inertia

$$\left[\frac{\partial P_l}{\partial r} = \mu_l \frac{\partial^2 u_l}{\partial y^2}\right]$$

Assume conduction main HT mode across the thin film

Now the bubble growth and merger okay is another significant topic that has been widely studied. Because how does the bubble grow, how does it merge okay. So the main work has been done by Son et al which is given here okay. Now most of these things are solved by numerically okay. There is no analytical solution per se.

But however what Son et al, I want to give you the spirit of what the thing is in general okay. So, that you have a good chance of attacking such problems in the future. So, basically what, Son et al did was that he divided into two segments there is a macro region and then there is a micro region.

Micro region is just that particular region. So, the macro region he solved it by the usual level set kind of a method okay. The micro region was solved by the lubrication theory. Micro region is really micro that means this length scale is very small okay. And you remember when the length scale is that small all your disjoining pressure and other things comes into the picture.

Remember we talked about this long, long time back okay. So, based on that particular argument okay what we can do is that we can kind of for the micro region because that is that this has to be solved numerically you cannot do anything about it. But the micro region we can give some you know some equations which may be useful okay.

So, conservation of mass this is only for the micro region, a micro layer and we assume that it is a micro layer laminar flow. The laminar flow is quite common okay so d delta by dt = Vl q double prime Rho l hlv okay. So, Vl is a velocity which is normal to the interface okay normal to the film surface, velocity is normal to the film surface okay.

So, this Vl from the regular continuity we can find it out to be like this 0 to delta rul dy right. So, you can see this that this is the change in the thickness of this layer okay which is given by the velocity and whatever is the heat. This is heat divided whatever is latent heat, so that is that m right.

So, whatever is the mass that is being added to the whole thing, okay. So, assume; so in this case we are going to assume that conduction is the main mode of heat transfer in the across the thin film, main heat transfer mode across the thin film okay across the thin film okay. So, if that is the case assume conduction also from if we neglect inertia.

So, we can write the lubrication equation basically that is the lubrication equation right. If you recall that is what the equation is all about okay.

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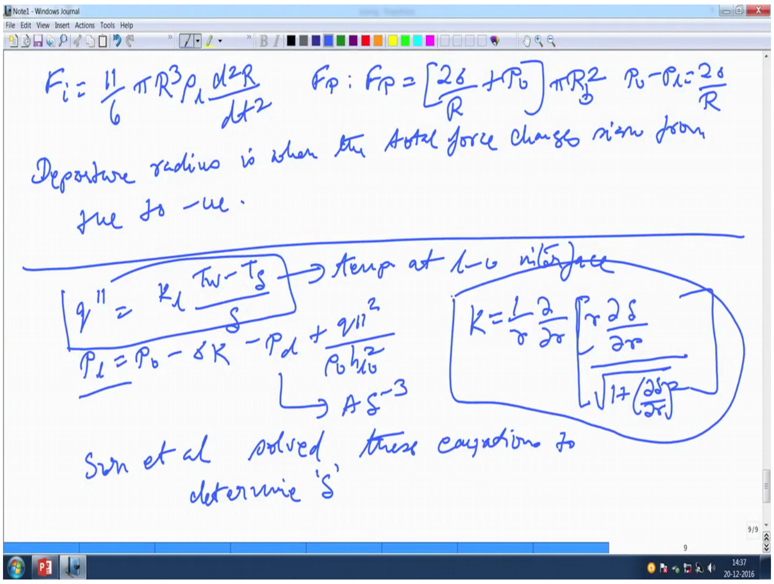

$F_i = \frac{11}{6}\pi R^3 \rho_l \frac{d^2R}{dt^2}$ $\quad F_p : F_p = \left[\frac{2\sigma}{R} + P_v\right]\pi R_b^2$ $\quad P_v - P_l = \frac{2\sigma}{R}$

Departure radius is when the total force changes sign from +ve to -ve.

$q'' = k_l \frac{T_w - T_\delta}{\delta}$ → temp at l-v interface

$P_l = P_v - \sigma K - P_d + \frac{q''^2}{\rho_v h_{lv}^2}$

$P_d \rightarrow A\delta^{-3}$

$K = \frac{1}{r}\frac{\partial}{\partial r}\left[\frac{r\frac{\partial \delta}{\partial r}}{\sqrt{1+\left(\frac{\partial \delta}{\partial r}\right)^2}}\right]$

Son et al solved these equations to determine 'δ'

Let us see; so we will and we will move to the journal once again okay. So in that particular case now that this is a different just to demarcate okay, so, that is the lubrication theory, so as you mean conductive heat flux what you have is that you have Tw - T delta divided by delta. So, the T Delta is the temperature at liquid vapour interface right okay.

The vapour interface also you can write Pl = Pv - Sigma K - Pd + q double prime square divided by Rho v hlv square. So, this is you know that this is the disjoining pressure which is given by this okay and k which is the curvature is actually given by r dr divided by 1 + okay. So, Son basically did was that he solved okay these equations to determine Delta got it, okay.

So, what was the thing, so, you already had the delta equation you have the corresponding pressure equation which is a lubrication theory. Then you had the heat transfer which is basically given by the conduction form. And then you had the pressure okay and you have the curvature.

So, all of these things combined you basically can find out, you solve this equation to determine what is going to be its delta okay. In the macro region the entire thing was solved by the level set algorithm okay. So, this was what Son actually did okay. Let us go back to our little PowerPoint presentation okay over here.

So, you can understand that how this region was basically, so it is very simple this equation and the heat conduction equation okay and that is how this was basically solved okay. Again we are not going to show the solution it is a lengthy process okay. It still falls numerically you cannot solve it analytically but these are the basic equation.

So, you should get an idea of the basic equation that what is happening. This is a continuity for example, this is the continuity, if we look at this is the continuity equation, this is the momentum equation and that is the corresponding energy equation right okay. So, three equations but we are solving specific versions of the three equations okay.

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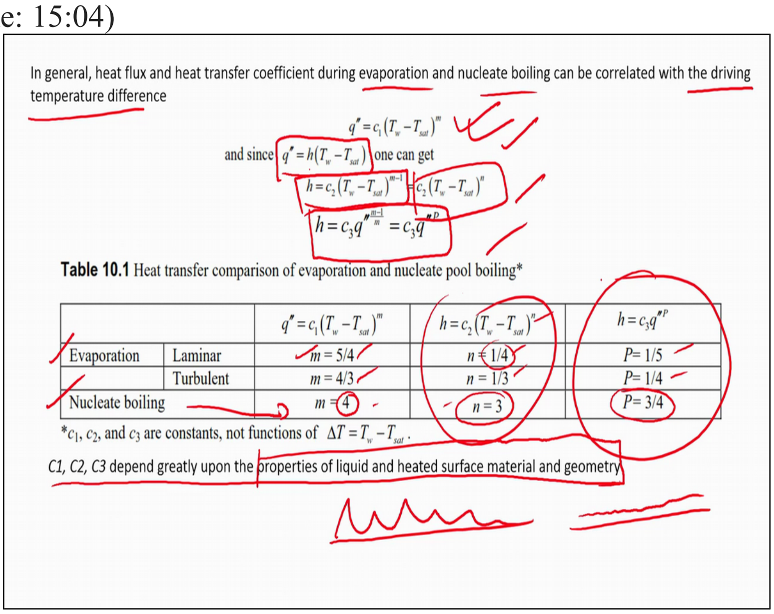

In general, heat flux and heat transfer coefficient during evaporation and nucleate boiling can be correlated with the driving temperature difference

$$q'' = c_1 (T_w - T_{sat})^m$$

and since $q'' = h(T_w - T_{sat})$ one can get

$$h = c_2 (T_w - T_{sat})^{m-1} = c_2 (T_w - T_{sat})^n$$

$$h = c_3 q''^{\frac{m-1}{m}} = c_3 q''^P$$

Table 10.1 Heat transfer comparison of evaporation and nucleate pool boiling*

		$q'' = c_1 (T_w - T_{sat})^m$	$h = c_2 (T_w - T_{sat})^n$	$h = c_3 q''^P$
Evaporation	Laminar	$m = 5/4$	$n = 1/4$	$P = 1/5$
	Turbulent	$m = 4/3$	$n = 1/3$	$P = 1/4$
Nucleate boiling		$m = 4$	$n = 3$	$P = 3/4$

*c_1, c_2, and c_3 are constants, not functions of $\Delta T = T_w - T_{sat}$.

C1, C2, C3 depend greatly upon the properties of liquid and heated surface material and geometry

So, now let us look at some of the correlation okay because we are more or less towards the end. So, the first correlation that we are going to look at in general the heat transfer and the heat flux and the heat transfer coefficient during evaporation and nuclear boiling can be correlated with the driving temperature difference.

So, for example this is the most usual form that is q double prime = c1 and into Tw - Tsat raised to the power of m okay. But we also know that q double prime is nothing but equal to the heat transfer coefficient multiplied by Tw – Tsat. So, one can get okay you want; if you substitute okay you can get that your h is given by this.

And h can be also written in terms of the heat flux right simple enough right. So, these are the so during evaporation and nuclear boiling. Now if we compare, so there are a lot of constants as you can see c1, c2, c3 etcetera, now during evaporation and nucleate boiling so there are two paradigm over here.

Now let us look at nucleate boiling part you will find that this m is of the order of 4. So, the heat flux is basically Tw - Tsat raised to the power of 4 right, h is raised to the power of 3 that is 3 okay and this is h and q relationship is q to the power of 3 by 4. Whereas in the case of laminar and turbulent flow whatever it is okay this exponent is very small, much smaller right.

Compared to nuclear boiling which is very normal like nucleate boiling is nucleate boiling. So, it is a lot it is a fundamentally a much aggressive mode of heat transfer right. So, the heat flux is quite a bit off okay in the case of evaporation this is only mildly above 1 right. It is just little above 1 okay and the heat transfer coefficient is a lot it is like one forth.

But in these two cases you can see that they are quite high okay. So, this c1, c2, c3 constants okay also depend greatly upon the properties of the fluid and the heated surface materials and whatever is the geometry. So, this is a geometry dependent, property dependent, the materials that means if you have a material which has got a lot of these kind of wedges right okay.

This c will be very different compared to a material which has got that kind of a texture. It also depends on the kind of fluid that you are actually dealing with okay.

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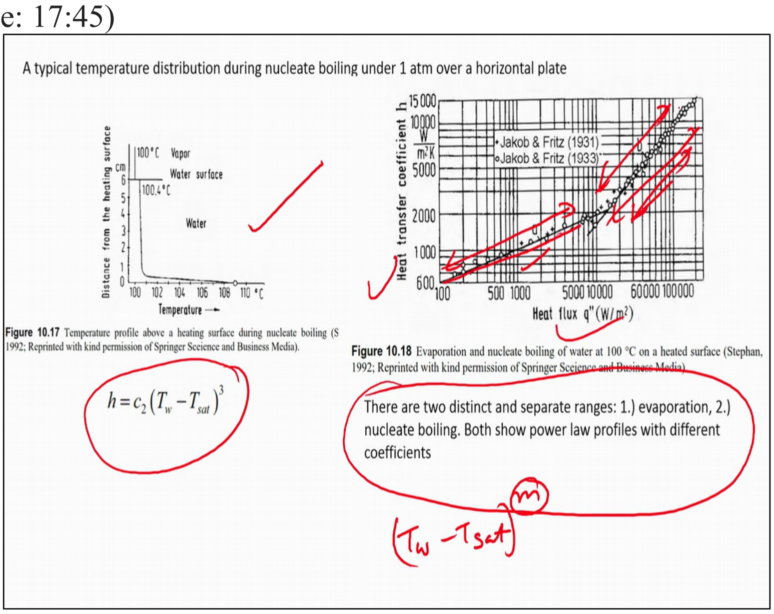

A typical temperature distribution during nucleate boiling under 1 atm over a horizontal plate

Figure 10.17 Temperature profile above a heating surface during nucleate boiling (S 1992; Reprinted with kind permission of Springer Sceience and Business Media).

Figure 10.18 Evaporation and nucleate boiling of water at 100 °C on a heated surface (Stephan, 1992; Reprinted with kind permission of Springer Sceience and Business Media).

$$h = c_2 \left(T_w - T_{sat}\right)^3$$

There are two distinct and separate ranges: 1.) evaporation, 2.) nucleate boiling. Both show power law profiles with different coefficients

$(T_w - T_{sat})^m$

So, this is for example a typical temperature profile of nucleate boiling over our horizontal plate okay. And this is another profile in fact more than this, this particular profile if you would understand it better. So, heat transfer coefficient and heat flux have been plotted, so you can clearly see that there is an evaporation regime.

And then there is this nucleate boiling regime right and you can see that the power law profile is the same. Though it does not share the same functional coefficient right, so it is still power law that means it is still Tw - Tsat raised to the power of some m right. But this value of m actually varies from here to here okay.

Obviously this being more aggressive m than that this looks almost linearish okay. This looks like a lot higher coefficient than that okay. So, this has been plotted on the log, log axis essentially okay. So, and for example in this particular case it is raised to the power of 3. So, you can see what is the difference okay.

So, evaporation is a lot milder process and boiling is a lot it is a lot more aggressive process. And these are that these are the correlations that we have given and these are the corresponding coefficients okay. So, that provides you with the capability of calculating that what is the heat flux and what is the heat transfer coefficient.

Because in many cases you may not be interested in knowing all the bubble dynamics and all the other things you may be just interested in knowing what is the heat transfer coefficient and what is the heat flux. So, that question we are able to answer here. The last discussion point is basically the critical heat flux right.

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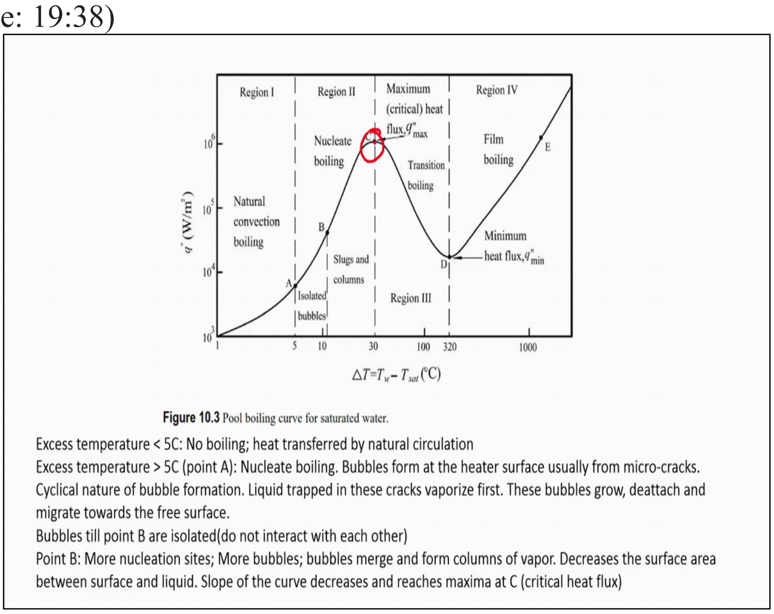

Figure 10.3 Pool boiling curve for saturated water.

Excess temperature < 5C: No boiling; heat transferred by natural circulation
Excess temperature > 5C (point A): Nucleate boiling. Bubbles form at the heater surface usually from micro-cracks. Cyclical nature of bubble formation. Liquid trapped in these cracks vaporize first. These bubbles grow, deattach and migrate towards the free surface.
Bubbles till point B are isolated(do not interact with each other)
Point B: More nucleation sites; More bubbles; bubbles merge and form columns of vapor. Decreases the surface area between surface and liquid. Slope of the curve decreases and reaches maxima at C (critical heat flux)

So, critical heat flux is as if you recall your boiling curve in fact we have it over here somewhere. So, this is the boiling curve and as you know that the critical heat flux occurs at the end of the nucleate boiling spectrum right okay.

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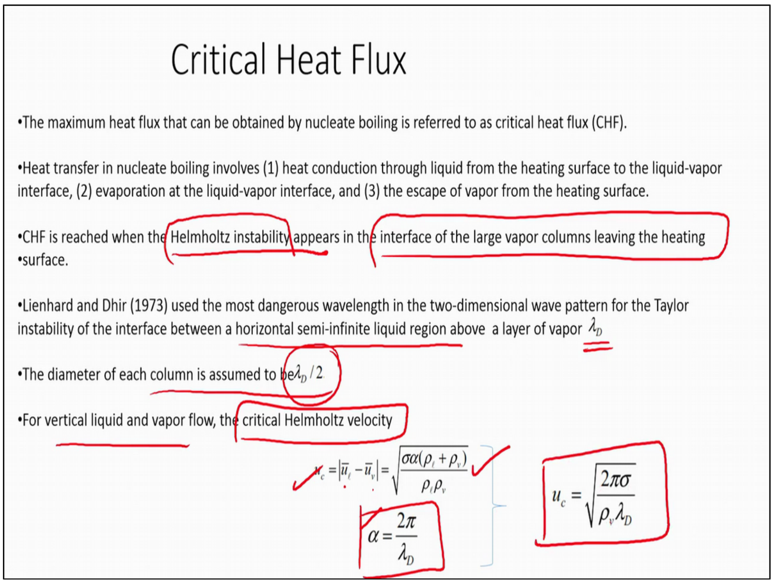

Critical Heat Flux

- The maximum heat flux that can be obtained by nucleate boiling is referred to as critical heat flux (CHF).
- Heat transfer in nucleate boiling involves (1) heat conduction through liquid from the heating surface to the liquid-vapor interface, (2) evaporation at the liquid-vapor interface, and (3) the escape of vapor from the heating surface.
- CHF is reached when the Helmholtz instability appears in the interface of the large vapor columns leaving the heating
- surface.
- Lienhard and Dhir (1973) used the most dangerous wavelength in the two-dimensional wave pattern for the Taylor instability of the interface between a horizontal semi-infinite liquid region above a layer of vapor λ_D
- The diameter of each column is assumed to be $\lambda_D/2$
- For vertical liquid and vapor flow, the critical Helmholtz velocity

$$u_c = |\bar{u}_\ell - \bar{u}_v| = \sqrt{\frac{\sigma\alpha(\rho_\ell + \rho_v)}{\rho_\ell\rho_v}}$$

$$\boxed{\alpha = \frac{2\pi}{\lambda_D}}$$

$$\boxed{u_c = \sqrt{\frac{2\pi\sigma}{\rho_v\lambda_D}}}$$

So, the critical heat flux if we recall, so the critical heat flux okay is what is referred to at the end of the nucleate boiling. So, this is the maximum heat flux that is obtainable by nucleate boiling. So, heat transfer in nucleate boiling basically involves what it involves heat conduction from the liquid to the liquid vapour interface or evaporation at the liquid vapour interface and escape of vapour from the heating interface okay.

So how is this critical heat flux reached okay what is the mechanism. Now if you recall earlier what we said is that towards end of the nucleate boiling okay these bubbles starts to merge with each other and form this vapour column like this is like columns of vapours that connects the surface that the heated surface with a liquid pool right.

So, there is like columns of vapour that actually forms. So, these columns of vapours are subjected to Helmholtz instability okay. They appear on the interface of this large vapour column that are leaving the interface okay. And people actually have done linear stability analysis on this okay.

Remember linear stability analysis we did a little bit in atomization. So, we did a little bit in Rayleigh Taylor and Kelvin- Helmholtz instability is also right. So, Leinhard and Dhir, Vijay Dhir use the most dangerous wavelengths in a two dimensional pattern for Taylor instability which was formed between a horizontal semi infinite liquid and the corresponding vapour column okay.

And that is given alpha D, alpha D is basically the wave length okay. The diameter of each of this column is assumed to be half the dangerous wavelengths okay. Now for a vertical liquid and vapour flow the critical Helmholtz velocity is given by this, is basically the difference in the flux of the liquid and the vapour. Liquid and the vapour is the flux it is a basically the flux difference between the two.

And that can be shown to be this okay where alpha is basically the wave number which is related to the wave length by 2 pi by lambda D right. So, combining these two you get that the critical Helmholtz velocity is given by 2 Pi sigma by Rho v into lambda D, lambda D is the most dangerous wavelengths.

It is also 2 times the diameter of each vapour column right that forms at the end of this nucleate boiling.

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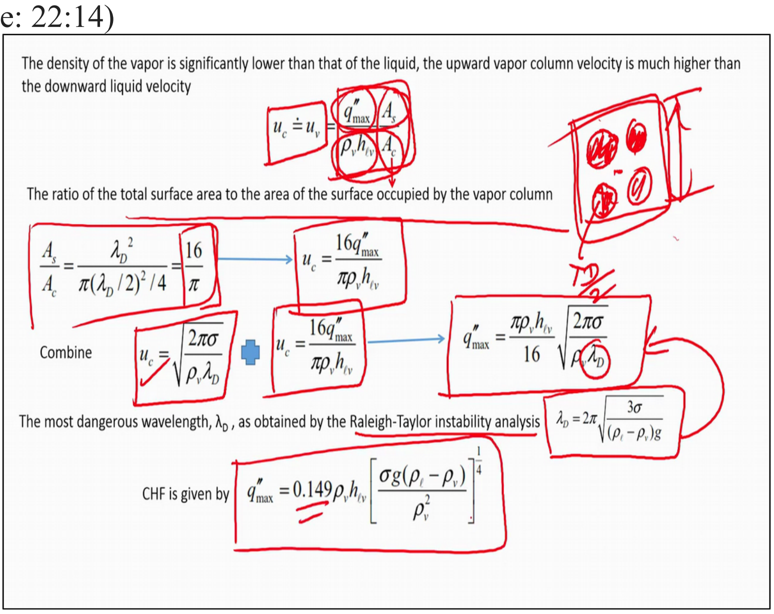

The density of the vapor is significantly lower than that of the liquid, the upward vapor column velocity is much higher than the downward liquid velocity

$$u_c \doteq u_v = \frac{q''_{max}}{\rho_v h_{\ell v}} \frac{A_s}{A_c}$$

The ratio of the total surface area to the area of the surface occupied by the vapor column

$$\frac{A_s}{A_c} = \frac{\lambda_D^2}{\pi(\lambda_D/2)^2/4} = \frac{16}{\pi} \rightarrow u_c = \frac{16 q''_{max}}{\pi \rho_v h_{\ell v}}$$

Combine

$$u_c = \sqrt{\frac{2\pi\sigma}{\rho_v \lambda_D}} + u_c = \frac{16 q''_{max}}{\pi \rho_v h_{\ell v}} \rightarrow q''_{max} = \frac{\pi \rho_v h_{\ell v}}{16} \sqrt{\frac{2\pi\sigma}{\rho_v \lambda_D}}$$

The most dangerous wavelength, λ_D, as obtained by the Raleigh-Taylor instability analysis

$$\lambda_D = 2\pi \sqrt{\frac{3\sigma}{(\rho_\ell - \rho_v) g}}$$

CHF is given by

$$q''_{max} = 0.149 \rho_v h_{\ell v} \left[\frac{\sigma g(\rho_\ell - \rho_v)}{\rho_v^2}\right]^{\frac{1}{4}}$$

Now since the density of the vapour is significantly lower than the liquid. The upward vapour column velocity is much higher than a downward liquid column velocity understood because the vapour because of its low density it can move much faster right than the liquid which have got a much lower velocity.

So, your uc = uv which is given by this particular term now this is interesting this is basically the ratio of the total surface area to the total surface area that is occupied by the vapour column. So, if you look at this particular diagram over here what I am drawing over here. So, these are say the pockets that are these are the vapour column okay all these are vapours rest are liquid right.

So, if this is the total area whatever this area is given by your Ac right and the vapours actually occupied together combined they occupied this area, As. So, this is basically the total area ratio to the area ratio that is occupied by the vapour converse actually the other way around, I am sorry okay.

So, it is basically the total area to the area of the surface that is occupied by the vapour column. So, you can understand this is the area occupied by the vapour column this is the total area okay. So, that can be easily calculated because this is this vapour column diameter is lambda D by 2 that is what we already said.

So, this is given by Pi, 16 by Pi which leads to the critical velocity as 16 q max divided by Pi Rho v into hlv okay. So, this you can imagine what how this relationship comes this is the total heat flux and this is the heat flux that is expended in basically vaporizing the liquid to the vapour state right.

So, this is the total heat flux that you are supplying and this is the heat flux that is actually taken up by the vapour in forming the vapour pool right. So, you combine the two relationships one gives uc as this, the other give uc as that. The two limiting cases and you get this is the combined relationship for the q max.

So, you basically use fall for q max okay. Now q max still has got this lambda D which is hanging over there about which we do not have a clue. So, for obtaining that you do are Rayleigh Taylor instability analysis of a column and you get this as that particular quantity got it. So, you put this back over here you get the total heat flux is given by .1492 Rho v into hlv multiplied this particular factor okay.

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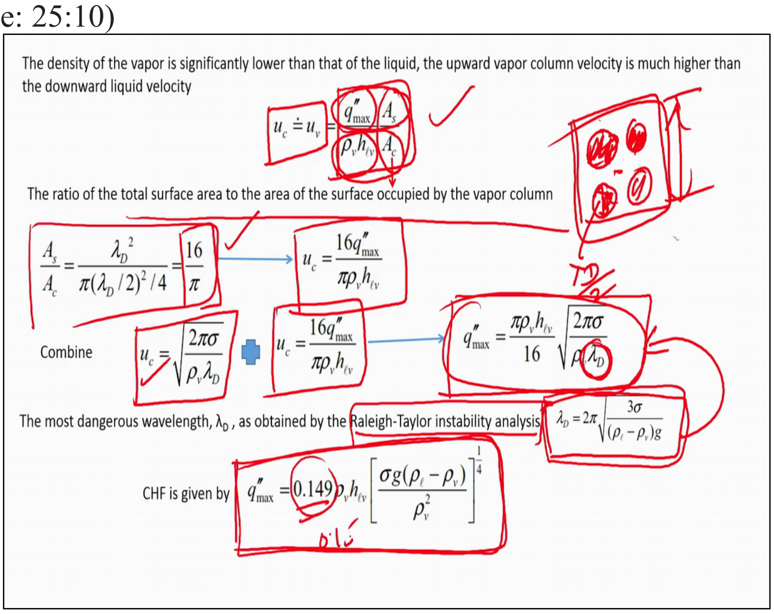

The density of the vapor is significantly lower than that of the liquid, the upward vapor column velocity is much higher than the downward liquid velocity

$$u_c \doteq u_v = \frac{q''_{\max}}{\rho_v h_{\ell v}} \frac{A_s}{A_c}$$

The ratio of the total surface area to the area of the surface occupied by the vapor column

$$\frac{A_s}{A_c} = \frac{\lambda_D^2}{\pi(\lambda_D/2)^2/4} = \frac{16}{\pi} \rightarrow u_c = \frac{16 q''_{\max}}{\pi \rho_v h_{\ell v}}$$

Combine

$$u_c = \sqrt{\frac{2\pi\sigma}{\rho_v \lambda_D}} + u_c = \frac{16 q''_{\max}}{\pi \rho_v h_{\ell v}} \rightarrow q''_{\max} = \frac{\pi \rho_v h_{\ell v}}{16} \sqrt{\frac{2\pi\sigma}{\rho_v \lambda_D}}$$

The most dangerous wavelength, λ_D, as obtained by the Raleigh-Taylor instability analysis

$$\lambda_D = 2\pi \sqrt{\frac{3\sigma}{(\rho_\ell - \rho_v) g}}$$

CHF is given by

$$q''_{\max} = 0.149 \rho_v h_{\ell v} \left[\frac{\sigma g (\rho_\ell - \rho_v)}{\rho_v^2} \right]^{\frac{1}{4}}$$

0.15

So, I gave you an idea that how to evaluate the total heat flux. How do we do it just recap once again the; at the end of the nucleate boiling you form this vapour column right which we call slug from the surface right. These are all liquids, this is liquid, this is vapour, is vapour, this is liquid, vapour liquid right.

So, these columns of vapours are subjected to instabilities of different kind because these vapours are moving up liquid is moving down right. So, naturally if you take a cylinder like this it will start to oscillate is not that so right. So, after that it starts to do that it developed that instability.

So, standard instability analysis applies over here right what we have assumed though is that the thickness of this or the diameter of this column this 2 times is to half of the wavelength of the most dangerous instability then what we did is that because these two streams are moving in opposite directions right.

We calculated what is the critical Helmholtz velocity and from there what we did was that we calculated that we also calculated in a different way assuming that the vapour velocity is too high. We calculated that what will be the velocity based from a heat transfer perspective right that is what we did.

And then we calculated the area that is occupied by the vapour bubbles assuming that this is lambda D by 2. So, combining these two expressions we get an expression for q max which has a term called lambda D. So, that lambda T now we are going to close by using a Rayleigh Taylor instability analysis where we show that this lambda D is given by this particular expression.

So, the CHF is given by this which is basically it is basically about .15 okay. So, these have got all the relevant parameters over here so if the surface tension goes down you know that the critical heat flux will also come down okay and similar and so long and so forth. So, the critical heat flux is actually given by this expression.

This is valid over a wide range very wide range okay of very, very wide range of conditions okay. So, with this we have covered many topics over here okay. We have we have just said how to evaluate the heat flux and the heat transfer coefficient, what is the definition of critical heat flux.

We have given you an idea how to calculate it and what it will be the relevant expression without actually solving them. These are the key relationships okay. We have also given you an idea how a bubble actually grows okay. What are the; during detachments what are the forces that are acting on the bubble how does a bubble actually grow from a heterogeneous surface heterogeneous nucleation.

There are two regimes that we showed over here how surface imperfections can actually lead to growth and when can a bubble grow this is the part where it grows this is this is the part where it is stable, this is the part where it is unstable. We already saw that in the previous ones okay.

And we also explain the entire boiling curve right which are the curve. So, we say this is the thing, this is the leading frost point, if you recall okay. So, latent frost point and the catastrophic-failure starts to happen when you actually have the heat flux much above the critical heat flux values.

We also said, what is what is sub cooled and saturated boiling okay sub cooled and saturated boiling over here. And of course we also compared what is the difference between evaporation and nuclear boiling. So, with this we end this particular lecture and this particular course. So, we have given you an idea about what boiling is okay.

What are the different classes of boiling and some key mathematical relationships that basically isolates boiling from the from evaporation and what are the key features of boiling of course there are a lot of more materials that needs to be covered if this is a full fledged course on boiling okay, thank you.