

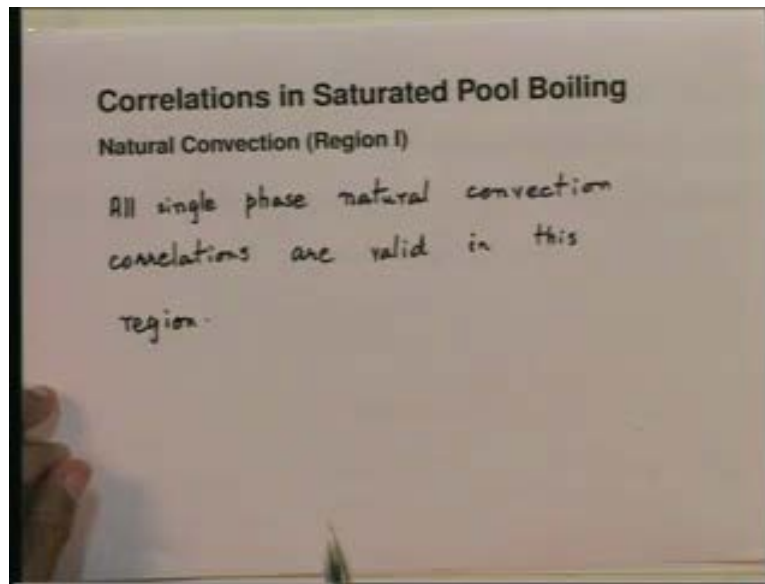
Heat and Mass Transfer
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Lecture no. 32
Boiling and Condensation 4

Last time we have started with the topic of boiling and I, first of all, I said I described to you when boiling will occur, then I classified two types, two types of boiling; I said there is pool boiling and flow boiling and then we focused our attention on pool boiling and I identified various regimes or various regions in pool boiling and I drove a typical pool boiling curve while identifying those regions. What were those regions? They were first of all the natural convection region, then the nuclear boiling region and the third one was the film boiling region. Even in the film boiling region, there were 2 parts, one part which I called the transition boiling region in which we have a transition from nucleate to stable film boiling and the second part which are called as stable film boiling. I also identified one important point on that pool boiling curve and I said that point is called that peak heat flux or the critical heat flux and I told you why that point is important.

If heat flux is the parameter that is under your control and if it is the quantity that is varying then if it goes past the critical heat flux, then the temperature difference T_w minus T_s - wall temperature minus the saturation temperature - will shoot up from a value which might be 10 or 20 degree centigrade to perhaps a few00 degree centigrade, even may be a thousand degree centigrade, and there is a possibility that the heated surface may get damaged. And that is why whenever heat flux is the controlling factor and it is in most in many situations, then one would see that the peak heat flux is that exceeded in order to prevent any damage to the heating surface.

Now, today we are going to look at a number of correlations equations to use in doing calculations in pool boiling. We will focus our attention on saturated pool boiling correlations in saturated pool boiling.

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So, today we are going to look at correlations in saturated pool boiling. By saturated pool boiling I mean that we have of course a pool of liquid and in that pool of liquid the water or the liquid - whatever it is - is at a certain pressure and at a temperature, saturation temperature corresponding to that particular pressure. So, that is what we call as a saturated pool. It is at a particular pressure and it is also at the particular saturation temperature corresponding to that particular pressure. We add heat to that liquid just as I had indicated in the sketch last time. We go on adding heat and we will go through the various regions of boiling and in those various regions, what are the correlations to use?

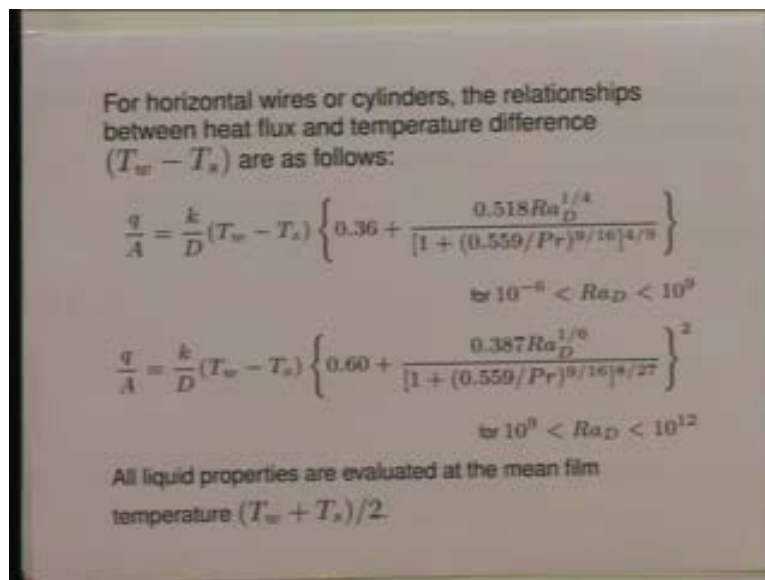
So, the first region which we have identified is natural convection that is region one. Now, in region 1, I have mentioned it but let me repeat, change of phase does not occur at the heated surface. That is a point which I made to you last time. The heated surface is at the bottom; the change of phase doesn't occur there. What happens is, because of the small temperature difference the water gets slightly superheated water or the liquid - whichever we are talking about - get slightly superheated may be by a degree 2, degrees or something like that. The superheated liquid will obviously have a lower density; it is going to rise and will set up a natural convection pattern in that pool, in that pool of

liquid. The superheated liquid then eventually will reach the free surface of the pool and at that free surface you will get evaporation. So, that is the nature of this region.

Obviously, if there is no change of phase, no vapor formation inside the liquid, it is clear that all you have is a natural convection single phase phenomenon taking place with superheated liquid and therefore it is also obvious that all the correlations which we have studied earlier in single phase natural convection will be valid in this region. So, that is the point I want to make first of all that all single phase - let me write that down - all single phase natural convection correlations are valid in this region.

So, there is nothing new to do. You can go back to our chapter on single phase natural convection, look up the various correlations we have got. Correlations, for example, for horizontal tubes - they have a correlation for a heated surface facing upwards; we have correlations for other situations are also available in the literature. Anyone of them is valid depending upon the heated surface that we are talking about in this particular situation.

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For example, let us say we have got a situation; as an example, let us consider that we have horizontal wires or cylinders which are being heated in a pool - horizontal wire, horizontal cylinder which is inside a pool of liquid. Then, if boiling is going to take place and it is the natural convection region, the relationship between heat flux and temperature difference T_w minus T_s are as follows. Now, I am going to read these out because you have done these correlations earlier in natural convection. What is the difference between what the way these are written and what was written earlier in natural convection? It is when we were studying natural convection, these relations were given in terms of a Nusselt number as a function of Rayleigh number and Prandtl number.

Now following the practice adopted in boiling, we have written these relations in terms of heat flux equal to something multiplied by temperature difference multiplied by the particular relationship. So let me just illustrate what I mean; what I mean is the following. Earlier, the relationships were of the form.

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The image shows a whiteboard with four handwritten equations:

$$Nu_D = f(Ra_D, Pr)$$

$$\frac{h D}{k} = f(Ra_D, Pr)$$

$$\frac{(q/A)}{(T_w - T_s)} \cdot \frac{D}{k} = f(Ra_D, Pr)$$

$$\frac{q}{A} = \frac{k}{D} (T_w - T_s) \cdot f(Ra_D, Pr)$$

Nu_D is some function of Rayleigh number and Prandtl number; these were how the relationship was given earlier. Now what is Nusselt number? Nusselt number is nothing but hD by k which is a function of Rayleigh number and Prandtl number and h is nothing

but q by A divided by T_w minus T_s multiplied by D by k equal to a function of Rayleigh number Prandtl number. So, these relationships which are, which I am showing you are written in the form q by A is equal to k by D multiplied by T_w minus T_s and multiplied by the functional relationship which is available from the correlation in natural convection. This is how these relationships which I am showing you are put down. It is, they are equivalent obviously as I had shown to the relationship given earlier.

So, let me again show these now. If the geometry is a horizontal wire or cylinder, the relationship between heat flux and temperature difference are as follows. Properties again as previously would be evaluated at the mean film temperature T_w plus T_s by 2. If the geometry something else, say for example heated plate facing upwards. Go back to the single phase natural convection chapter, look up the correlation there. Nusselt number is a function of Rayleigh number and Prandtl number, whatever it is. And convert it into this form q by A equal to k by L into T_w minus T_s into something. So, you should be able to write down such relationships depending upon the particular geometry you are studying. I have given one as an example; now let us move on to region two. In region 2, we have nucleate boiling. Nucleate boiling means bubbles now form at the heated surface.

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Nucleate Boiling (Region II)
 Rohsenow correlation

$$\left[\frac{C_{pf}(T_w - T_s)}{\lambda} \right] = K_{sf} \left[\frac{(q/A)}{\mu_l \lambda} \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} \right]^{1/3} Pr_l^n$$

It is now a situation in which, a typical situation is - at particular sites on the heated surface, a bubble is formed, it grows in size, then when it grows to a certain particular size because of buoyancy forces, it detaches from the surface and rises. Another bubble forms at the same size, again grows in size and again rises, and this phenomenon takes place at a number of sites. As you go on increasing the temperature difference the number of sites at which this happens goes on increasing. The frequency with which the bubbles form per minute at a particular side also goes on increasing, so that is the nature of nucleate boiling and we have described it last time.

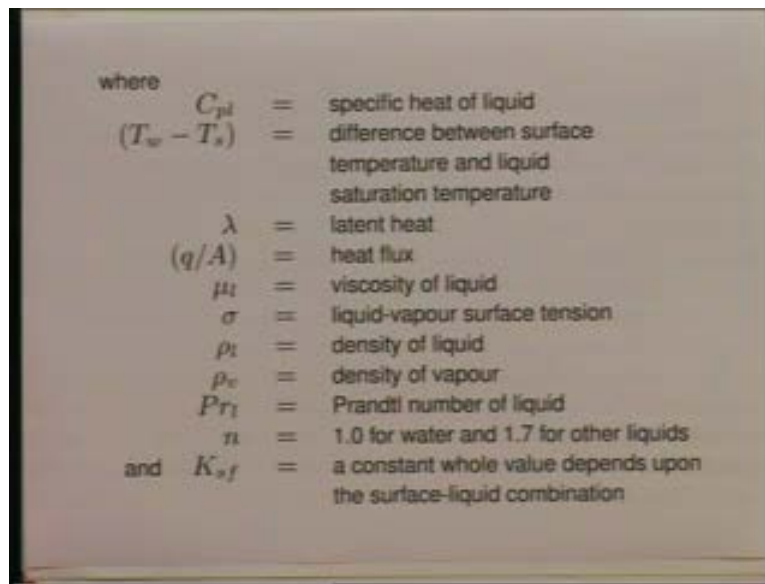
Now many correlations have been developed by various investigators over the years for this particular phenomenon and I am going to give in this lecture one particular correlation. The correlation that I am going to give is a correlation given by Rohsenow; it is called the Rohsenow correlation quite appropriately. Now, let me just read out the correlation. Then, I will describe what are the parameters in this correlation. The correlation is on the left hand side - C_{pl} multiplied by T_w minus T_s upon λ that is on the left hand side, this is a dimensionless parameter.

And you know the symbols, what they mean? C_{pl} is going to be the specific heat of the liquid, T_w minus T_s is the temperature difference between the wall and the saturation temperature of the liquid divided by λ which is the latent heat of vaporization. It is a dimensionless number making up the left hand side of the equation equal to K_{sf} - K_{sf} is a constant which I will talk about in a moment - again multiplied within square bracket by a quantity q by A , that is the heat flux being supplied, divided by $\mu l \lambda$. μ is the specific, is the viscosity of the liquid; λ is the latent heat of vaporization. Within the square root sign square root of σ upon $g \rho_l$ minus ρ_v ; σ is the surface tension and g is the of course the acceleration due to gravity; ρ_l - the density of the liquid, ρ_v - the density of the vapor. The quantity within the square bracket is also a dimensionless number, keep that in mind. It is often called also some kind of a Reynolds number - bubble Reynolds number. It is sometimes referred to as a bubble Reynolds number; one can attach some physical significance to it. And then the third

dimensionless number is the Prandtl number P_{rl} ; P_{rl} which is the Prandtl number of the liquid.

So what Rohsenow did was to correlate data for a wide variety of liquids which had been obtained by various investigators and show that these 3 dimensionless parameters which I have mentioned could be correlated through an equation of this form. Now let us talk a little about this correlation; first of all, again let me go back to the symbols. I will not go through these in detail because I have taken them up one by one.

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C_{pl} - the specific heat of the liquid, T_w minus T_s - the temperature difference between the surface and the liquid saturation temperature, λ - the latent heat of vaporization, q by A - the heat flux in watts per meter squared, μ_l - the viscosity of the liquid, σ - the liquid vapor surface tension, ρ_l - the density of the liquid, ρ_v - the density of the vapor; these are known symbols to you. P_{rl} - the Prandtl number of the liquid, n the constant at the end, P_{rl} to the power of n in that equation is an exponent on the Prandtl number. From the experimental data, it is found that for water the data fits best if n is taken as one. For other liquids, the experimental data fits best if n is taken as 1.7. So, n has 2 values depending upon the liquid which is being boiled and finally we have a

constant K_{sf} , a constant whose value, it is not a whole value, whose value depends upon the surface liquid combination. And the value of K_{sf} was determined by Rohsenow and by others for a variety of surface liquid combinations. So, let me just show you a table in which values of K_{sf} are tabulated. Here is a table; it is available in various books.

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Values of K_{sf}	
Surface-liquid combination	K_{sf}
Copper-water	0.013
Platinum-water	0.013
Nickel-water	0.006
Brass-water	0.006
Stainless steel-water (mechanically polished)	0.0132
Stainless steel-water (chemically etched)	0.0133
Stainless steel-water (Teflon coated)	0.0058
Stainless steel-water (ground and polished)	0.0080

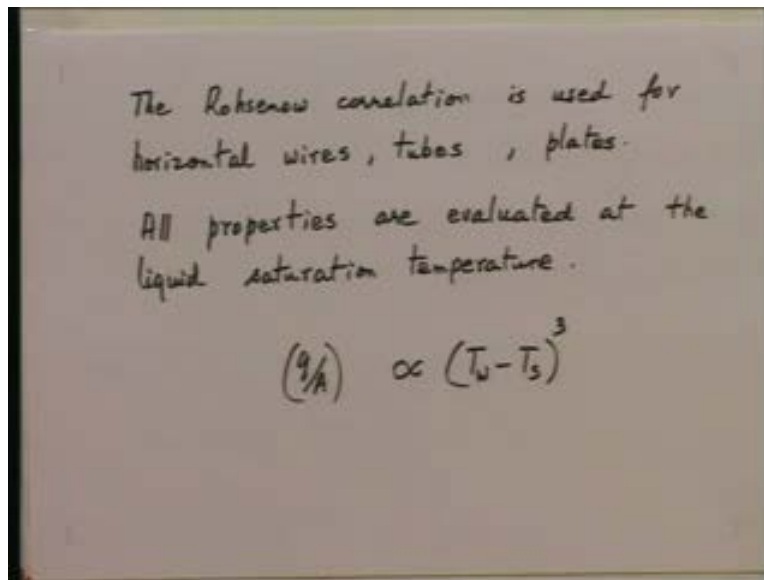
I have just given and there are more values of K_{sf} for other surface liquid combinations as well. So, on the left hand column is surface liquid combination, the right hand side is the value of K_{sf} as obtained by correlating the experimental data. What do we have? Typical values if the surfaces is copper and water is the liquid being boiled .013, for platinum-water .013, for nickel-water .006, for brass and water .006. Then, there are 4 values here for stainless steel and water with the stainless steel surface being subjected to different surface treatments.

So, the first one is stainless steel and water with the stainless steel surface mechanically polished .032, stainless steel and water where it is chemically etched .0133, third one stainless steel and water where the stainless steel is coated with Teflon - .0058 and finally stainless steel and water where it is ground and polished .0080. Notice that as the stainless steel surface becomes smoother which is the case in the last 2 surfaces.

Compared to the first 2 there, the first 2 it is mechanically polished or chemically etched, the last 2 it is Teflon coated and ground and polished. Notice that in the last 2 cases the value of K_{sf} is about half compared to the value earlier. So, the value of q by A for, thus the value of T_w minus T_s for the same q by A will be half the value that you get for the mechanically polished surface. Not half, I shouldn't say that because there is the cube one third power on the q by A but it will be less. So, these are typical values of K_{sf} and there are values of K_{sf} for other surface liquid combinations as well.

Now in this correlation, let me make some remarks on this correlation. First of all the correlation was developed for horizontal wires.

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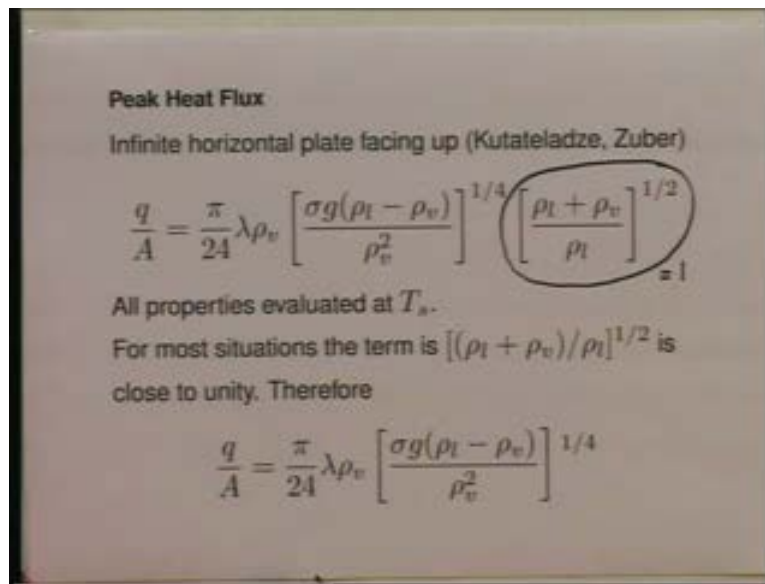


The Rohsenow correlation is used for horizontal wires, horizontal tubes, horizontal plates. All properties are evaluated at the liquid saturation temperature and the value of constant K_{sf} - I have already discussed what it means and shown you typical values. Keep in mind that the Rohsenow correlation, what it is basically saying is that q by A , if I cube both sides of the Rohsenow correlation, what the Rohsenow correlation is saying is for a given liquid, for a given surface and a liquid, the q by A is proportional to T_w minus T_s to

the cube. That is what the Rohsenow correlation is saying; it is useful to keep this dependence in mind.

Now, let us go on to the next point. On the curve the nucleate boiling region ends when we reach the point A on the pool boiling curve which I mentioned to you last time and what is that point A? The point A is what we call as the critical or the peak heat flux. Now for this particular point a number of equations have been developed to calculate the critical or the peak heat flux. I will give you a few of them.

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Peak Heat Flux
Infinite horizontal plate facing up (Kutateladze, Zuber)

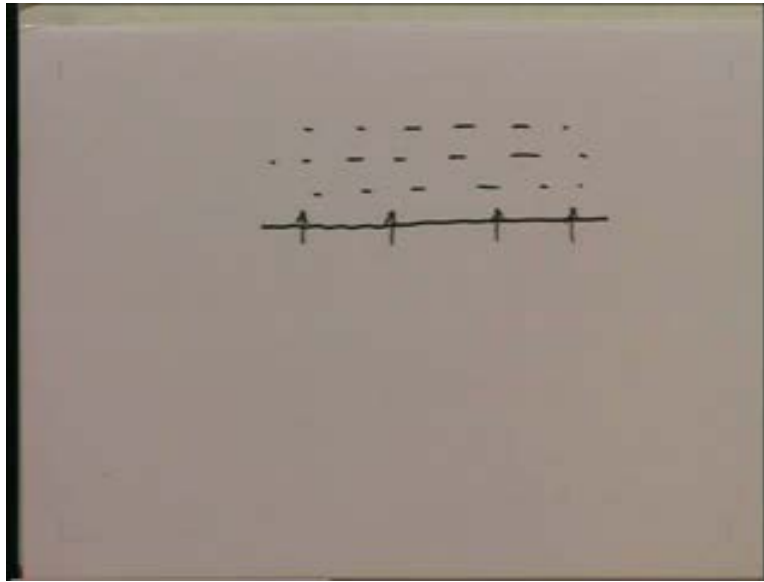
$$\frac{q}{A} = \frac{\pi}{24} \lambda \rho_v \left[\frac{\sigma g (\rho_l - \rho_v)}{\rho_v^2} \right]^{1/4} \left[\frac{\rho_l + \rho_v}{\rho_l} \right]^{1/2} \approx 1$$

All properties evaluated at T_s .
For most situations the term is $[(\rho_l + \rho_v)/\rho_l]^{1/2}$ is close to unity. Therefore

$$\frac{q}{A} = \frac{\pi}{24} \lambda \rho_v \left[\frac{\sigma g (\rho_l - \rho_v)}{\rho_v^2} \right]^{1/4}$$

First one that I am going to give you is a correlation; an equation I should say developed for an infinite horizontal plate facing upwards that is something like this. I have a plate; let me draw it on separate paper.

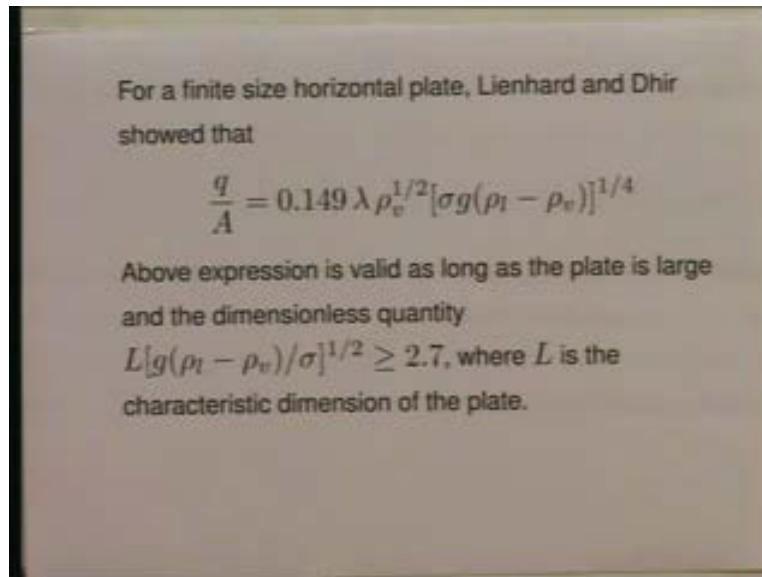
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The first equation is for a plate like this which is heated facing upwards and receiving heat and there is the pool of liquid above it like this and it is supposed to be infinite in extent. Based on a stability analysis, a hydrodynamic stability analysis, Kutateladze and Zuber derived an expression for the peak heat flux for an infinite horizontal plate which is of this form - $q_{\text{critical}} = \frac{\pi}{24} \lambda \rho_v \left[\frac{\sigma g (\rho_l - \rho_v)}{\rho_v^2} \right]^{1/4} \left[\frac{\rho_l + \rho_v}{\rho_l} \right]^{1/2}$. It is a classical expression derived based on hydrodynamic stability considerations. All properties are evaluated at the saturation temperature T_s of the pool.

Now, for most situations the second term $\frac{\rho_l + \rho_v}{\rho_l}$ divided by ρ_l to the power of half, for most situations this second term here tends to be almost unity. And if you put that simplification in, then the expression reduces to the simpler form $q_{\text{critical}} = \frac{\pi}{24} \lambda \rho_v \left[\frac{\sigma g (\rho_l - \rho_v)}{\rho_v^2} \right]^{1/4}$. This would be the value of the critical heat flux and this expression is very widely used. There is a slight modification to this expression which was derived few years later and I am going to give you that. If the plate is finite sized, not very small but finite sized, then

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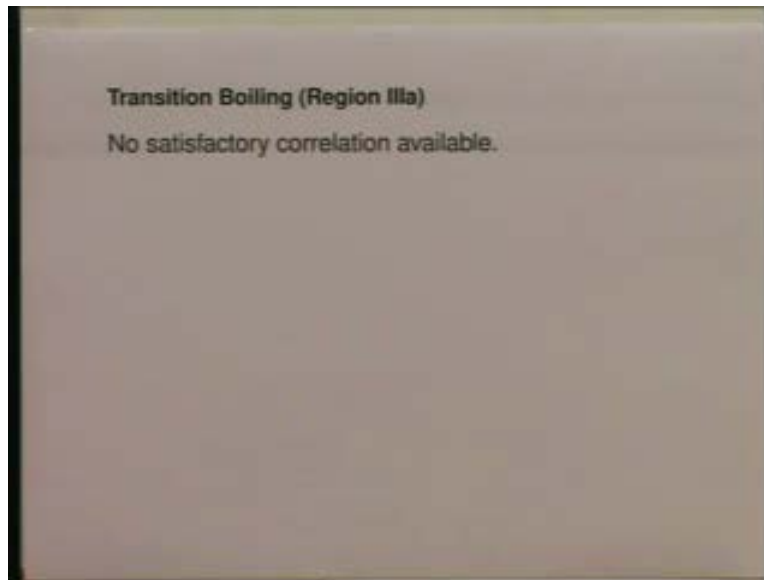
For a finite sized horizontal plate, Lienhard and Dhir showed that the expression was slightly modified. Instead of having a pi by 24, they derived a constant .149; the rest of the expression is the same that we had earlier. So, q by A derived by them was: q by A critical is equal to .149 lambda rho v to the power of half multiplied by sigma g rho l minus rho v the whole thing to the one fourth power. So, we use this expression or the earlier one depending upon which one we prefer. There is a 10 percent difference or so between the two. This expression derived by Lienhard and Dhir is valid so long as the plate is not too small or shall we say large and the way to show it is to calculate the dimensionless quantity L into bracket g rho l minus rho v upon sigma to the power of half and to show that this quantity is greater than 2.7 where L is the characteristic dimension of the plate.

So, what one finds for typical liquids is that unless the plate is extremely small, a few millimeters or so, this expression generally you will get a value greater than 2.7. So, for calculating peak heat flux the preferred expression is the expression given by Lienhard and Dhir which is q by A equal to .149 lambda rho v to the half into bracket sigma g rho l minus rho v the whole thing to the power of one fourth. This is the expression that is now

a days preferred; there are expressions for other geometries also. I am not giving them here but there are expressions available for other geometries like horizontal tubes, etcetera for the peak heat flux.

Now, finally we come to the boiling region; I mean the film boiling region. First, we have the transition boiling.

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And you recall my mentioning to you the transition are, sure describing to you that transition boiling is the region in which T_w by the q by A value decreases as T_w minus T_s increases. And this particular thing happens, this situation occurs because it is a region in which part of the surfaces covered by a film and part of the surface nucleate boiling is occurring. And when the film boiling takes over suddenly then the vapor having a low thermal conductivity puts an additional thermal resistance in the path of the heat flow. So, for a certain T_w minus T_s you require, you get a lesser q by A flowing across the vapor film. That is why one gets a decrease in the q by A with increasing T_w minus T_s .

Transition boiling is not something that is widely studied and the reason is it is not something that occurs that often in practice. It has been studied by few investigators.

There are some paper showing curves of what you get for different liquids and surfaces but no satisfactory correlation which can go across various sets of data has ever been obtained. So, we will not give any correlation at this in this particular for this particular phenomenon.

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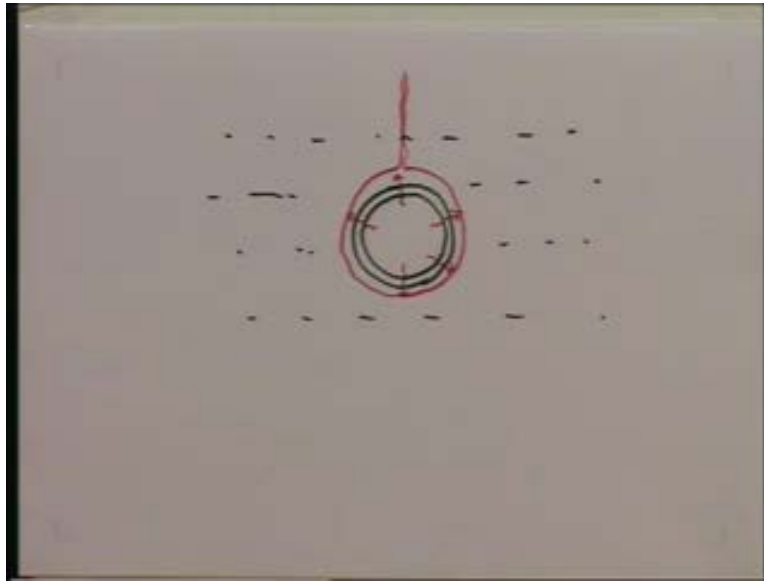
Stable Film Boiling (Region IIIb)
Bromley

$$h_c = 0.62 \left[\frac{\lambda' \rho_v (\rho_l - \rho_v) g k_v^3}{(T_w - T_s) \mu_v D} \right]^{1/4}$$

where h_c = heat transfer coefficient associated with convection
and λ' = difference between the enthalpy of the vapour at the mean film temperature $(T_w + T_s)/2$ and the enthalpy of the liquid at saturation temperature

The next in the same region is the stable film boiling region and here for stable film boiling we will give a correlation which was derived first by, give an expression which was derived first by Bromley. The particular expression which I am showing you is valid for a horizontal tube so Bromley derived this expression for the geometry of a horizontal tube something like this. That means we have a horizontal tube

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Let me draw one draw across section of the horizontal tube. Let us say this is the horizontal tube sitting in a pool of liquid, this is the pool of liquid. Sitting in a pool of liquid, heat is being supplied like this to the pool of liquid and the temperature difference is large enough that we have got stable film boiling. So, what will happen? What will happen is you will get a film of vapor all around that tube forming something like this. Let me draw a film. I will draw an exaggerated thickness again; we will get a film of vapor like this forming around the tube flowing upwards because the density of the vapor will be less than that of the liquid. So, this is vapor flowing upwards and then forming some kind of a pattern as it goes out of the liquid upwards. So, this is what we will get if you have got stable film boiling - a film of vapor all around the heated surface, the film of vapor rising and then going up as a flume at the top. That is what you will get so this is what we are talking about.

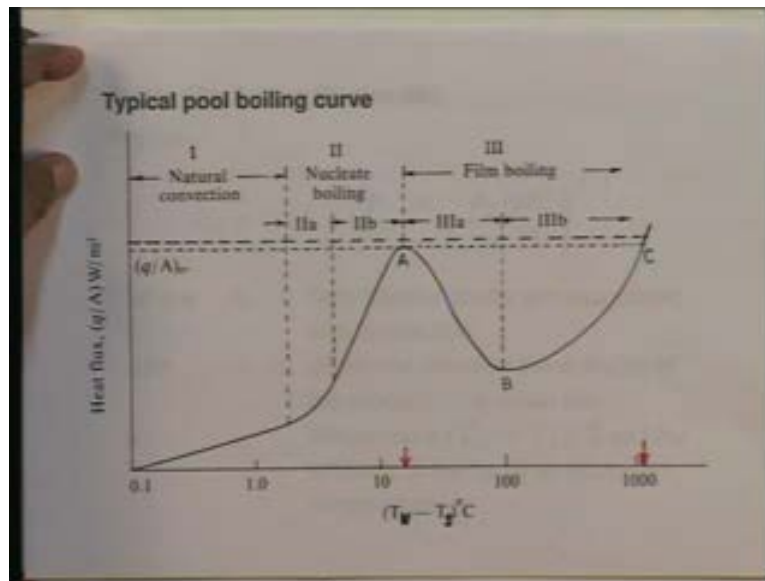
Now, notice the similarity between this and what we saw in film condensation. There we had a film of liquid flowing downwards now we have a film of vapor flowing upwards. One has to flow downwards because the liquid was heavier; here this has to flow upwards because the vapor is lighter but keeping this similarity in mind Bromley derived an expression for the heat transfer coefficient. Basically, Bromley did a derivation very

similar to what the Nusselt derivation was like which we talked about when we studied condensation. So, you see the similarity of the expression now. The expression obtained by Bromley was h_c is equal to $.62 \left[\frac{\lambda' \lambda \rho v}{\rho l \text{ minus } \rho v g \nu^3} \right]^{1/4} \frac{1}{T_w \text{ minus } T_s \mu v \text{ into } D}$, the diameter of the tube, the whole thing to the power of one fourth.

You will see it is very similar to the expression we had in condensation which was $\lambda \rho^2 g \nu^3 \text{ upon } T_w \text{ minus } T_s \text{ Ts minus } T_w \text{ into } \mu D$. Very similar excepting that instead of the properties of the liquid, now you have the properties of the vapor. You have $\mu v \nu \rho v$ and then you have $\rho l \text{ minus } \rho v$ because you have buoyancy. You have the liquid moving, the vapor film moving upwards. You also have, instead of λ you have λ' and what is λ' ? λ' is the difference between the enthalpy of the vapor at the mean film temperature $T_w \text{ plus } T_s \text{ by } 2$ and the enthalpy of the liquid at saturation temperature. This is the definition of λ' so it is not just latent heat of vaporization it is a latent heat plus an enthalpy of vapor associated with superheat of the vapor. That has to be taken into account.

Now, when you have a film of vapor surrounding that tube and the temperature difference $T_w \text{ minus } T_s$ now is going to be high; if you recall the curve I showed you last time I mentioned that in stable film boiling, the value of $T_w \text{ minus } T_s$ can be a few00 if not a few thousand. Let me go back and show the step, typical pool boiling curve of last time.

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We have, talking of this region, the stable film boiling region where T_w minus T_s is in 00s. When you are in this region and you have a vapor film, obviously radiation across the vapor film is also going to be an important factor and we have to therefore take that into consideration. So, what Bromley did was doing a Nusselt type of analysis, he derived what he called as a convective heat transfer coefficient.

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Since radiation is significant in film boiling, the radiation component has to be added on in order to obtain the total heat transfer.

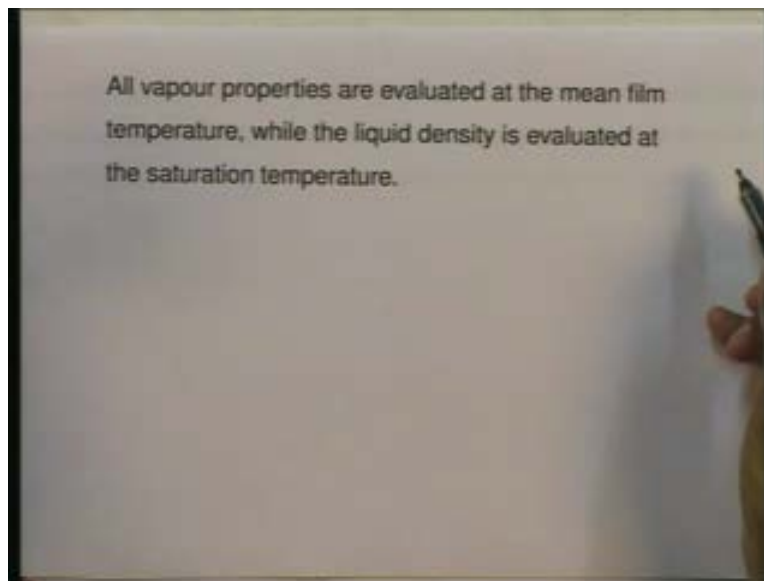
$$h = h_c + \frac{3}{4}h_r \quad \text{when } h_r < h_c$$

h_r = the radiation heat transfer coefficient calculated from formula for radiative heat exchange between parallel planes, taking the emissivity of the liquid to be unity.

Then he went onto say radiation is also important and said since radiation is significant in film boiling because of the high values of T_w minus T_s , the radiation component has to be added on in order to obtain the total heat transfer. And he showed that the total heat transfer coefficient is the convective heat transfer coefficient h_c plus 3 by 4 times the radiative heat transfer coefficient. Whenever h_r is less than h_c , he showed that his expression is valid within the accuracy that one wants.

We will not go into the details; I am just asking you to accept this. I am saying calculate the convective heat transfer coefficient from the expression which Bromley gave earlier which I have shown you that is this expression. Then, calculate the radiative heat transfer coefficient by using formulae for radiant heat exchange between parallel planes taking the emissivity of the liquid to be unity. So, h_r is the radiation heat transfer coefficient calculated from the formula for radiative heat exchange between parallel planes taking the emissivity of the liquid to be unity and then say that the total heat transfer coefficient is h_c plus 3 quarters h_r . That is what I am asking you to do; so this is how one would calculate the heat transfer coefficient in stable film boiling. All vapor properties are evaluated at the mean film temperature; all vapor properties means μ , ν , k_v , etcetera that we need.

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All vapor properties are evaluated at the mean film temperature; the liquid density is evaluated at the saturation temperature. So, this set of equations, the convective heat transfer coefficient and the radiation heat transfer coefficient appropriately added on gives us the total heat transfer coefficient. Now, let us do a few problems to illustrate the use of these correlations which I have given you. We will first of all do the following problem.

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Problem

A 0.14 cm dia. horizontal platinum wire is held in a pool of saturated water at 100°C and 1.013 bar. The wire is electrically heated so that boiling occurs. Calculate the heat flux supplied when the temperature difference ($T_w - T_s$) is (a) 1°C (b) 15°C.

The diagram shows a rectangular pool of liquid. A horizontal red line represents the platinum wire. Above the wire, the saturation temperature is labeled as $T_s = 100^\circ\text{C}$. To the right of the pool, the temperature difference $(T_w - T_s)$ is listed with two cases: 1 and 15, each followed by a question mark. A label 'platinum wire at T_w ' points to the red line.

Problem is the following, we say - there is a pool of liquid A; let me read it out - A .14 centimeter diameter horizontal platinum wire is held in a pool of saturated water at 100 degree centigrade and 1.013 bar. This 100 degree centigrade corresponds to this saturation pressure. The wire is electrically heated so that boiling occurs. Calculate q by A when the temperature difference T_w minus T_s is 1 degree centigrade. Calculate T_w minus T_s when the temperature difference is 15 degrees centigrade; that is the problem.

So, let me just draw a pool, let us say we have a pool of liquid like this. This is our pool of liquid like this and we are told that it is at 100 degree centigrade, T_s . It is a saturated pool at 100 degree centigrade. In this pool, I have a horizontal heated platinum wire. Let us say this is the wire shown in red here. This is the platinum wire which is electrically

heated; I would like to know for T_w minus T_s and T_w is the temperature surface temperature of this wire, platinum wire at T_w . So, the problem is if T_w minus T_s is 1 and 15, what is q by A for these 2 values of T_w minus T_s ? That is the problem. It is a straight forward substitution into the correlation for natural convection and for nucleate boiling. So, let us do the problem now.

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For $(T_w - T_s) = 1^\circ\text{C}$, we will assume that we are in the natural convection region

Mean film temp. = $\frac{100 + 101}{2} = 100.5^\circ\text{C}$

Properties $\beta = 7.55 \times 10^{-4} \text{ K}^{-1}$
 $\nu = 0.294 \times 10^{-6} \text{ m}^2/\text{s}$
 $k = 0.683 \text{ W/m-K}$
 $Pr = 1.74$

Let us, in the first case we will make the assumption for T_w minus T_s – let us do that first - equal to 1 degree centigrade. We will assume that we are in the natural convection region which is a good assumption; up to a few degrees this is usually true. We are in the natural convection region in pool boiling so if I am to use a natural convection correlation, I will use the single phase correlation for horizontal wires which I showed you earlier. What do I need for doing calculations now? I need first the mean film temperature; now systematically, I will go about the calculation. I will say mean film temperature is equal to 100 plus 101 by 2 which is equal to 100.5 degree centigrade. The properties of water will be, which if you look up you will get at the mean film temperature, would be beta. You need the expansion coefficient, you need the Kinematic viscosity, you need the thermal conductivity and you need the Prandtl number for substituting into the correlation. The values - if you look up in a table, you will get the

following. Beta Kelvin to the minus 1 nu is .294 into 10 to the minus 6 meter squared per second, thermal conductivity - .683 watts per meter Kelvin and the Prandtl number of the liquid - 1.74. These are properties which you look up for water at 100.5 degree centigrade. Calculate the Rayleigh number now.

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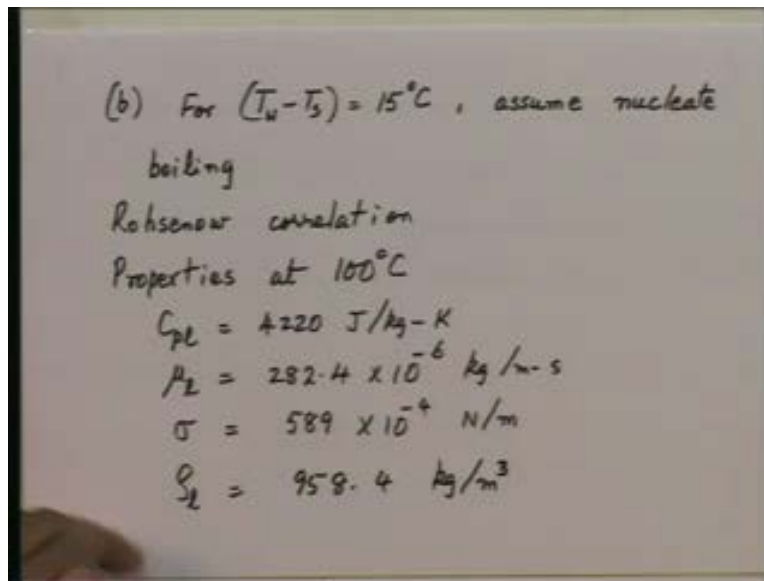
The image shows a handwritten derivation on a whiteboard. It starts with the Rayleigh number equation: $Ra_D = Gr_D Pr$. This is expanded to $Gr_D = \frac{g \beta (T_w - T_s) D^3}{\nu^2}$, so $Ra_D = \frac{g \beta (T_w - T_s) D^3}{\nu^2} Pr$. The result is calculated as 409.1. Then, the heat flux equation is shown: $\frac{q}{A} = \frac{0.683}{0.14 \times 10^{-2}} \times (101 - 100) \left\{ 0.36 + \frac{0.518 \times 409.1^{1/4}}{\left[1 + \left(\frac{0.559}{1.74} \right)^{9/16} \right]^{4/9}} \right\}$. The final result is 1117 W/m², with a red arrow pointing to the result.

So, you get the Rayleigh number Ra_D is equal to $Gr_D Pr$ which is equal to $g \beta (T_w - T_s) D^3 / \nu^2$ - this is the Grashof number with D as the characteristic dimension divided by ν^2 the whole thing. say Grashof number multiplied by Pr . Substitute the numbers which we have got and I am skipping the substitution step; you will get in this particular case 409.1. Now, go to the correlation for natural convection and you will get q/A is equal to .683, which is k for water, divided by D .14 into 10 to the minus 2. That is the diameter of the wire into $T_w - T_s$ 101 minus 100 multiplied by the correlation is .36 plus .518 multiplied by the Rayleigh number to the power of one fourth the whole thing divided by 1 plus .559 divided by the Prandtl number 1.74 to the power of 9 by 16 the whole thing to the power of 4 upon 9.

This is the correlation for natural convection and just substituting it is nothing very deep and if you calculate this, you will get 1117 watts per meter squared so this side the first

answer that we are looking for. We are saying for a temperature differential of T_w minus T_s equal to 1, we are likely to be in the natural convection region. So, we have used natural convection correlation for single phase for a horizontal wire and got the q by A which we would need. In the heat flux we were needed to supply for this particular temperature difference.

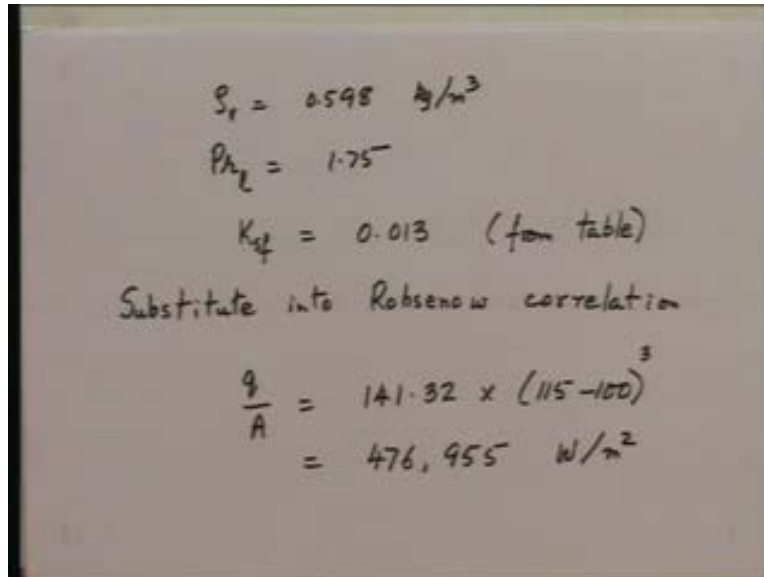
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Now let us go on to the next part; the next part is calculating q by A for T_w minus T_s equal to, for T_w minus T_s equal to 15 degrees, that is the second part. Quite obviously, we are now going to be in the nucleate boiling region; for this particular T_w minus T_s assume nucleate boiling. Nucleate boiling usually starts 3, 4, 5 degrees centigrade for water, may go up to 25, 30 degrees for water. Assume nucleate boiling; now we will need, for using the ρ , we will need the Rohsenow correlation and in order to use the Rohsenow correlation we will need properties at the saturation temperature 100 degree centigrade. And what are the properties? I will just put down the values and then just say - what the answer will be. You will get, if you look up the properties of water at 100 degree centigrade, you will get C_{pl} equal to 4220 joules per Kelvin, joules per kilogram Kelvin, μ_l the viscosity equal to 282.4 into 10 to the minus 6 kilograms per meter second, σ the surface the liquid vapor surface tension 589 into 10 to the minus 4

Newtons per meter, density of the liquid equal to 958.4 kilograms per meter cubed, then we will need the density of the vapor ρ_v .

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Handwritten calculations on a whiteboard:

$$\rho_v = 0.598 \text{ kg/m}^3$$
$$Pr_L = 1.75$$
$$K_{sf} = 0.013 \text{ (from table)}$$

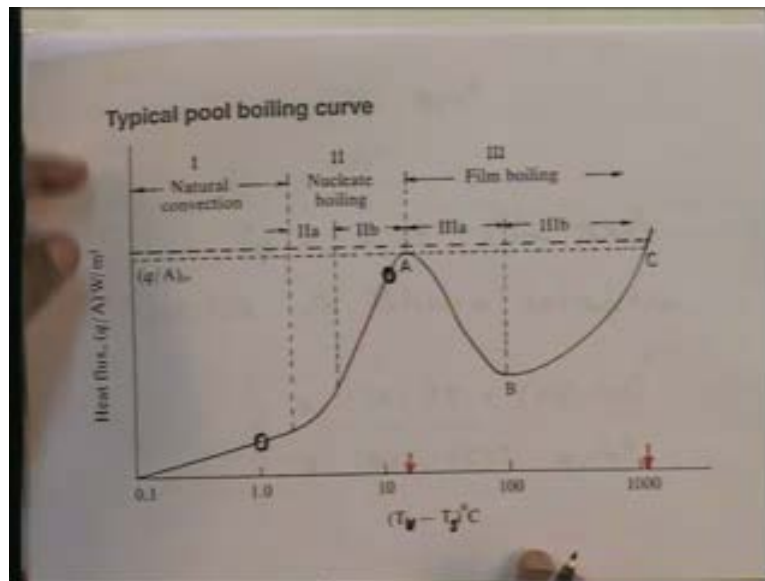
Substitute into Rohsenow correlation

$$\frac{q}{A} = 141.32 \times (115 - 100)^3$$
$$= 476,955 \text{ W/m}^2$$

So, we will get from the table ρ_v density of the vapor .598. If this is not available in the liquid tables, of giving the properties of the liquid, you may have to go to steam tables. .598 kilograms per meter cubed and the Prandtl number of the liquid equal to 1.75. You will also need the constant K_{sf} so go to the table which I showed you. The constant K_{sf} is, for this particular case platinum and water, .013 from the table. So, we have got all the values. Now, it is a straight forward substitution into the Rohsenow correlation; substitute into the Rohsenow correlation.

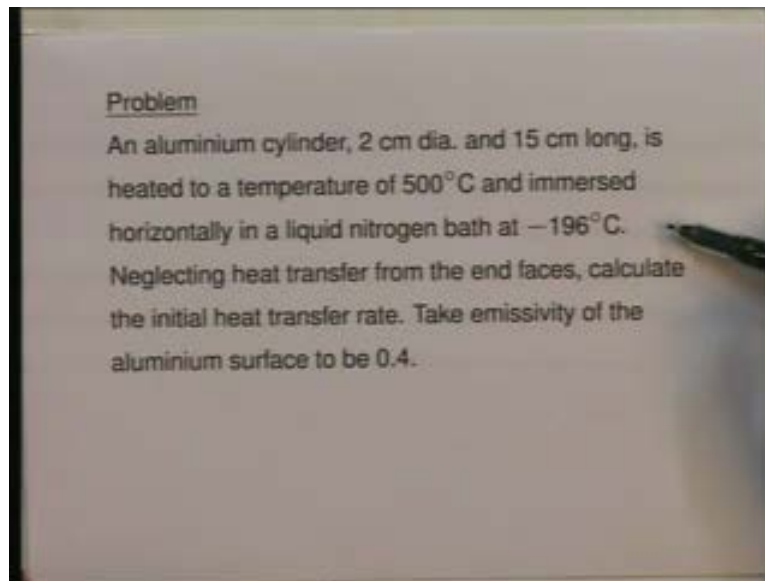
I am now skipping the steps; I am not going to substitute all these numbers but if you do that you will get q by A is equal to 141.32 multiplied by 115 minus 100, this is the temperature difference, T_w minus T_s the whole cubed and that comes out to be 476955 watts per meter square. Notice the steep increase in the value of q by A when T_w minus T_s goes up from 1 to about 50. We have gone up by an enormous factor; earlier the q by A in natural convection was only about 1000 now it is 476000. And just to illustrate that, let us go back again look at the pool boiling curve.

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Notice it is a log plot here; this is the natural convection region so our first point was somewhere here, which we are calculating some region here. Now, we are calculating a point which is somewhere here and it is a steep rise where q by A is proportional to T_w minus T_s to the q power. So, our first point that you have calculated is somewhere here in this problem; the second point that we are calculating is somewhere here in this problem. Now, so this is our second answer; these were the 2 answers we were looking for. Use appropriate correlations to calculate q by A for different temperature differences. Now let us do one more problem in film boiling so that we illustrate the use of Bramley's equation.

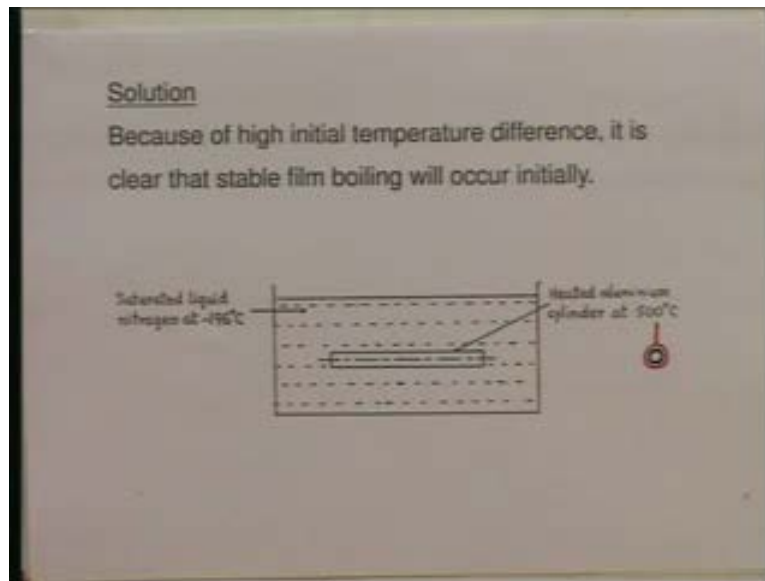
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The problem we are going to do is the following, the problem is - an aluminum cylinder, 2 centimeters in diameter and 15 centimeters long, is heated to a temperature of 500 degrees centigrade and immersed horizontally in a liquid nitrogen bath at minus 196 degrees centigrade. Liquid nitrogen has a saturation temperature of minus 196 degree centigrade at around atmospheric pressure. Neglecting heat transfer from the end faces, calculate the initial heat transfer rate. Take emissivity of the aluminium surface to be .4. This is the problem which we want to do next; now here is the solution.

The first thing to notice - the surface of the aluminum cylinder which is heated is at 500. The liquid nitrogen is at minus 196 so when you immerse the cylinder in the liquid nitrogen horizontally you have got a temperature difference initially of 696 degrees centigrade. At that temperature difference, you are going to get stable film boiling, that is what you are going to get. So, that is the first thing to recognize; so we are going to use the equations for stable film boiling.

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So, here is our pool of liquid which I am showing in this sketch; here is the heated aluminium cylinder at 500 and this is the saturated liquid at minus 196 so stable film boiling is going to occur. So, if I look in the cross section of this, this is my aluminium cylinder and around it a film of vapor is going to form like this and rise to the surface. A plume is going to rise to the surface. We want to calculate the heat transfer coefficient; it is again a straight forward substitution so let us go through the whole procedure. The first thing to know - it is the mean film temperature at which we will need properties.

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Mean film temp. = $\frac{500 + (-196)}{2} = 152^{\circ}\text{C}$

Nitrogen gas has the following properties at 152°C

$k_v = 0.0349 \text{ W/m-K}$ $\rho_v = 0.80 \text{ kg/m}^3$

$\mu_v = 23 \times 10^{-6} \text{ kg/m-s}$

Also $C_{pv} = 1048 \text{ J/kg-K}$

$\rho_L \text{ at } -196^{\circ}\text{C} = 800 \text{ kg/m}^3$

$\lambda = 201 \times 10^3 \text{ J/kg}$

Mean film temperature of the vapor equal to 500 plus minus 196 by 2 which is 152 degree centigrade. So, we will need properties of the vapor at this temperature. This case, the particular vapor is nitrogen. It is liquid nitrogen so nitrogen gas, we have to look up these properties, has the following properties. You have to look them up in the property tables for nitrogen; it has the following properties at 152 degree centigrade. You have k_v the thermal conductivity .0349 watts per meter Kelvin, ρ_v is equal to .80 kilograms per meter cubed, μ_v the viscosity 23 into 10 to the minus 6 kilograms per meter second. Also we will need the C_{pv} ; the average value of this specific heat of the vapor which is .10 not point sorry 1048 joules per kilogram Kelvin. We will also need the density of the liquid at minus 196 which is 800 kilograms per meter cube and we will need the latent heat of vaporization for nitrogen at that particular temperature which is 201 into 10 to the power of 3 joules per kilogram. One has to look up all these properties in appropriate property tables; I am giving you the values here. Now, we calculate first of all λ prime; λ prime is the latent heat plus the enthalpy associated with the superheat.

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$$\lambda' = 201 \times 10^3 + 1048 [152 - (-196)]$$
$$= 565.7 \times 10^3 \text{ J/kg}$$

Substituting into the Bromley equation

$$h_c = 91.34 \text{ W/m}^2\text{-K}$$

Calculate h_r

$$\left(\frac{q}{A}\right)_{\text{radiation}} = \frac{5.670 \times 10^{-8} (773^4 - 77^4)}{\frac{1}{0.4} + \frac{1}{1} - 1}$$
$$= 8096.9 \text{ W/m}^2$$

So, 201 into 10 to the power of 3 plus the average specific heat of the vapor multiplied by 152 minus 196, that is at the mean film temperature, and this will come out to be 565.7 into 10 to the power of 3 joules per kilogram. Then, substitute into the Bromley equation and now I am not going to do the substitution; I am just going to give you the result. If you substitute into the Bromley equation, substituting into the Bromley equation I am skipping putting down the details of the numbers, you will get h_c is equal to 91.34 watts per meter squared Kelvin. So, I want you to do this calculation on your own with the property values I have given.

Now, you have to calculate h_r ; calculating h_r means I need to know the heat, the flow of heat, by radiation - q by A radiation. I use the formula for parallel plates, q by A by radiation is the Stefan Boltzmann constant 5.67 into 10 to the power of minus 8, T_w to the power of 4, 773 to the power of 4 minus 77 to the power of 4 divided by 1 upon .4; .4 is the emissivity of the aluminium surface, 1 upon 1 one is the emissivity of the liquid minus one, which comes to be 8096.9 watts per meter square and now from this I calculate h_r so I will get h_r is equal to - the heat flux in radiation point 8096.9 divided by the temperature difference 773 minus 77 which comes out to be 11.63 watts per meter squared Kelvin.

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$$h_r = \frac{8096.9}{(773-77)} = 11.63 \text{ W/m}^2\text{-K}$$
$$h = h_c + \frac{3}{4} h_r$$
$$= 91.34 + \frac{3}{4} \times 11.63$$
$$= 100.07 \text{ W/m}^2\text{-K}$$

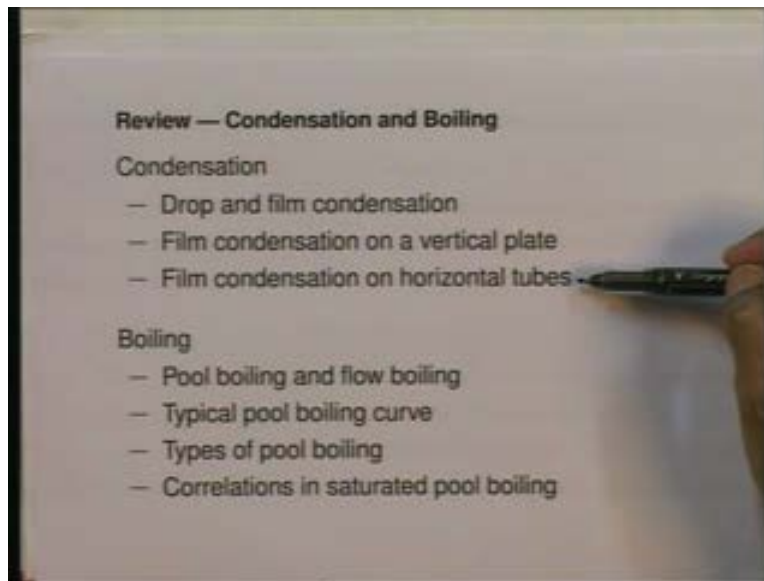
Initial heat transfer rate

$$= 100.07 \times (773-77) \times \pi \times 0.02 \times 0.15$$
$$= 656.4 \text{ W}$$

Therefore, the total heat transfer coefficient is h_c plus 3 quarters h_r which is 91.34 plus 3 quarters into 11.63 which is equal to 100.07 watts per meter squared Kelvin. This is the total heat transfer coefficient and therefore the initial heat flux or the initial heat transfer rate rather - that is what we are to calculate. Initial heat transfer rate is equal to the heat transfer coefficient multiplied by the temperature difference 773 minus 77, this gives the heat flux, multiplied by the area pi into .02 multiplied by .15 and this comes to 656.4 watts.

We are neglecting as we have told neglect the heat transfer from the end faces from the horizontal cylinder. So, this is the answer we are looking for; we have done it in steps remember. We calculated first the convective heat transfer coefficient using the Bromley equation, then we calculated the radiation heat transfer coefficient. We added them up with the formula given and then got the total heat transfer rate. Now, let us just sum up for one minute what we have done in this topic in condensation and boiling.

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Under condensation, we did drop and film condensation. We did film condensation on a vertical plate and film condensation on a single horizontal tube and a bank of horizontal tubes. In boiling, we first described what is pool boiling and flow boiling. We discussed a typical pool boiling curve; we then did various types of pool boiling while we were discussing the curve. And then gave correlations in the saturated pool boiling region for natural convection region, for the nucleate boiling region, for the stable film boiling region and correlation for the peak heat flux and finally we did some problems today to illustrate the use of these correlations. With this we have come to the end of the topic of condensation and boiling.