Multiphase Flow
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Lecture No. # 33
Cycle of Bubble Growth and Departure

Good morning, everybody. Now, we will have the continuation of our earlier discussion. We were discussing the nucleation process due to the presence of heterogeneous cavities for which act as the nucleation sight.

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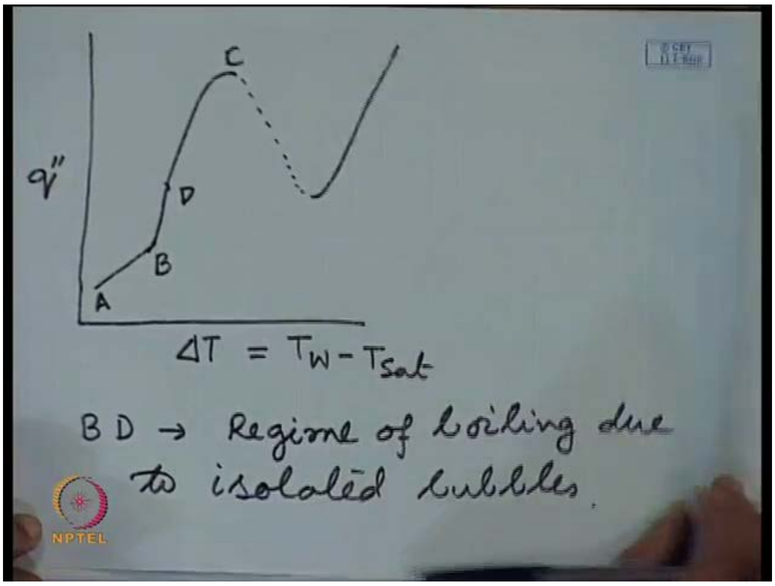

Now, we will proceed with that discussion only. Now, if you recall that sometimes back I have given you the boiling curve, the very famous pool boiling curve and if it is a heat flux controlled process, then the boiling curve will be something like this, with the transition region we will not be able to we will not be able to catch the transition region. But let us say we have got different notations; so, A to B is the a natural convection or free convection cooling due to natural convection and free convection, and B to C is the nuclear boiling curve on this particular plain, where we have got the variation of heat flux as a function of delta T which is nothing but T wall minus T saturated.

So, on the nuclear boiling curve B C we get different regimes of boiling, this also I have told. Now, the first regime which I get probably upto this point that is the regime of let us say we call it some D. So B D is the regime of boiling due to isolated bubbles.

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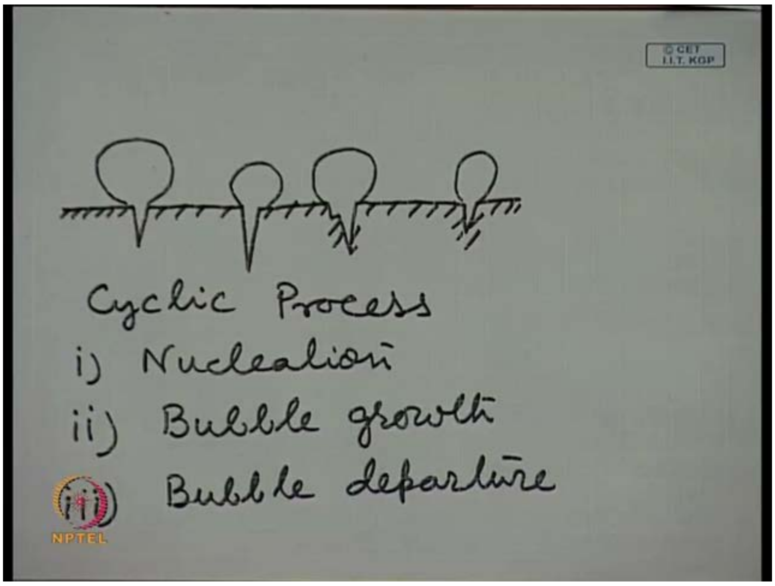

So, here if I idealize the process, let us say this is the hot surface, here we have got different kind of nucleation sites something like this and each of this sites these are actually there could be many more sites, but these are activated sites based on the operating condition.

So, on each of the sites we are having some sort of a bubble. So this is your state of isolated bubbles or boiling due to isolated bubbles; and you can understand that this is due to heterogeneous nucleation on the heater surface there are different cavities which have been activated and we are having this. Now, basically in this isolated bubble region 1 bubble is not influencing the growth or the heat transfer process of another one that is 1 of the assumptions. So, that means you can do the analysis based on what is happening to a single bubble.

So, that kind of analysis already we have done and we will proceed some more or we will discuss some more regarding the same process; that means that there is an isolated bubble which is growing and then there is heat transfer process and phase transfer process. Now, you see the one particular nucleation site if we observe or if we concentrate on a particular nucleation site then what we will see that the process is a cyclic process, it is a repetitive or cyclic process. So far, we are keeping the condition constant. So, far we are keeping the condition constant mans we are keeping the wall temperature constant. It is a dynamic process definitely, but we have kept a steady operating condition that means the wall temperature we have kept constant, the heat flux imposed to the wall that we have kept constant. If we do that then we will find that more or less a repetitive process is taking place at the mouth of a particular nucleation site. So, the process is a cyclic process.

So, what is this cyclic process? What are the components of the cyclic process? First is nucleation, then second one is bubble growth and third one is bubble departure. So, these 3 processes will take place over and over. So, once it will nucleate and then we will see a growth it is also following a pattern which we will discuss and then it will depart.

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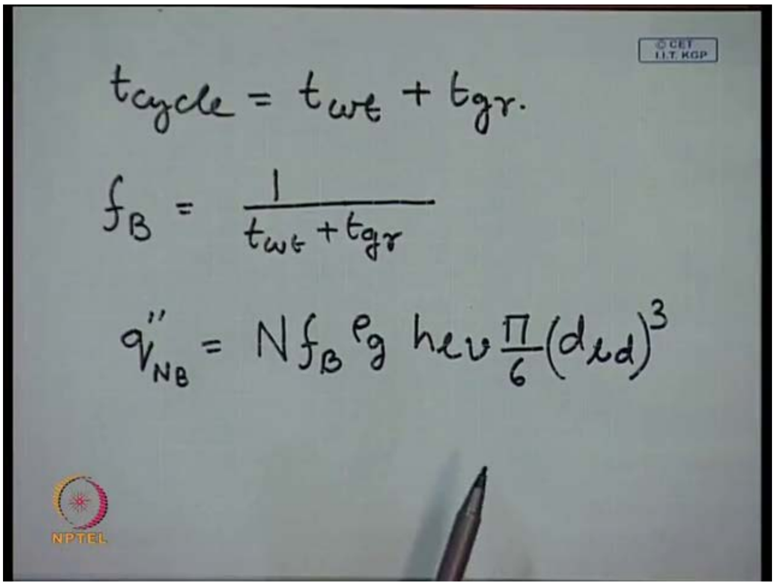

And the time involved is that time can be divided into two parts if the time we denote as t cycle then it is t waiting plus t growth. There is a waiting time which we can which we can think of or which we can call as the preparation time for the nucleation of a bubble or for the formation of a bubble. And then there is time for growth and of course, departure is instantaneous phenomena. Departure is a very important phenomena, but it is instantaneous phenomena so there is no time for departure, as it grows to a particular size then it will depart. So, this is the process which will take place. So, t w t is the waiting time and t g r is the growth time and t cycle is the total cycle time.

So, then you see we can also calculate the frequency of bubble formation. So, frequency of bubble formation if we call it f B, so that will be 1 by t w t plus t g r; so, the frequency of bubble formation also we can calculate. So, once we have calculated this or once we know this then what we can do, we can have a rough estimate of the heat transfer during nucleate boiling particularly in the isolated bubble region. So, you see the boiling curve what I have drawn this is a relationship or this is this shows the function this shows the variation of heat flux with t w minus t z.

So, these generally is determined from experiment, but suppose we want to do it theoretically at least for this part of the curve we will see for the other parts of the curve later on, but at least for this part of the curve we can determine theoretically what is the value of q double prime, what is the value of wall heat plus. How can we do it? A very simple equation can be written, for isolated bubble we can write q nucleate boiling that is equal to capital N f B rho g h l v rho g or rho b whatever you may like it pi by 6 and d b d whole cube.

So, what are the different components here? N is the nucleation site density on the surface, N is the nucleation site density on the surface, f B is the frequency already I have told that frequency of bubble formation or bubble departure, rho g or rho v I mean you can represent it by rho v also, this is the density of the vapor phase, h l v is the latent heat of vaporization and the last part that shows the volume of the particular bubble. So, you can see that dimensionally it will also give you the heat flux value which is there on the left hand side. Now, how are you going to determine all this things? rho g and h l v they are properties of the fluid, f B that is the that is the frequency of vapor bubble vapor formation or vapor bubble departure.

Now, this frequency again it depends on 2 times. One is the waiting time and one is the growth time. So, already we have got some growth model. Already we have discussed that the growth bubble growth could be either inertia controlled or it could be heat transfer control or thermal thermally controlled. So, some sort of equations we can we have already seen, some sort of analysis we have seen. So, 1 estimate of f B can be made from there. Now, d b d is the bubble volume at the it is based on the diameter at the departure. Again, I will explain how it can be estimated, but from some sort of force balance one can estimate the volume of the bubble at the departure.

Then remaining is N. N is the density of the active activated nucleation sites on the particular surface on which boiling is taking place. Now, N is the most crucial of all these components. How to estimate N because N is the surface characteristics which comes from many things, which comes from the process by which the surface has been manufactured, the contamination through which this surface has gone, that means the amount of oxidation etcetera, amount of how boiling that has taken place on the surface and of course, the number of activation site also will also depend on temperature as I have described in our last class.

So, you see that this is one of the very crucial point, which we which we do not have very straight forward method for determining though there are models. So, those are basically statistical model. So, roughly one can calculate or estimate what is the number of nucleation site on a particular surface. So, you see then this equation gives us a method a mechanistic method for estimating the heat transfer during nucleate boiling. That is why we have learnt all these things this bubbling process, what are the different growth model. So, ultimately as an engineer we have to find out the heat transfer coefficient, but the process is complex there are many more intriguing phenomena which are taking place both from the heat transfer point of view and from the fluid flow point of view.

So, what we have done we have segmented it to small parts so that each of the part can be analyzed little bit conveniently, little bit easily and then ultimately if we intimate them, if we collate them then we can find out the what transfer coefficient which is an engineering requirement. Well, I will come to other models not today may be in our next class, but at least whatever we have learnt the bubble growth and different growth process etcetera that gives us some means of calculating the heat transfer coefficient. Now, let us try to see whatever I have explained that there will be a cycle of bubble nucleation, bubble growth and departure.

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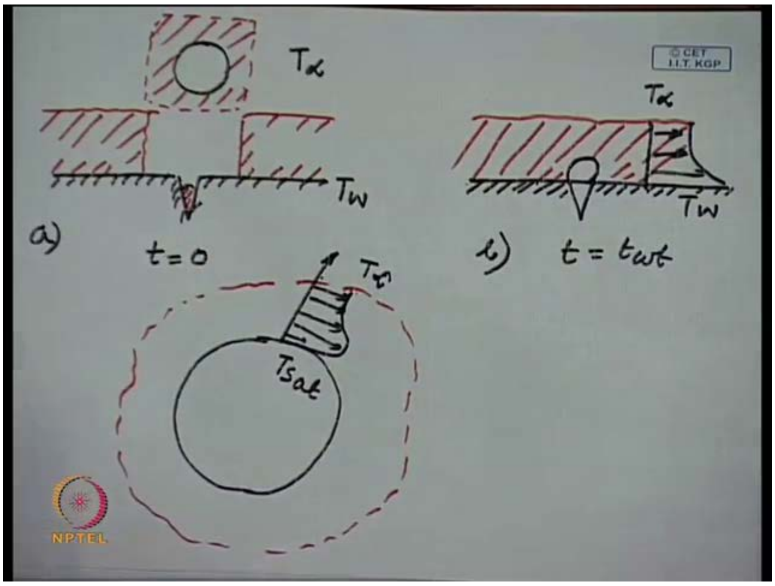

So, let us see that cycle in a little bit detail. So, let us say we start with this particular process, this is a solid surface and we have got as I have told thermal boundary layer. So, this is the heated liquid, this is the heated liquid. And what happened already a bubble have departed this surface. So, when it has departed it has taken this much amount of heated liquid along with it. So, it has taken this much amount of heated liquid along with it. So, we can tell that this is the our first phase.

Let us say this is a. Here, the temperature is t infinity, here the temperature is t wall and this temperature is higher than t infinity, this temperature is higher than t infinity and then actually at time t is equal to 0 this phenomena is occurring. What is time t is equal to 0? 1 bubble has just laid and the next cycle is starting that is called t is equal to 0. So, at this movement 2 incidents are very important. One incident is that the bubble which has laid it has the bubble which has departed it has laid a small portion which will act as nucleation for the next bubble and second thing it has taken away the liquid of the thermal boundary layer so that is why your waiting period is needed because here the liquid as is to be heated back to the temperature which was earlier there which is a higher temperature.

So, that is why a waiting period is required. So, at the end of the waiting period which is the next phase what I will what we will find is this, probably there is a very small protrusion of the bubble and then we will have this thermal boundary layer which has been punctured, by this time it has been repaired, very small protrusion of the bubble and thermal boundary layer has been repaired. And if you take the temperature profile, the temperature profile is something like this. Here it is t infinity, here it is t wall. So, this is very important at this point we are coming back again and again that the super heat is very important and if you see this particular bubble. So, let us say the way I have drawn slightly let us modify this diagram slightly.

Let us say this is this has created some sort of a jagged liquid layer over the bubble not exactly rectangular whatever I have drawn, but may be some sort some shape like this. So, suppose here I want to know how the temperature variation is along this radial line? So, it will be something like this. This is your t sat, this is your t infinity.

At least physically you have to understand the process. So, at the inter phase the temperature is the saturation temperature and the saturation temperature is lower compared to the surrounding fluid temperature here and of course, it is a boundary layer kind of a situation. So, this temperature gradually decreases and it becomes t infinity which is the bulk fluid temperature. Now, why it is necessary? If t sat has to be lower than the local fluid temperature over here otherwise there will not be any heat transfer and there will not be any bubble growth. So, the bubble growth is taking place because the inter phase temperature is smaller or is lower compared to the fluid temperature which is just outside the vapor liquid inter phase.

And then again if you move along the thermal boundary layer the temperature will reduce and ultimately it will go to the bulk fluid temperature which is t infinity. So, these are the first 2 phases. Here, I can write t is equal to t w t so this is at the end of the waiting period. So, this is at the beginning of the waiting period, this is at the end of the waiting period. So, after the waiting period the growth period comes.

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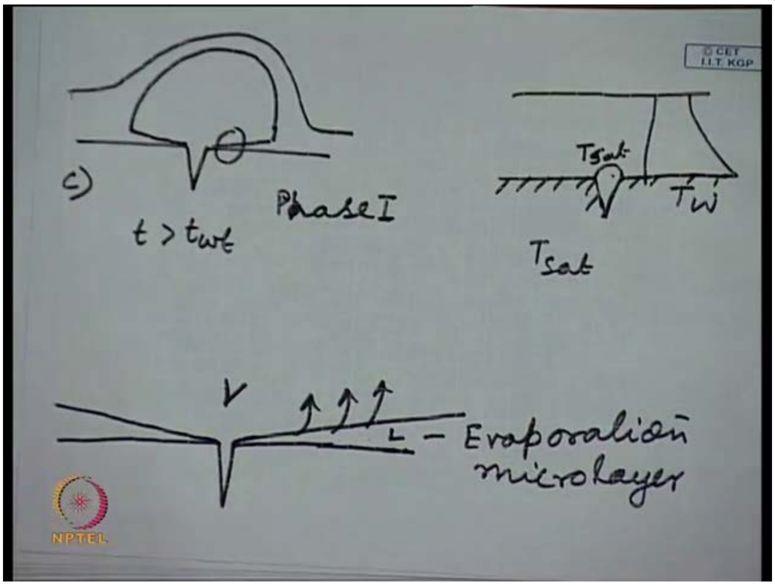

So, the growth period if I see it has got 2 phases. So, here of course, t is greater than t waiting, but this is phase 1. So, in the phase 1 the growth is inertia controlled and here what we will find the here we will find that the vapor bubble will go almost hemi spherically, it will grow almost hemi spherically. So, this as usual we were pointing out so these may be termed as c. So, a was at the beginning of the waiting period, b was just the waiting period is over and c that the initial growth that is phase 1 it is beyond the waiting period. In this period the bubble growth, the bubble shape is hemi spherical shape.

Now, let us try to understand now we know the temperature etcetera let us try to understand what is inertia controlled growth though we have done the mathematics etcetera, but once again let us try to see. See, initially when the bubble forms the bubble forms inside the thermal boundary layer. So, this is the thermal boundary layer; t wall that is the highest temperature anywhere we are considering, anywhere we are considering the phenomena t wall is the highest temperature.

And we are having the bulk temperature which is lower. Here, we are having t sat. So, t sat is the saturation temperature corresponding to the existing pressure. Now, as the t wall is very high here also temperature is very high. So, what we can find that there is a large temperature gradient. t sat is really low compared to the surface rounding fluid temperature. So, due to this high gradient what will happen? There will be large amount of heat transfer.

The vapor growth will be or the bubble growth will be fast and this we have learnt earlier that inertial control I mean regime the bubble growth is faster. Why it is inertial controlled? Because as the heat transfer is very fast heat transfer is not putting any sort of limitation to its growth, to the bubble growth heat transfer is not putting any limitation. Limitation is only put how fast the gas can expand and the interphase can move apart so that the bubble can become bigger. So, that is why it is called a inertial control. Heat transfer is really helping so at this time heat transfer is not opposing and we will have a faster growth, but the bubble shape will be kind of mass room shape or hemi spherical shape. The way I have shown.

Let me draw it in a bit detail manner. If I take so basically if I draw it in an exaggerated manner so you will get some sort of liquid over here and this is your vapor. So, basically then you are having you can imagine that you are getting some sort of (( )) kind of a shape and this is called evaporation micro layer. So, there are many models that they model this micro layer and now the bubble growth is mainly due to evaporation from this micro layer. This is a micro layer so there will be evaporation from this micro layer and you can understand that it is very thin actually where it comes close to this nucleation site, it is in the molecular level. So, many people had modeled it, mechanistic modeling is there. Even now a days people are doing c f d modeling. So, people argue that a single scale for modeling is not sufficient probably very near this vapor stem, this is the vapor stem.

One has to go for some sort of molecular scale modeling then some sort of intermediate scale modeling and then one should go for some macro scale modeling, then only this process can be modeled because here it is very thin in the molecular level.

Now, what you can understand that if it is very thin of course, even in the microscopic sorry macroscopic level also it is very thin then the heat transfer will be by conduction. By conduction analysis one can catch what is the amount of heat transfer. Now, if there is only conduction. Conduction is the pre dominant method of heat transfer then there is no we are assuming that there is no fluid flow. So, fluid is also not replenishing whatever evaporation. So, from this surface evaporation is taking place. Now, it is not being replenished because we do not have much flow, much liquid flow we do not have, this is a very thin region.

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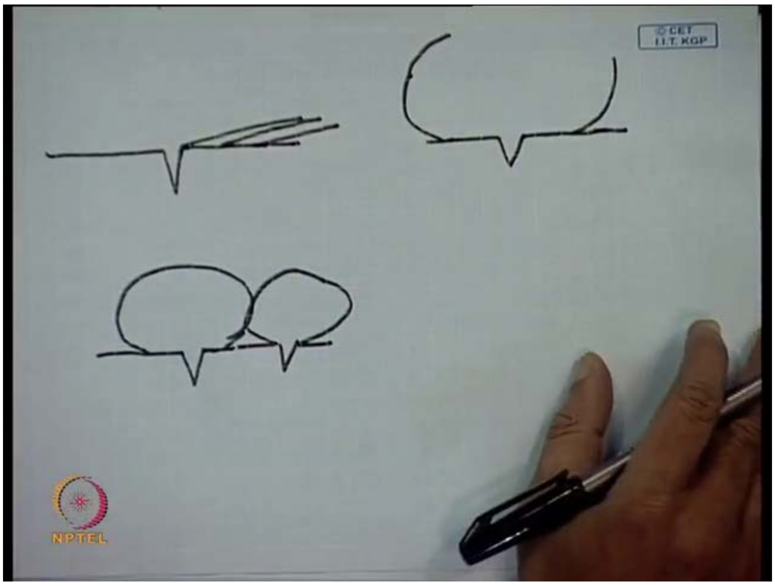

So, what will happen depending on the operating condition the initially my micro layer have started from here then some sort of dry out will take place, then some sort of dry out will take place. So, that means after some time your dried zone could be like this. Now, it will depend on the operating condition and let us say that very close to this there is another bubble. So, then this 2 bubble can (( )) and intermediate range intermediate sorry intermediate area can be totally dried up that means here there is 1 bubble and very close to this there is another bubble.

So, they will they will intermingle together to form a bigger bubble and the entire place will be dried below these 2 vapor mass flow. So, depending on the operating condition, depending on the situation of heat flux, wall temperature etcetera; so you see how we are going from the isolated bubble region to this (( )) region or to the columnar bubble region. Now, it will make not a vapor bubble, but a column and ultimately if this process continues then it will go to critical heat flux type of condition.

Ok, that we will discuss late on. So, but what we have understood that at the first stage of growth we will have inertial controlled growth. Why inertial controlled growth? Because heat transfer is quite high at the fast range.

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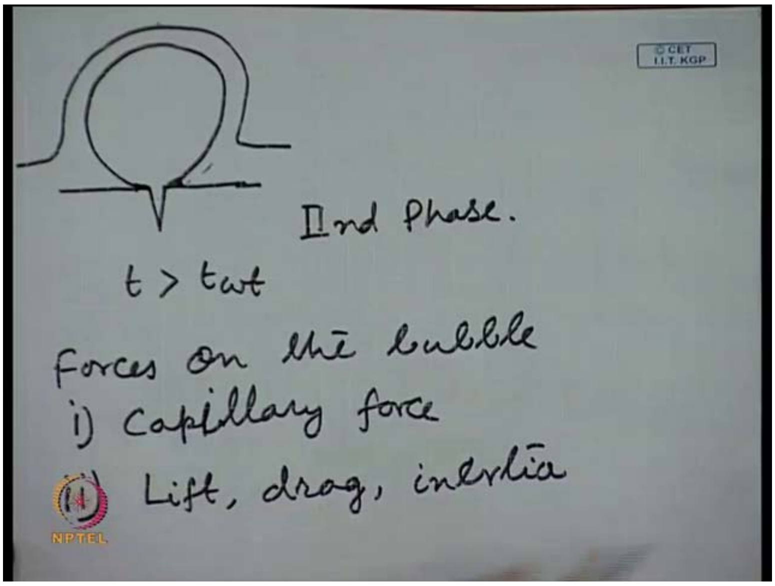

Then if we go to the second stage of growth we will have something like this. So, here already what has happened already what has happened that this is also t greater than t waiting period, but second phase. Already, what has happened the temperature in this vicinity of this bubble that is not very high, that is higher that the saturation temperature, but that is not very high.

So, as that is not very high then the heat transfer now it has become slower. Evaporation has also become slower. Now, this bubble growth is not inertial controlled, it is heat transferred and another thing also you can see the bubble has I have represented the bubble as a spherical bubble. Why I have represented the bubble as spherical bubble? Because now from the lower side heat transfer has really reduced. Now, more or less uniformly heat transfer is there all over the periphery. So, the bubble has become some sort of a spherical bubble, but one thing you have to remember these are all ideal discussion based on some ideal model. In actual practice you will get something in between.

So, this has become the spherical bubble. Now, the forces which are acting on the bubble 1 is your capillary force and 2 all the other forces I am clubbing together, there could be lift, there could be drag, there could be inertia. So, generally what happens that capillary force tries to attach or keep the bubble fixed to the surface, capillary force acts over here and it tries to fix the bubble along with the surface. And the other forces generally tries to push the bubble away from the surface. Generally, capillary force is larger or rather relatively larger when the bubble is small and when the bubble is large the other forces that that start dominating. So, as the bubble grows so what will happen? The other forces will dominate and at one time the bubble will depart.

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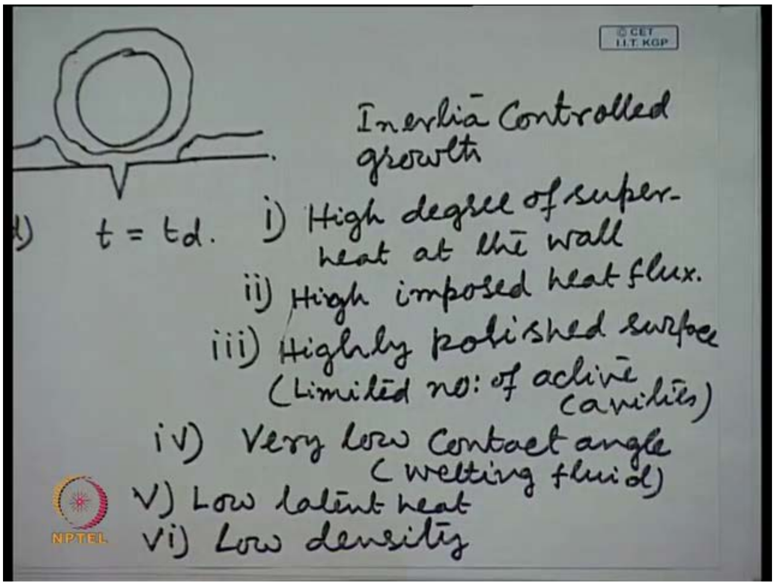

So, the bubble departure is the next phase we can have a schematic view of that. This bubble is departing so probably it will have some sort of a liquid surrounding this. So, this is your d, t at t d at departure so bubble will departure. So, this will complete cycle and this cycle will continue. Now, as I have described I have told that these are based on some idealization. So, as I have described ideally I have told that it is inertia controlled and then it will be controlled by the heat transfer process, but actually it need not be show I mean depending on the working condition either it can be inertia controlled or it can be controlled by the heat transfer process.

Or in other words inertial controlled process could be very small, the mainly the bubble growth is dependent on the heat transfer control process. Now, if we see if we list down the parameters which are responsible for bubble growth and when we can have inertial control growth these are like this. Inertial controlled growth, first it needs high degree of supper heat at the wall that means high wall temperature. Second, it needs high imposed heat flux, high imposed heat flux. Third, it needs highly polished surface that means limited number of active cavities, limited number of active cavities.

Then very low contact angle. So, what does it mean? Very low contact angle means it is having waiting fluid, fluid is highly waiting fluid. Then low latent heat and then low density. So, if these factors are there then we will have inertial controlled growth, means suppose we want to use a particular model for some sort of design calculation are not or some such thing then should we go for inertia control growth or should we go for temperature sorry heat transfer control growth. So, if we if we decide that we will adopt only 1 model then probably these things we have to check. Now, you see it is very easy to explain why it will be inertial controlled when this kind of operating condition are there high degree of super heat.

So, high degree of super heat means the wall temperature is very high, the surrounding liquid temperature will be very high. So, heat transfer will be predominant, high imposed heat flux is also the same thing, highly polished surface what it will give? That means it is giving limited number of active cavities. So very near I mean close to one cavity there is no other cavity. So, one cavity means one vapor bubble. So, only 1 vapor bubble is there and then far apart there are other vapor bubbles. So, the particular vapor bubble is surrounded by a very large mass of heated liquid.

So, the growth will not be controlled by the heat transfer. It will have enough supply of thermal energy. Very low contact angle is also the same implication is also having the same implication and the last 2 the low latent heat and low density that means the vapor generation is much easier. So, vapor growth will be much faster. Now, first four points give a high degree of super heat during the waiting period and second point second sorry the last 2 points give a faster growth of vapor bubble. So, if there is a combination of these two then we will have inertia controlled growth.

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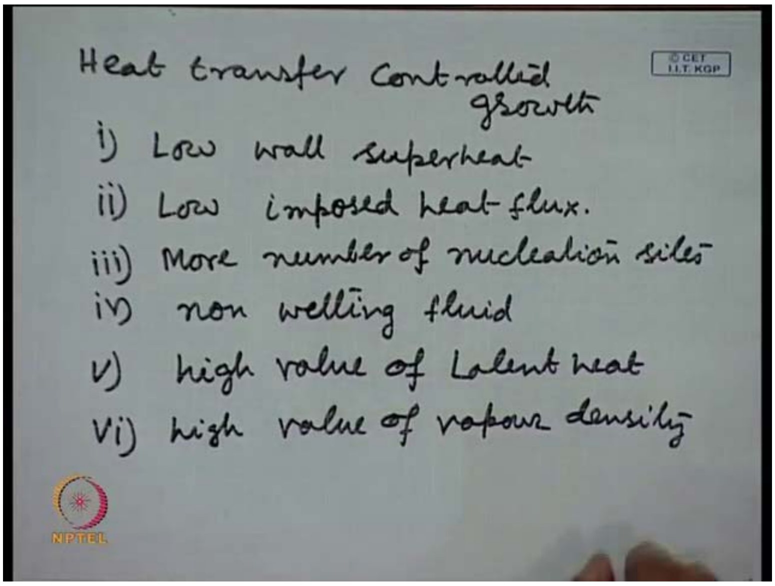

The reverse is true for your heat transfer controlled growth. So, we can quickly write the condition. We can quickly write the condition, it will be low degree of super heat or low wall super heat, low imposed heat flux, more number of nucleation sites, non waiting fluid, then you will have high value of latent heat, this will slow down the process of growth and then high value of vapor density. So, these are the factors by which we will decide that whether we will go for heat transfer controlled growth or not. Now, let us see some more equations which can be utilized for the analysis of this process.

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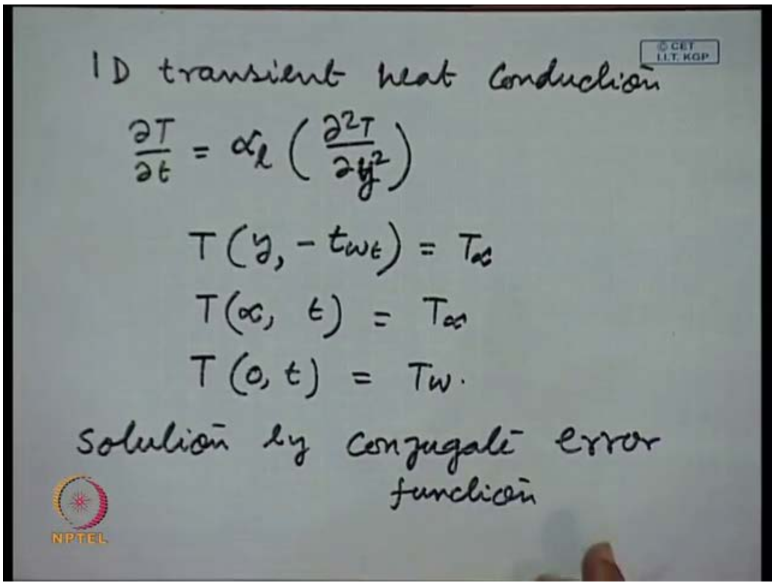

Now, let us come to the heat transfer controlled growth. So, as I have told heat transfer controlled growth or the heat transfer process we are we are analyzing considering 1 dimensional transient heat conduction. So, 1 D transient heat conduction, we had we are having d T d t is equal to this is thermal sorry thermal diffuser of the liquid d 2 T d t 2. Now, the analysis what has been done I mean already we have written the equation and shown you the boundary conditions earlier, but slightly in a different way the boundary conditions have been written here, what has been assumed which one? Please del T 2 by oh del yes y or y direction we have taken along the direction of this one; thermal boundary layer away from the one. Thank you.

Now, as I have told that we have done it earlier, but slightly different boundary conditions we are going to take. See, what it is assumed that the time count starts from the growth of the bubble, time count starts from the growth of the bubble.

So, what we can write that T y this is actually time, this is equal to T infinity and T at infinity that means beyond your thermal boundary layer at any time this is also T infinity and T at the wall at any time that is T wall. So, same boundary condition we are putting only here it is important because from where we are from which instant we are counting time. The solution can be obtained, this is classical solution; solution by conjugate error function.

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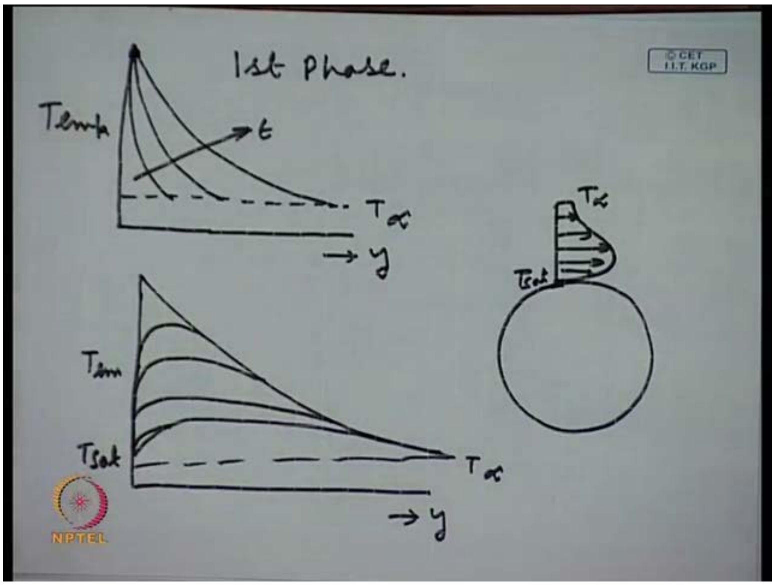

So, this solution we can get by conjugate error function. First instead of writing the conjugate error function, let us show that during the two phases what will be the temperature profile. This direction is the y direction and this is your temperature as a function of this. So, the solution will be something like this. This is your T infinity if you like to put it and this side your time integers. So, this is for the first phase, already this type of diagram I have shown earlier. In the second phase or what we can tell that this also holds good for waiting period when we are repairing the thermal boundary layer.

In the second phase or in the growth phase particularly when it is heat transfer controlled, so one what we will get we have started from this curve, this is your temperature, with time we will get something like this, this is your t infinity basically. And this says actually all the curves are starting from some sort of a value here which is T sat. What I am drawing here is the boundary layer T sat, then it is increasing and then it is going to the T infinity. So, this is your T sat. Now, as it is transient conduction. So, this is not a stationary picture, this picture will change and that is what has been shown in the diagram below.

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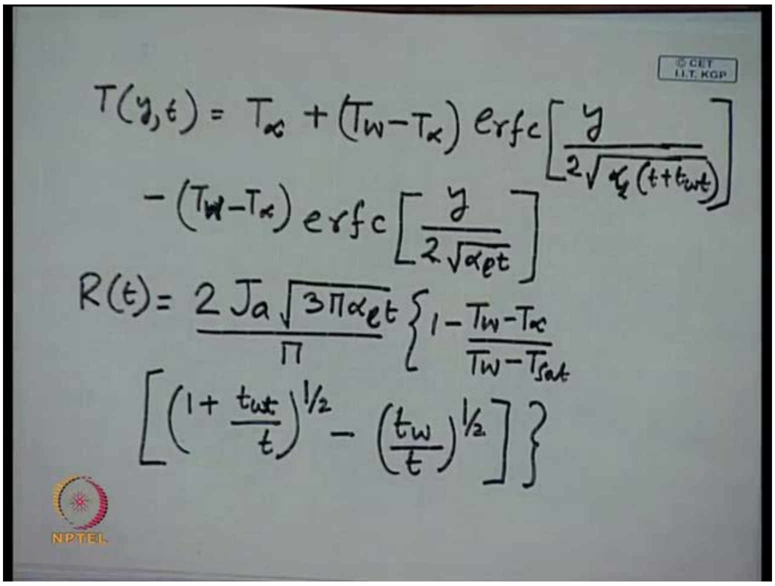

So, mathematically what you will get is this. T y t is equal to T infinity, anywhere temperature will be more than T infinity within the thermal boundary layer, T w minus T infinity, conjugate error function e r f c alpha l t plus t waiting minus T infinity minus sorry T w minus T infinity conjugate error function. So, by this particular expression we will get the variation of temperature with respect to time and the direction y. Alright, now actually what can be done with this equation one can do little bit more simplification and then what one can do, one can also predict how the radius of the bubble that is growing. From the vaporization rate what can be predicted from the temperature equation, this is the temperature equation what we have got.

So, if this temperature equation we know then what we can predict? We can predict what is the temperature gradient k into temperature gradient that will give you the heat flux at the bubble inter phase and if that heat flux is related to the phase transfer then we can get at what rate the bubble radius is increasing. So, doing all these things one can get the expression for the bubble radius as a function of time. That is what I am going to write, that will be a function of jakob number which is which I have already defined.

So, all sorts of temperatures are important here that means wall temperature, saturation temperature and the bulk liquid temperature and with this the times are also important. This is the waiting time by the time at which we are interested to know the bubble radius. So, by this then we will get what is the radius of the bubble. How does the radius of the bubble changes with time. Now, here one can make 1 assumption, the suppose I want to estimate the waiting period.

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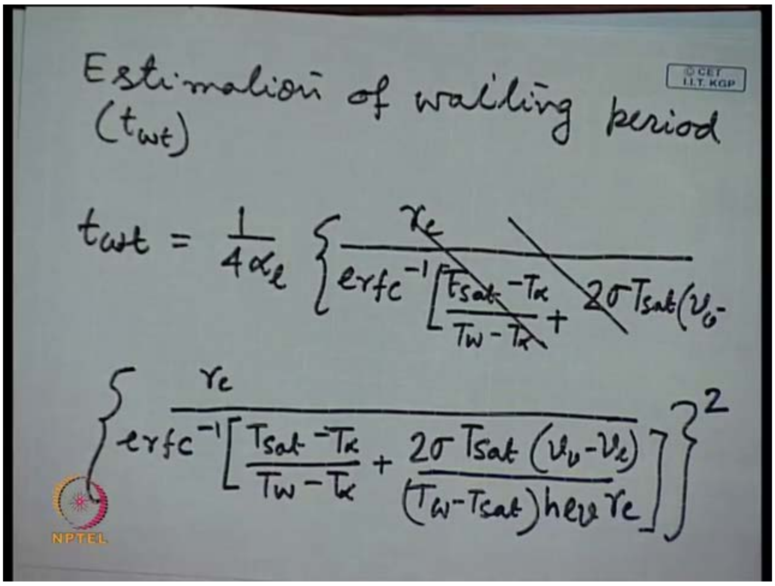

So, estimation of waiting period; so, basically this is t w t. I want to estimate the waiting period. How I am going to estimate the waiting period? Now, the temperature that will exceed the equilibrium super heat for the bubble, then our growth will begin. Bubble growth will begin when the temperature exceeds the equilibrium super heat temperature. And from where the growth will begin? Growth will begin from a vapor nucleus which is there on a cavity of radius r c. So, you see two things are important here.

For a particular cavity that cavity radius r c is important and also the equilibrium super heat temperature that is important. Now, earlier whatever relationship we have got taking a particular r c value if we want to manipulate this equation then we can find out the waiting time. So, waiting time we can write like this t w t that is equal to 1 by 4 alpha l r c waiting time will be different for different cavity radius, this is temperature T sat minus T infinity by T wall minus T infinity plus 2 sigma T sat v v minus I think I have to write this part separately otherwise it will not be clear. So, let me write it under the.

So, basically this part will be r c divided by e r f c conjugate error function T saturated minus T infinity, T wall minus T infinity plus 2 sigma T saturated v v minus v l by h l v and r c. So, basically this will be within bracket and this is there is a square. So, this is how we will get the waiting time. Now, it is a very t d s way of matching these 2 equations and then to find out the waiting period, but one can get the waiting period by this particular equation. There could be a simplified equation for waiting period also.

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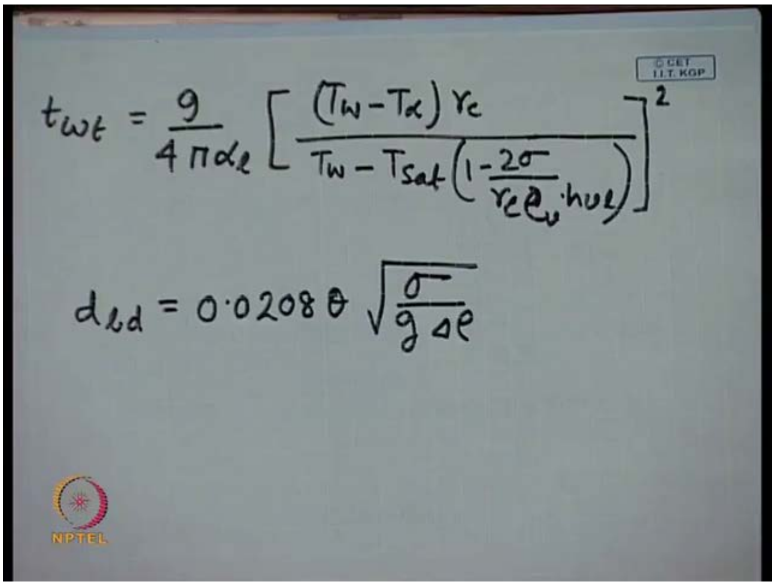

Let me write this; I think you will be more comfortable with the simplified equation that is 9 by 4 pi alpha l T w minus T infinity r c rho v h b l. So, some simplification of the above equation, earlier equation we will give you this simplified relationship or waiting period. So, waiting period also we could get some sort of a equation. Then another equation I like to give quickly so that we can complete today’s discussion. The bubble departure at bubble departure what is the diameter of the bubble departure? So, if I denote it by d subscript b d then they are again number of formula, but 1 formula very simple formula if I give, here theta is in degree, this is some sort of a empirical formula not totally mechanistic derivation. So, here it is theta is in degree.

So, that means in by today’s discussion what we have got some analysis which can give us the waiting time by which we can also calculate the growth time, departure diameter. So, ultimately the first discussion which we have started that we can we can we can estimate the heat transfer during nuclear boiling so using these calculation we can try to do that. At least approximately we can try to do that that in isolated bubble region we can calculate what is the heat transfer coefficient or what is the heat flux during nucleate boiling. Thank you.