Heat and Mass Transfer

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Lecture No. 31

Boiling and Condensation - 3

Last time we derived the expression for the heat transfer coefficient during condensation of a saturated, pure saturated, vapor on vertical plate. The expression we derived was first derived by Nusselt and after deriving the expression based on the fundamental laws of conservation of mass, Newton's second law of motion and the first of law thermodynamics, after deriving that simple expression we then went on to use it to solve a numerical problem of condensation on a vertical tube. Now, today we will extend that result further; we will use a similar result for condensation on horizontal tubes. So today, we are going to take up film condensation on horizontal tubes.

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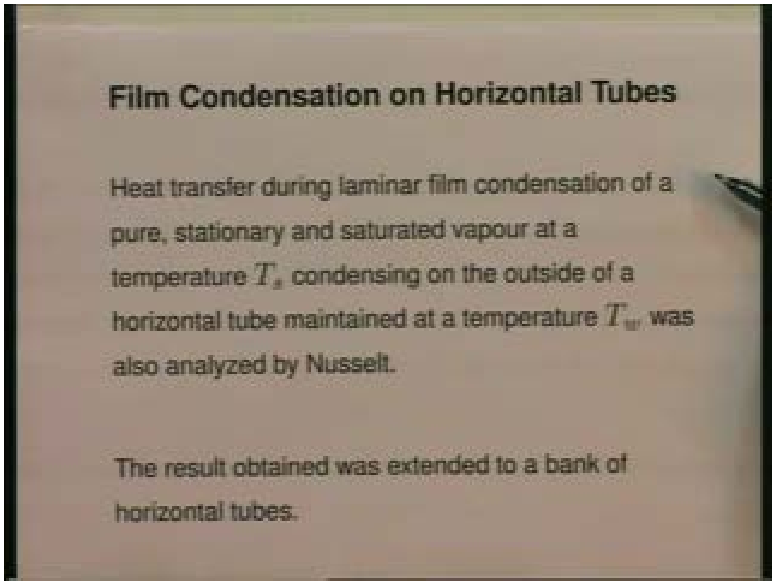

Film Condensation on Horizontal Tubes

Heat transfer during laminar film condensation of a pure, stationary and saturated vapour at a temperature T_s condensing on the outside of a horizontal tube maintained at a temperature T_w, was also analyzed by Nusselt.

The result obtained was extended to a bank of horizontal tubes.

The expression for the heat transfer coefficient will be derived. So, we are going to study heat transfer during laminar film condensation of a pure stationary and saturated vapor at a temperature T_s condensing on the outside of a horizontal tube maintained at a temperature T_w. This is what we are going to study and this problem was also analyzed by Nusselt. The difference between this problem and the earlier problem is in the geometry. Earlier, it was a vertical plate, now it is a horizontal tube on the outside of which the condensation is taking place; this is the difference. Let us look at the geometry; focus your attention first on the left hand side of the figure

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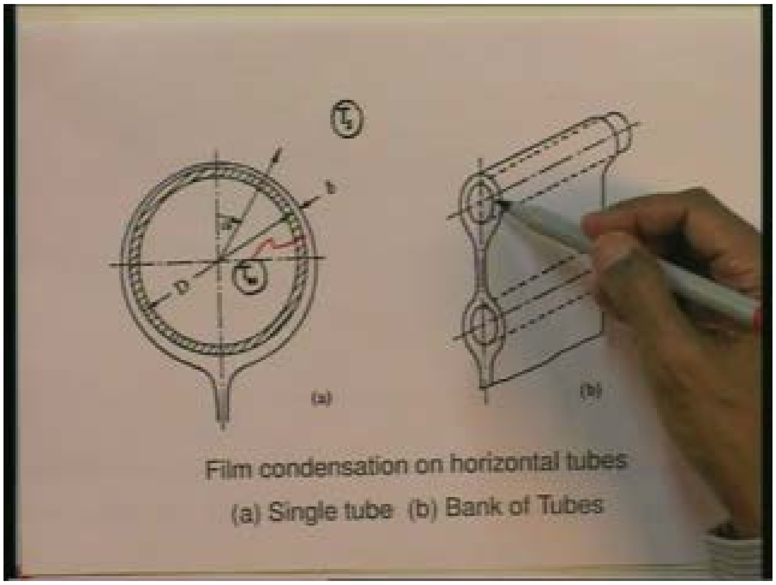

Film condensation on horizontal tubes

(a) Single tube (b) Bank of Tubes

That is film condensation on a horizontal single horizontal tube; this is the tube of diameter D, outside diameter D and vapor which is at a temperature T_s - saturation temperature T_s, pure saturated vapor at temperature T_s - is condensing on the outside of this tube and it is maintained at a temperature T_w. The wall of this tube is maintained at a temperature T_w; this is the outside wall and this is maintained at a temperature T_w. So, it is an identical problem to the problem we studied earlier with the difference that now instead of vertical plate you have a horizontal tube and Nusselt analyzed this problem also. Then he went on to analyze the problem ba ba; just let me go back of a moment.

Look at this horizontal tube. Notice I have drawn on the outside is the liquid film growing in thickness as we go down along the circumference and finally the liquid film falls off at the bottom of the tube. It is of course, its thickness is shown exaggerated. It is very thin film I have made that point repeatedly earlier also. So, it is a very thin film here in this sketch; the thickness of this liquid film is shown exaggerated. Having studied this problem, then Nusselt went on to look at the problem of a bank of tube. So it is, this is one tube, this is a second tube, there could be a third tube one above the other. And he studied condensation on this with the assumption that the condensate from the first tube fell on to the second tube, added to the flow rate on the second tube which in turn fell on to the third tube and so on.

So, he also studied condensation on a bank of n tubes - n horizontal tubes. So, I will give you both those formula. We are not going to derive those now because, as I said, the derivation proceeds along similar lines. It is a little more complicated in terms of the integration that is to be done because we have to move along a curved surface. So, the integration is a little harder but in principle he has used the same equations that we used earlier in deriving the expression for a vertical plate; there is no difference. It is only the geometry; that means your work working your way around the circumference and the thickness of the film is increasing. Instead of going down along a vertical plate as was the case earlier, now the expression which Nusselt obtained for condensation on a single horizontal tube, the expression for the heat transfer coefficient which he obtained was the following.

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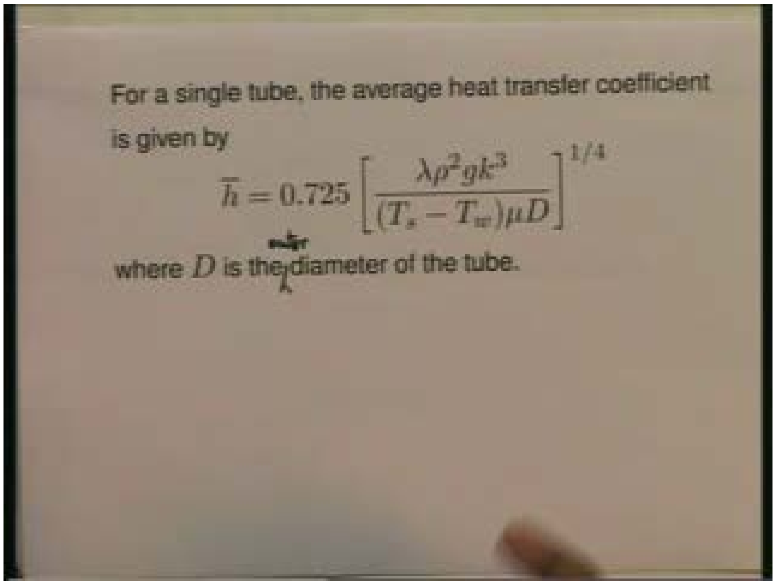

For a single tube, the average heat transfer coefficient is given by

$$\overline{h} = 0.725\left[\frac{\lambda\rho^2 g k^3}{(T_s - T_w)\mu D}\right]^{1/4}$$

where D is the outer diameter of the tube.

For a single tube the average heat transfer coefficient is given by and this is the expression - h bar is equal to .725 within square bracket lambda rho squared gk cube divided by T_s minus T_w multiplied by mu D close the square bracket. The whole thing raise to the power of 1 by 4 where capital D is the diameter of the tube outer diameter of the tube. So, there is, if you look at this formula, let me write that - D is the outer diameter of the tube. You will notice how similar this expression is to the one we had earlier for vertical plate. Earlier also we had in the numerator lambda rho square gk cube rise to one fourth T_s minus then the denominator T_s minus T_w into mu.

Earlier we had a length L which was the length of the vertical plate. Now, we have a diameter D which is the diameter of the horizontal tube and the constant earlier was .943, now the constant becomes .725. This is to be expected if the same type of derivation, the same type of assumptions so you have to get the similar expression. Only the constants change because of the nature of the integration which we have to do in moving along the circumference of a horizontal tube. And of course, instead of L you have to get D because D is now the characteristic dimension. So, the expression is very very similar to what we had earlier and as I said we are not deriving this but it is available in certain books. One can look it up the classical derivation of Nusselt for this formula.

Now, having done this it is possible also to express the result in term of a film Nusselt number, film Reynolds number sorry exactly as we did for a vertical plate. So, the result can also be expressed in terms of the film Reynolds number.

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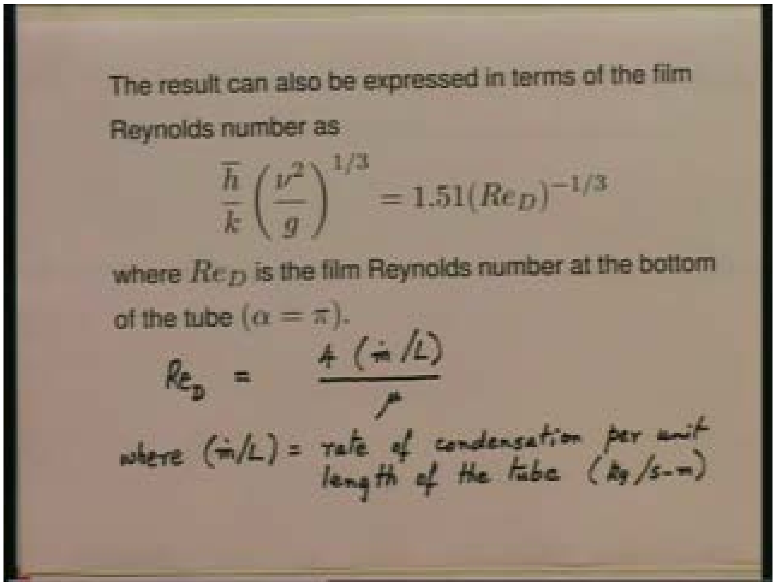

The result can also be expressed in terms of the film Reynolds number as

$$\frac{\overline{h}}{k}\left(\frac{\nu^2}{g}\right)^{1/3} = 1.51(Re_D)^{-1/3}$$

where Re_D is the film Reynolds number at the bottom of the tube $(\alpha = \pi)$.

$$Re_D = \frac{4\,(\dot{m}/L)}{\mu}$$

where $(\dot{m}/L)$ = rate of condensation per unit length of the tube (kg/s-m)

This is the result h bar by k within bracket mu square by g to the one third. The left hand side is the same as what we had for a vertical plate, is equal 1.51 Re_D to the minus one third. Now, I would like to derive this on your own. It should be possible just as I asked you to derive the similar expression for a vertical plate on your own. You should be able to derive this on your own. The constant notice again is different; earlier it was something else now it is 1.51. Otherwise, the nature of the expression is the same. Earlier the film Reynolds number was Re_L - it was the Reynolds number at the bottom of the plate. Now Re_D is the film Reynolds number at the bottom of the tube and it is given by - the film Reynolds number at the bottom of the tube is given by, Re_D is the film Reynolds number at the bottom of the tube given by - Re_D is equal to 4 m dot by L divided by mu, very similar to what we had earlier where m dot by L is equal to the rate of condensation per unit length of the tube. So, the units of m dot by L will be kilograms per second per meter length kilograms per second meter - that will be the unit.

So, Re_D is the Reynolds number is the film Reynolds number at the bottom of the tube and alfa here, in case you are wondering what it is, alfa is the angle measured from the top of the tube. We haven't used it because we haven't done the actual derivation but alfa is this angle. You start as the alfa equal to 0 at the top of the tube here and as you move along, alfa increases from 0 all the way to the bottom that is at alfa equal to pi. So Re_D is effectively the film Reynolds number at alfa equal to pi. So, these are our 2 expressions for the heat transfer coefficient on a single horizontal tube. Now, as I said, Nusselt extended this result to a bank of n tubes and let me give you that result also. It is very simple result which he derived for a bank of n tubes.

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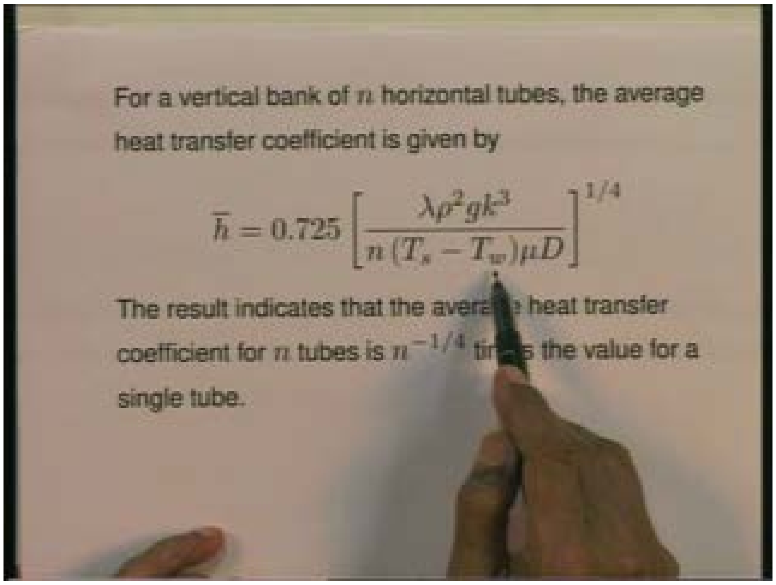

For a vertical bank of n horizontal tubes, the average heat transfer coefficient is given by

$$\bar{h} = 0.725\left[\frac{\lambda\rho^2 g k^3}{n\,(T_s - T_w)\mu D}\right]^{1/4}$$

The result indicates that the average heat transfer coefficient for n tubes is $n^{-1/4}$ times the value for a single tube.

For a vertical bank of n horizontal tubes the average heat transfer coefficient h bar is given by same constant as for one tube .725 lambda rho square g k cubed divided by n T_s minus T_w mu D the whole thing to the power of 1 by 4. So, what is the difference? The difference is due to the fact - an extra symbol n here in the denominator. That is what you have when you have a bank of n horizontal tubes one above the other. So, the result indicates that the average heat transfer coefficient for n tubes is n to the minus one fourth times the value for a single tube. That is what the result indicates so if you have bank of n tubes, you get the value for the topmost tube single tube. And then if you just multiply it by n to the power of minus 1 by 4 - whatever n is, n may be bank of 2 tubes, 3 tubes, 4 tubes, 5 tubes - then you will get the value for all those number of tubes, the average value for all those number of tubes so there is a slight reduction in the average heat transfer coefficient when you go from a single tube to bank of n tubes. And the reduction is multiplication by a factor n to the power of minus 1 by 4.

Now, these were the expressions all derived by Nusselt as I said. Now, let us do a problem just to illustrate the use of this expression

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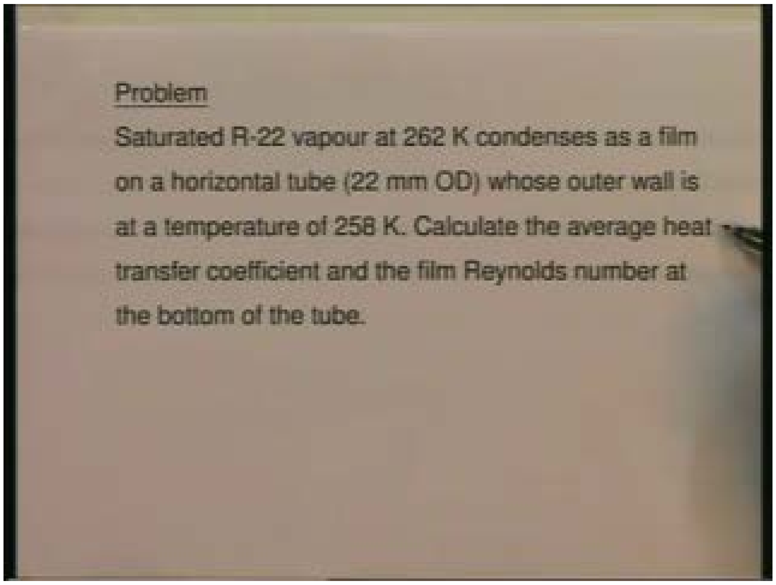

Problem

Saturated R-22 vapour at 262 K condenses as a film on a horizontal tube (22 mm OD) whose outer wall is at a temperature of 258 K. Calculate the average heat transfer coefficient and the film Reynolds number at the bottom of the tube.

The problem we are going to do is the following. Let me read it out slowly. Saturated R-22 vapor at 262 Kelvin condenses as a film on a horizontal tube (22 mm OD) whose outer wall is at a temperature of 258 K. Calculate the average heat transfer coefficient that is h bar for that single tube and the film Reynolds number at the bottom of the tube. It is a straightforward substitution into the Nusselt expression for a single horizontal tube which I have given you just now. So, let us do the problem; so what does the problem say? Let us put down the data now; we have a single tube.

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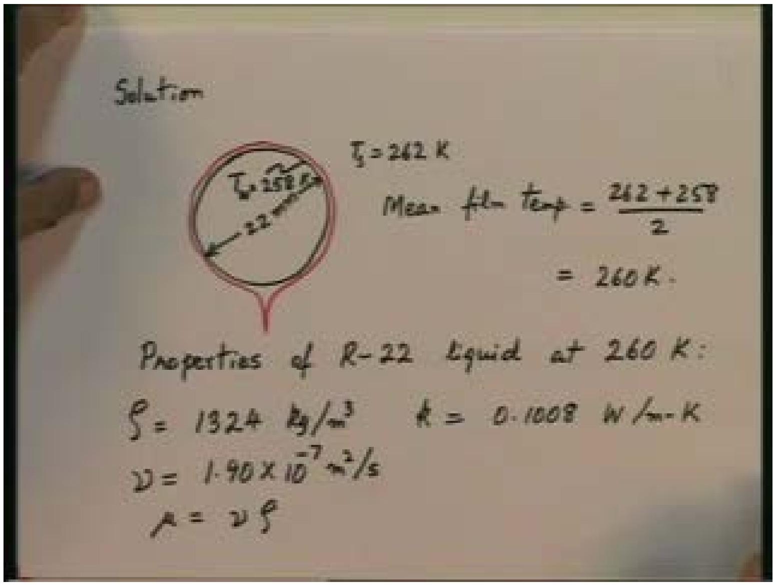

Solution

$T_s = 262$ K

Mean film temp $= \frac{262 + 258}{2}$

$= 260$ K.

Properties of R-22 liquid at 260 K:

$\rho = 1324$ kg/m^3 $\quad k = 0.1008$ W/m-K

$\nu = 1.90 \times 10^{-7}$ m^2/s

$\mu = \nu \rho$

We have a single tube whose diameter is 22 mm. This is single tube; condensation is taking place out on the side of this tube. I will show that the film condensation taking place on the outside of this tube like this and falling off at the bottom, this is liquid film being formed at the outside of this tube and falling off at the bottom. Now, the saturation temperature, it is a pure saturated vapor and it is at a temperature T_s equal to 262 K. This is R-22 vapor, 260 K and you are told that T_w, that is the wall temperature inside, is T it is maintained, the outer wall of the tube is maintained at 258 K. Find the average heat transfer coefficient.

Now, the first thing is properties. We need properties of R-22 and you have to take properties at the mean film temperature. So, what is the mean film temperature? Mean liquid film temperature, mean film temperature, is equal to 262 plus 258 divided by 2 - that is equal to 260 K. Properties of R-22: liquid refrigerant - 22, liquid at 260 K. You have to look these up in the tables for R-22. We will need the following properties; we will need the density rho of the liquid which is, if you look it up, will be 1324 kilograms per meter cubed. We will need the thermal conductivity K which is .1008 watts per meter Kelvin. You will need the viscosity. In the table set I looked up the kinematic viscosity was available so nu which is 1.90 into 10 to the minus 7 meter squared per second. You can always get mu once you know nu because mu is equal to kinematic viscosity into density. So, you always get mu from that; so these are the 3 liquid properties we will need. In addition we will need the latent heat of course. So, let me put that down, from the tables if you look up - as we need the latent heat and would be at the saturation temperature - so latent heat would be at 262 K

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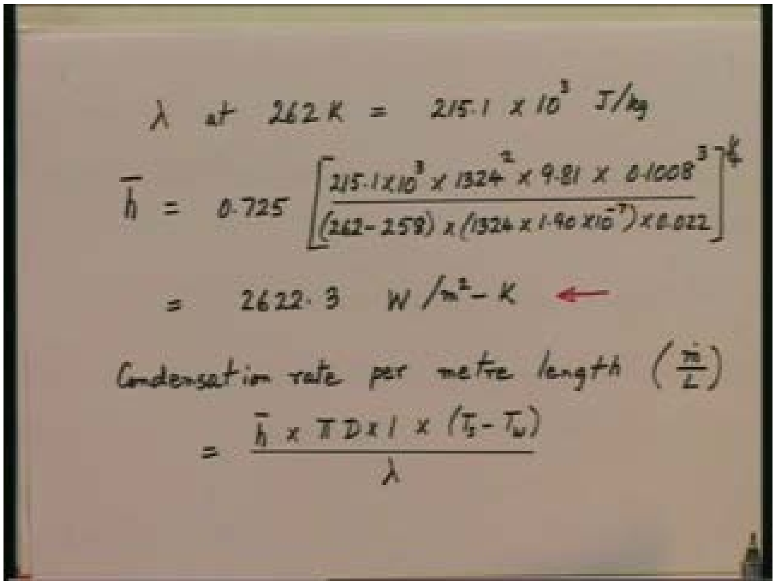

λ at $262\,K = 215.1 \times 10^3$ J/kg

$$\bar{h} = 0.725 \left[\frac{215.1\times10^3 \times 1324^2 \times 9.81 \times 0.1008^3}{(262-258)\times(1324\times1.90\times10^{-7})\times 0.022}\right]^{1/4}$$

$$= 2622.3 \ W/m^2\text{-}K \leftarrow$$

Condensation rate per metre length $\left(\frac{\dot{m}}{L}\right)$

$$= \frac{\bar{h} \times \pi D \times 1 \times (T_s - T_w)}{\lambda}$$

For R-22 vapor, if you look it up in the tables for R-22, it is 215.1 into the 10 to the power of 3 so many joules per kilogram. So, these are the relevant properties that we need; now substitute into our formula. So, we have, h bar is equal to .725 into lambda. lambda is 215.1 into 10 to the power of 3, rho squared is 1324, the whole squared into g which is 9.81 into k cubed .1008 cubed the whole thing divided by 262 minus 258 that is the delta T - T_s minus T_w - multiplied by mu. mu is nu rho so it will be rho multiplied - the kinematic viscosity 1.90 into 10 to the minus 7. This is mu and finally D which in meters will be .022 the whole thing to the power of 1 by 4 the whole thing to the power of 1 by 4. And if you work this out you will get equal to 26262.3 watts per meter squared Kelvin. So, this is the first answer that you are looking for - the value of the average heat transfer coefficient.

The second thing you are asked to find, we have been asked to find is the Reynolds number, the film Reynolds number at the bottom of the tube. So, first let us get the condensation rate per meter length. Condensation rate per meter length, condensation rate per meter length, that will be m dot by L will be equal to h bar that is the average heat transfer coefficient multiplied by the area pi D into 1 meter length 1 multiplied by T_s minus T_w. This would give you the heat flux and if you divide this heat flux in watts per meters, this is not heat flux, sorry, it is the rate at which heat is flowing q if you divide this by lambda, that is the latent heat. Then we will get the condensation rate for 1 meter length because we are taking 1 meter length, l equal to 1. So, now again, substitute the numbers here.

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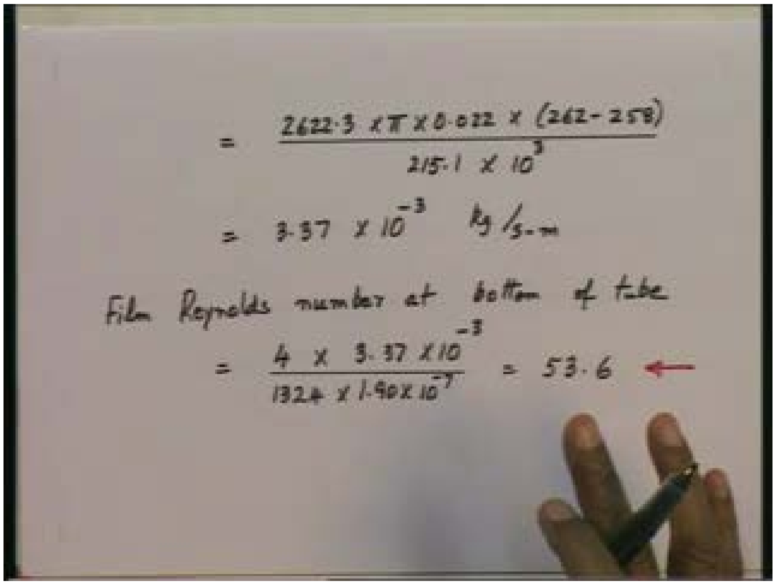

$$= \frac{2622.3 \times \pi \times 0.022 \times (262-258)}{215.1 \times 10^{3}}$$

$$= 3.37 \times 10^{-3} \text{ kg/s-m}$$

Film Reynolds number at bottom of tube

$$= \frac{4 \times 3.37 \times 10^{-3}}{1324 \times 1.90 \times 10^{-7}} = 53.6 \leftarrow$$

If you substitute the numbers we get this is equal to m dot by l is equal to 2622.3 multiplied by pi .022 into 262 minus 258, that is the delta T, divided by lambda which is 215.1 into 10 to the power of 3. So, this comes to 3.37 multiplied by 10 to the minus 3 so many kilograms per second per meter length. Therefore, the film Reynolds number at the bottom, film Reynolds number - this is the condensation number rate at the bottom of the tube because it is for the whole tube. So, film Reynolds number at bottom of tube is equal to 4 multiplied by m dot by l that is 3.37 into 10 to the minus 3 divided by the viscosity mu. So, we will get divided by viscosity, mu is 1324, multiplied by 1.90 into 10 to the minus 7; so this comes out to be 53.6 so the film Reynolds number at the bottom of the tube is 53.6.

Let us look at the sketch again, we are talking of the film Reynolds number right here at the bottom. The condensate comes to the bottom right here at the bottom; this is the film Reynolds number as it drips off as the condensate falls off from the bottom of the tube. Film Reynolds number will go on increasing because the condensation goes on accumulating on this, more and more vapor condenses and finally it is at its maximum value and that is 53.6 at the bottom of the tube. So, these are the 2 answers that we were looking for - the average heat transfer coefficient and the film Reynolds number at the bottom of the tube.

Now, you might want to note that the Nusselt formula which we have given is generally experimentally found to be valid up to film Reynolds numbers of about 30. Above 30 what happens is - above 30 ripples form on the condensate surface because the there is more condensation taking place, film Reynolds number higher means more condensation rate. So, above 30 there are ripples on the surface and these ripples tend to enhance the heat transfer coefficient a little. It is still laminar flow but they tend to enhance the heat transfer coefficient by 15, 10, 15, 20 percent.

This is what is observed experimentally. Therefore, in the present case this value 53.6 seems to indicate that perhaps the value which we have got in this case of the h that is 2622 may be slightly underestimated. The actual value h bar in this case for this tube may be about 10 or 15 percent higher. It is possible because the film Reynolds number at the bottom is more than 30; 30 is considered a kind of a dividing line. Upto 30 we get a very smooth interface, above 30 one finds that ripples tend to form on the condensate film surface. So, this is one comment which you may want to note at the end.

Now we want to pass on. We have now finished with what we wanted to do with condensation. We have studied condensation on a vertical plate, we have studied condensation on a single horizontal tube, we have studied - not studied - but we have at least given the expression for condensation on a bank of horizontal tubes. In all cases are given you the expressions but the h bar when a saturated vapor condenses on a surface which is at the temperature T_w a little less than T_s. Now we want to move on to the second half of this topic and that is towards boiling. We want to start today now with boiling so let us first of all now let us start with boiling

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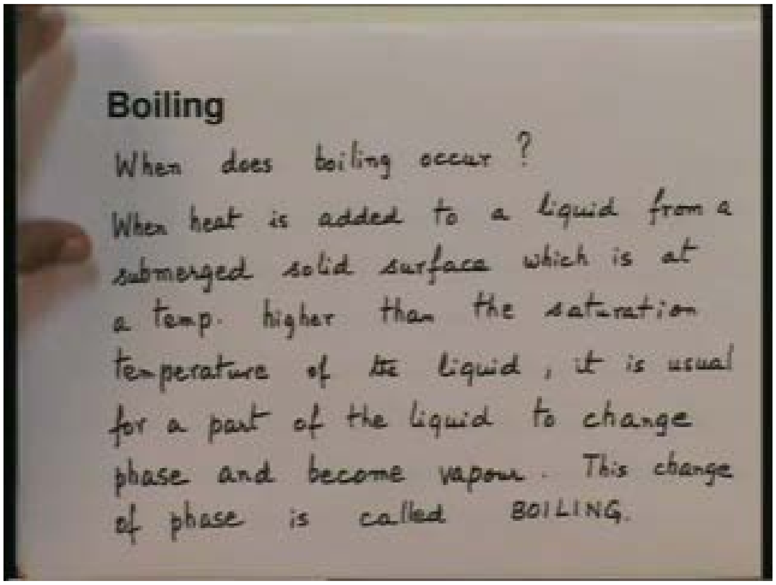

Boiling

When does boiling occur?

When heat is added to a liquid from a submerged solid surface which is at a temp. higher than the saturation temperature of the liquid, it is usual for a part of the liquid to change phase and become vapour. This change of phase is called BOILING.

The first question we are going to ask in boiling is - when does boiling occur? That is the first question we want to answer. Well, let me state, make the statement. When heat is added to a liquid from a submerged solid surface, when heat is added to a liquid from a submerged solid surface which is at a temperature higher than the saturation temperature of the liquid, it is usual for a part of the liquid to change phase and become vapor. This is an experimental observation. If I have liquid and heat is added to it from a submerged solid surface which is at a temperature higher than the saturation temperature of the liquid, it is usual for a part of the liquid to change phase and become vapor. This change of phase is called boiling. Now, let me just show a sketch to illustrate this idea. Let us look at a figure. Here are 2 examples of boiling which could take place.

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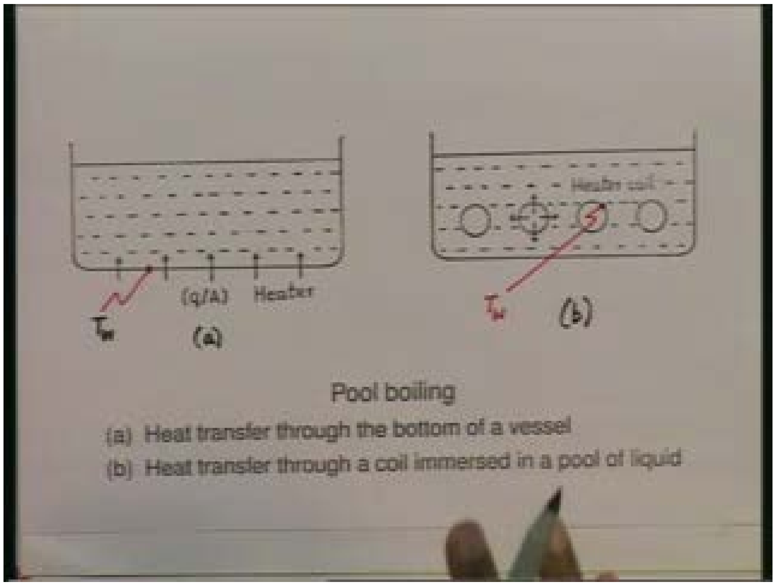

Pool boiling

(a) Heat transfer through the bottom of a vessel

(b) Heat transfer through a coil immersed in a pool of liquid

Here is a vessel, this is a figure a and this is the figure b. In figure a, there is a vessel containing a liquid - could be water or could be any other liquid - and let us say saturation temperature of this liquid it is at some pressure. So, obviously corresponding to that pressure there would be saturation temperature T_s. The liquid may be at a temperature lower than T_s; it doesn't have to be at the saturation temperature but corresponding to its pressure there is a saturation temperature T_s and the vapor, I am sorry, the liquid is contact with the bottom of this vessel and through the bottom heat flux is being supplied. Heat is being supplied through a heater and the temperature of the bottom is T_w, the temperature of the bottom is T_w.

The liquid is at a pressure corresponding to which the saturation temperature is T_s or in b, slightly different example in which we again have pool of liquid. In a pool of liquid in a vessel but the heat is being added through a heater coil; that means it could be an electrical heater coil which is emerged in that liquid and heat is coming out of the surface of that heater coil. In which case, the temperature of this heater coil - the surface temperature here - is what we mean by T_w. This is T_w and again the liquid is a pressure and the temperature saturation temperature corresponding to that pressure is T_s.

Now if T_w is greater than T_s - that is what we have said earlier - if T_w is greater than T_s, then it is usual for a part of this liquid which is surrounding this heated surface either here or here to change phase, that means to go into the vapor form and we call this as boiling. In this particular example that I am showing you, note that the liquid is contained as a pool in a vessel. Out here it is in pool and heat is being supplied from the bottom. Out here also, the liquid is in pool and heat is being supplied through a heater coil. That is the only difference but in both cases the liquid is in the form of a pool, in a pool of liquid in some vessel, therefore it is also referred to as pool boiling.

We call this as pool boiling. So, pool boiling means the liquid is in the form of a pool in some vessel. There is no bulk motion of the fluid, any bulk any motion of the fluid that occurs, any motion of the liquid that occurs will occur only because of the heat that I give. If I give heat some bubbles may be formed or some natural convection currents may be formed whatever it is, any motion is because of the heat I am giving. There is no other motion if I stop giving the heat. The liquid will just be sitting stationary then as a pool. So, that is why this is called pool boiling; the example that I have shown is called as pool boiling. In contrast to this - this is one classification of boiling that is we could have pool boiling - the other classification is that we could have flow boiling. So in boiling there are 2 classifications - one is pool boiling which I have shown you.

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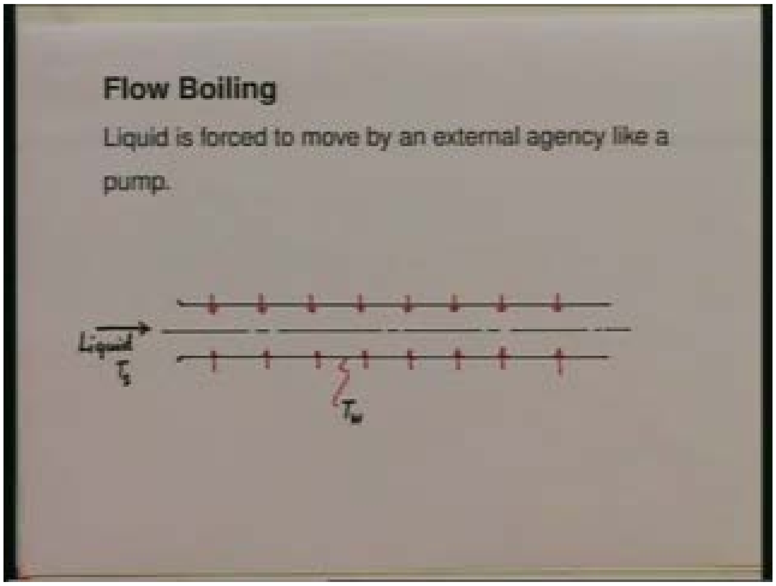

Flow Boiling

Liquid is forced to move by an external agency like a pump.

And now let us look at the other which is flow boiling. Flow boiling means the following - the liquid is forced to move by an external agency like pump through a tube or tubes. Let us draw say one tube, let me draw one tube here. Let us say this is a tube like this. This is one tube and liquid. Let us say, from the left hand side, liquid is being forced through this tube. Some pump is used to pump the liquid through this tube. And the saturation temperature of this liquid is T_s; it is a certain pressure P_s and the saturation temperature corresponding to that pressure P_s, the saturation temperature is T_s.

Now, as the liquid goes through this tube, heat is added through the walls of the tube like this. Heat is added through the walls of this tube by some means - there could be a hot liquid flowing on the outside, there could be an electrical heater on the outside, whatever it is - heat flux is supplied from the outside like this. And let us say that the wall of this tube is maintained at a temperature, the wall of this tube is maintained at a temperature T_w because of the heat being supplied. Now if T_w is greater than T_s, we have the same situation that the wall is maintained at a temperature higher than the saturation temperature of the liquid which is flowing through and therefore at the surface of the tube, at the inner surface of the tube, boiling will take place.

And in this case, since the liquid is being forced through the tube, it is called as flow boiling. The boiling may be in the form of bubbles, in the form of film of vapor formed at the surface, whatever it is. The fact is boiling will take place - that means change of phase will take place from the liquid to vapor. So this is called as flow boiling. Flow boiling means the liquid is going through a series of tubes or single tube, so enforced by an external agency, through that tube. Like external agency like a pump and at the same time heat is being added and the surface temperature is greater than the saturation temperature of the liquid.

So, these are 2 classifications of boiling. Now we are only going to look at pool-boiling. In this, in this, in the lectures that we are giving here, we are going to only do an elementary study of pool boiling. Now let us go back again for a moment. Let us say I do the following experiment now. Let me go back to the sketch of pool-boiling and say I have a pool of liquid heat is added. Heat flux is q by a and the surface temperature is T_w and T_w is greater than T_s, Ts is the saturation temperature of the liquid. So, let me draw an arrow and say the pool of liquid is having, is at a, let us say it is a saturated pool at a temperature T_s, T_w is greater than T_s. So, boiling is going to take place and we are going to conduct the experiment as follows.

We are going to systematically raise the value of T_w. T_s is fixed - it depends of the particular liquid and the condition of pressure that it is in. So, we are going to systematically raise the value of T_w. We will first work by say T_w minus T_s equal to 1 degree, then T_w minus T_s equal to say 2 degrees, then 5 degrees, then 10 degrees, then 20 degrees, then 100 degrees, as much as we can go. So, we are going to systematically raise the value of T_w and get in each steady state different value of T_w minus T_s ranging from say 1 all the way up to a few hundreds. For each case, we will measure what is the q by a that we have to supply because you got to supply heat in order to maintain this T_w.

So, what is the q by a? What is the heat flux watts per meter squares that we will supplying at the surface? That is what we would like to measure at the same time. So the 2 parameters are T_w minus T_s which we are controlling and q by a is the heat flux that we are supplying in order to get that particular value of T_w minus T_s. Now, if you do this experiment for pool of saturated liquid, a typical pool boiling curve which you will get is as follows. This is the pool boiling curve that you will get.

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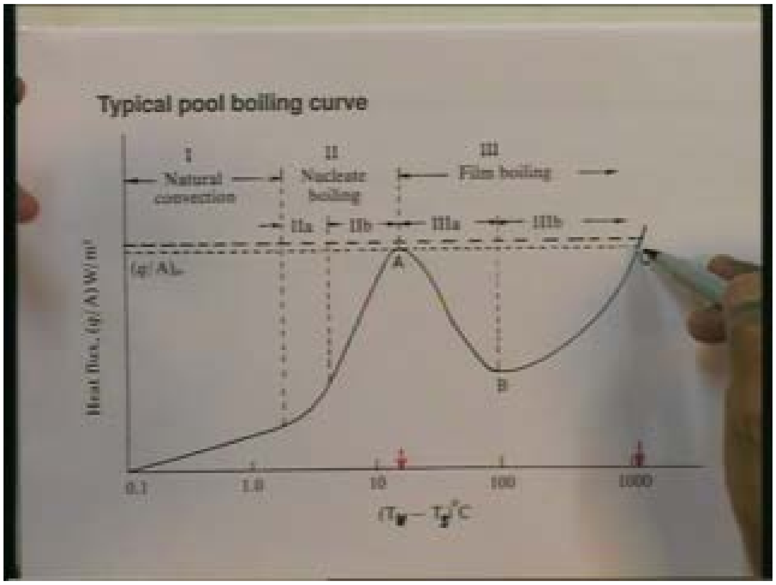

Typical pool boiling curve

On the x axis you have T_w minus T_s and it is on a logarithmic scale. So, you can see .1, 1, 1000 and a thousand. So, this is the values of T_w minus T_s which we are controlling during the experiment. Then on the y axis we have the values of heat flux - the heat flux that we are supplying for maintaining these values. So, in each steady state, a T_w minus T_s equal to one steady state. What is the q by a? Measure that and put down that value. Next go to say 10, find a value of q by a, you get another experimental. So, you generate a series for experimental points and then draw the curve and the curve which you get is something like this.

It is a very interesting shape - q by a doesn't keep on going up with T_w minus T_s. It first increases slowly, then it increases more sharply, then it goes through a maximum and goes down and then again it goes through a minimum and keeps going up. This is the nature of the curve that you get as you increasing, repeating the experiment with higher and higher values of T_w minus T_s. Now, the curve that we have got is called the pool boiling curve. The curve that we have got is called pool boiling curve. It is a typical curve first generated by Japanese scientist Nukuyama I think in 1934 and it is a curve that is being very widely studied.

Now let us break up into regions - the first region is the region in which q by a is increasing with T_w minus T_s but increasing with the slope; this is the logarithmic slope. This is log scale that I am talking about - increasing slowly. This is the region of natural convection - this is called the region natural convection. Now in this region, in this region of natural convection, if you are observing the pool, let us say I will go back to the pool of liquid here, if you are observing the pool through a window on the side, what you will observe is the following. You have got a very low value of T_w minus T_s so you need a low heat flux and in this natural convection region, the first one, what really happens is the temperature is just a little more than the temperature T_s. T_w is just a degree or 2 more than T_s, a natural convection current is set up inside this pool of liquid and the natural convection current is set up because the liquid at the bottom gets super heated, goes a little above T_s by a degree or half degree more. Its density decreases so it rises so the heated liquid rises, comes to the surface and from the surface evaporation takes place; a little evaporation takes place. And this is what we call as the natural convection region. There is really no boiling taking place, it is more of a natural convection occurring inside the pool of liquid.

The hot liquid - superheated liquid - rising to the surface, an evaporation taking place from the surface in the form of the vapor which comes off from this pre surface of the liquid. Let us go back again now so this is the first region the natural convection region. Then at a certain stage, you will see that the q by a starts increasing more steeply with T_w minus T_s. The slope of the curve becomes much steeper and again if you were to observe the boiling phenomenon, what you will find? In this region which is called the nucleate boiling region, what you will observe is the following. In the nucleate boiling region, one observes if one keeps looking at this heated surface at which heat is being supplied, one observes vapor bubbles forming at the surface.

Vapor bubbles form at particular points on the surface. The vapor bubble increases with size; after it increases to a certain size under the effect of buoyancy it separates from the surface and goes to the top. Then the next one forms, so like this bubbles keep forming at the surface. The bubbles keep on increasing in size and then they leave at a certain point because of buoyancy effects. They detach from the surface and rise to the free surface; this is the region which is called as the nucleate boiling region and as you go on increasing T_w minus T_s the number of places where these bubbles nucleate increases; the frequency with which bubbles form also increases.

So, you just, first you may see a few bubbles forming here and there, then you will see more bubbles forming at the same locations more frequently and then you will see bubbles forming not just a few locations but all over on the heated surface. So as you go up along this curve, you and the T_w minus T_s goes on increasing. You get nucleate boiling in bubbles, nucleate at the surface grow in size, leave the surface, more bubbles form and then gradually they go up. Now at a certain point, what we observe is that the curve goes through a maximum and this is called the peak heat flux. This is the point a which is called as the peak heat flux.

Now interestingly so many bubbles are being formed on the surface that some of the locations at which the bubbles are formed are very close to each other. So. bubble forming at 1 location and another location is so close that they tend to coalesce with each other - that close to each other. Now, the moment that happens on the heated surface, instead of having bubbles forming, you have a small vapor film on the surface because they are forming too close to each other, joining up and forming a vapor film on the surface. Now, when this happens, when partly the heated surface is covered by film of vapor and partly it is having bubbles forming on the surface, then we find that because of the formation of a film, the film of vapor - the vapor obviously - has a lower thermal conductivity so the heat flux in fact decreases with temperature difference. And then at a certain stage, so much bubble formation takes place and they are so close to each other that they are all coalesced with each other and we have a vapor film separating the liquid from the heated surface. Then we have a region of what is called a stable film boiling.

So, let me go back now. We have natural convection region. Let me show the regions again.

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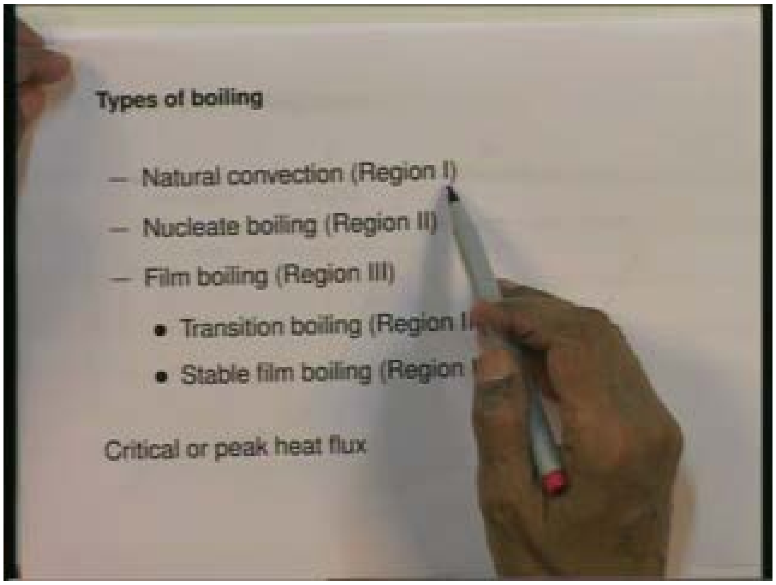

Types of boiling

- Natural convection (Region I)
- Nucleate boiling (Region II)
- Film boiling (Region III)
    - Transition boiling (Region I
    - Stable film boiling (Region

Critical or peak heat flux

We have the natural convection region that is region 1 in which we have superheated liquid rising to the surface and evaporation taking place only from the pre surface. Then, secondly, region 2 we have nucleate boiling region in which bubbles form at the surface and the bubbles grow in size and leave the surface. The frequency of formation goes on increasing as T_w minus T_s increases. Then we go through a maximum and once we have gone through a maximum, we have a region 3 which we call as a transition boiling region in which part of the heated surface is covered by a vapor film and partly bubbles are nucleating and finally we have so many bubbles forming so close to each other that the whole heated surface is covered by a stable vapor film which separates the liquid from the heated surface that we call as the stable film boiling region. The point a which is the point at which the heat flux goes through a maximum is called the critical heat flux or peak heat flux. Now this point is particularly important. Why is it so?

Let me just tell you why. Suppose, instead of being able to control, let us go back to the figure of the pool boiling, suppose instead of being able to control T_w minus T_s - this is

T_w minus T_s. Suppose instead of being able to control T_w minus T_s, I am controlling the y axis coordinate that is q by a. That is, I am systematically giving more and more heat flux to the surface. Then what will happen? Let us say I give this heat flux; at this heat flux if I go horizontally and come down I will get this value of T_w minus T_s. I go up, go in heat flux; let us say I go to a value here. Then if I go to this value here, go horizontally, go down vertically, I will get a value of T_w minus T_s say about 10. Now let us say I approach this point a at this point. I will get a value which is q by a - the critical heat flux. I will get a value of T_w minus T_s equal to say 20 or something.

Now let us say I go to a value of heat flux which is just a little higher than the critical heat flux. Let us say I go to a value which is a little higher than the critical heat flux. Let me draw that - a value of q by a which is just a little higher than the critical heat flux. Now see what happens. I am controlling critical heat flux so I have given a value slightly higher than value corresponding to the point a. Now notice the value of T_w minus T_s now suddenly will go up; earlier the value of T_w minus T_s - if I was at the critical heat flux that is at this point - value of T_w minus T_s was given here, out here with q by a critical. Now suddenly if I go to a value which is just a little higher than the critical heat flux; now notice what happens. I have gone to value of T_w minus T_s which will be somewhere here. That means instead of having a value of T_w minus T_s which might be about 20, I have gone to value which could be few hundred or even thousand.

Now what are the implications? Suddenly, in order to supply that heat flux, the surface temperature has to rise from a value which is only about 20 degrees more than T_s to a value which is probably a hundred degrees or thousand degrees more than T_s. This could be dangerous. The surface T_w because of this high temperature may melt or may get damaged and that is why we call this point the critical heat flux and in practice wherever heat flux is the controlling factor - and it is in many situations - it is important not to exceed this value in order to see that the wall temperature doesn’t go above the critical value, which wall temperature doesn’t go above some safe value and doesn’t get damaged. So, that is why we have, it is important that this point be known and the value of critical heat flux be known.

So let me again repeat the types of boiling: natural convection - region 1, nucleate boiling - region 2, film boiling - region 3. Film boiling itself has 2 parts - a part in which heat flux decreases with temperature difference - transition boiling - which is region 3 a and if part later where heat flux increases with T_w minus T_s which is called as stable film boiling region 3 b. And finally we made a comment on what is the critical heat flux. Now we need to – next, what we are going to do is to look at a number of correlations. I am going to give you next a number of correlations in saturated pool boiling. We will look at correlations in natural convection, correlations in nucleate boiling correlations, in film boiling or equations derived in film boiling and solve a few problems in the next lecture.