Multiphase Flow
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Lecture No. # 32
Ibullition from Hot Surfaces

Good morning everybody. So, we will continue with our previous topic and we will; today, what we will do can be termed as ibullition from hot surfaces.…

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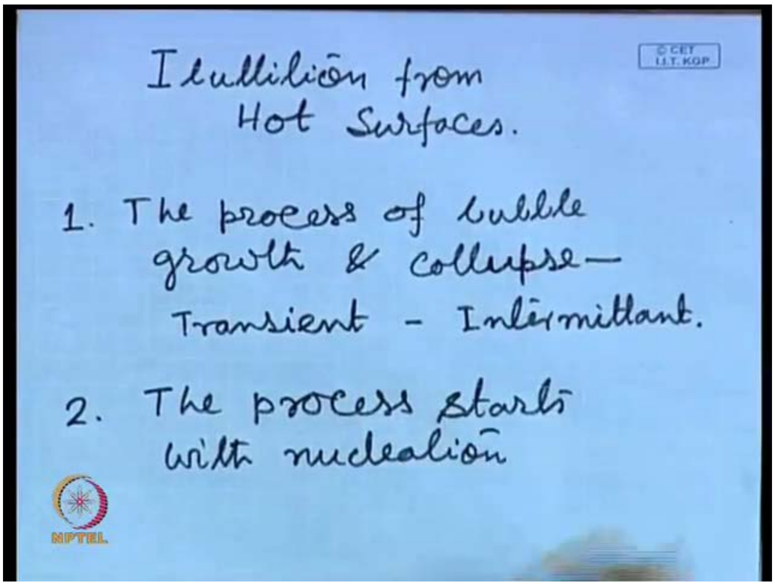

Now, as we have seen that, in case of boiling heat transfer, heterogeneous nucleation is very important, because most of the practical; in most of the practical situation, we have got heterogeneous nucleation and that is from a surface, which is being heated.

So, basically from that hot surface, the heat is being transferred to the liquid and the mechanism is predominantly evaporation. Now, in the solid surface, as I have told that there are number of peats and cavities; on these peats and cavities, some vapour nucleus that is formed and that grows as the as the bubble embryo; embryo bubble and then it becomes bigger and bigger.

Now obviously, a bubble which becomes bigger and bigger, that cannot go go on growing continuously infinitely it cannot grow. So, it has to grow come up to certain size and then it will leave the surface. Then again, a new bubble will grow. So, this cycle is known as ibullition. So, ibullition what we going to study today is, this cycle.

Now you see, the first thing which we have to remember is that, the process of bubble growth and collapse, that is transient. Obviously, there is a change with time and also this process is intermittent. So, this process is intermittent.

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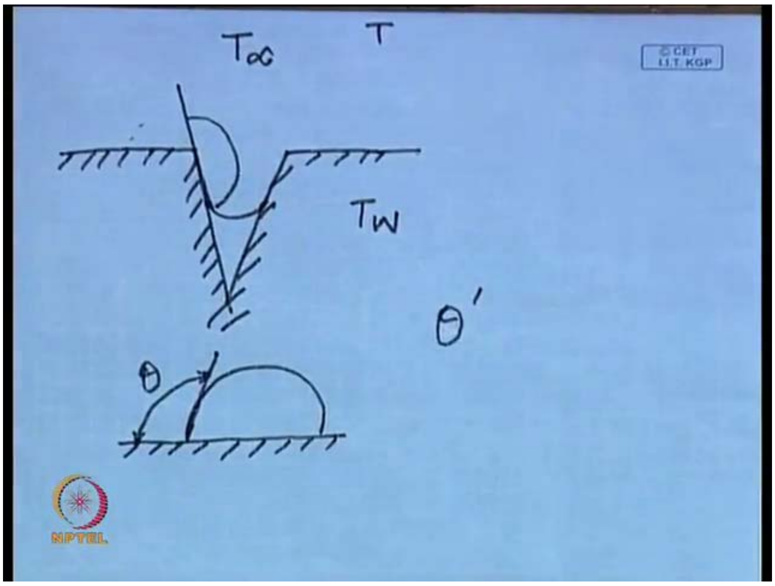

And then it start with; it starts with nucleation; process starts with nucleation. So, in this connection, in our last class we have described the heterogeneous nucleation and we have shown or discussed that, the cavities in a solid surface that can be idealized as a conical hole. So, this is some sort of a conical hole. And this has got a temperature T wall. This hole, though I have shown it in a exaggerated manner, but it is very small and it is embedded in the solid surface itself, whose temperature is T wall. And somewhere away from the wall, we have got a temperature of the fluid that is equal to T infinity, away from the wall.

Now here, as I have told that these pores, they may have some amount of vapor in it or they may have some amount of permanent gas. So, initially we will have a; we will have some meniscus over here like this and one can see this is the angle. So, this is the angle one can see.

Now, what happens, on a flat surface when boiling is taking place, we can have some sort of a contact angle or for that matter; on the flat surface, if there is a bubble, we can have a contact angle and that contact angle is called theta. So, this can have some sort of a contact angle and that contact angle can be called as theta or can be termed as theta.

In these, what is happening that, we can measure the contact angle; the way I have shown or we can measure the contact angle with respect to the flat surface itself. So, if we measure the contact angle with respect to the flat surface, then we call this angle or then we refer this angle, as theta dash and theta dash is called the appearent contact angle.

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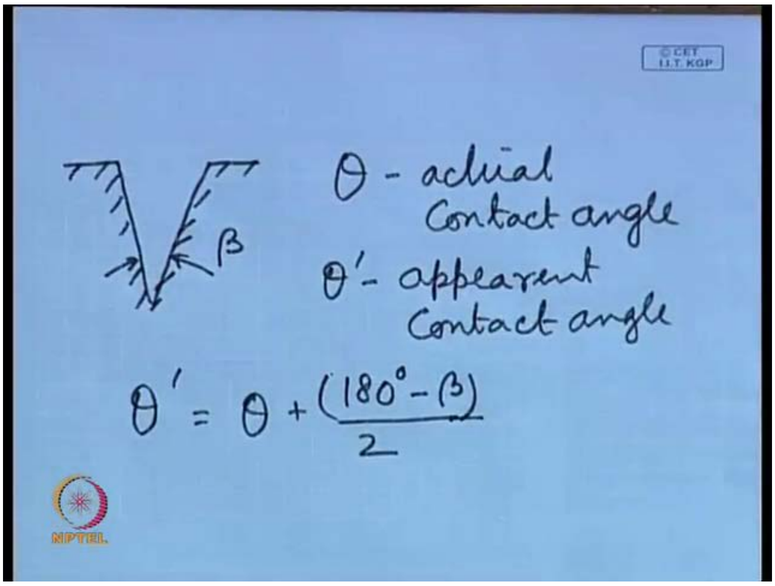

So theta dash, if we do little bit of analysis, suppose this is our cavity, which is having an included angle of beta; this cavity is having an included angle of beta. And let us say the; for this solid liquid pair, the actual contact angle is theta. So, theta is the actual contact angle, then we have got theta dash, that is the appearent contact angle. So obviously, theta and theta dash, they are related through beta. The relationship will be, theta dash is equal to theta plus 180 degree minus beta by 2, all the angles are measured in degree.

Now you see, this relationship, it gives a very unique situation; it can give rise to a very unique situation that, sometimes this theta dash can be even more than 180 degree. Depending on the value of beta, the theta dash could be more than 180 degree and smaller the value of theta; smaller the value of beta, that is the included angle of the conical pore, the possibility of theta dash becoming more than eight 180 degree that increases

In other words, one can tell that apparet appearent contact angle will increase, as the included angle of the conical pore that decreases. So, what does it give, that if theta dash become more than 180 degree, then what does it give.

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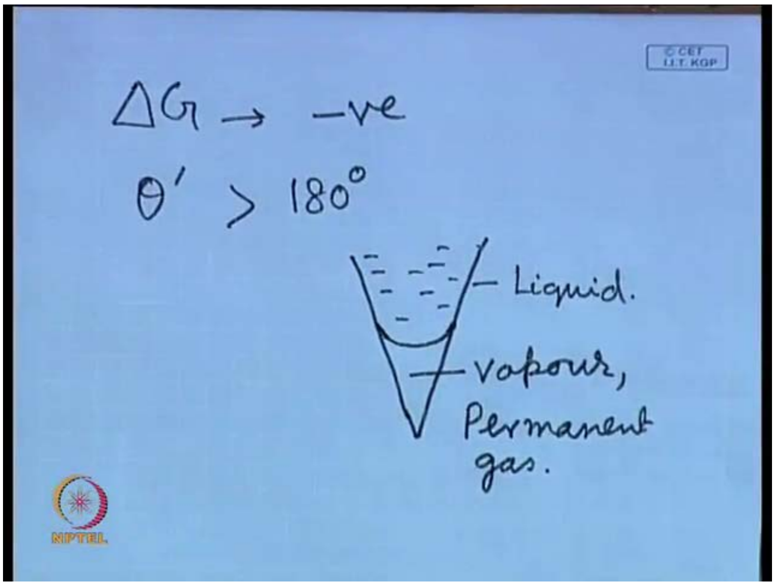

So, this is giving a very unique situation. So, if theta dash become more than 180 degree, then we get; we have told that, delta G is the energy required for a vapour nucleus or a bubble nucleus to form. Now, delta G will become negative, if theta dash becomes greater than 180 degree, physically what does it mean; physically it means that, even without any degree of super heat; even when the liquid is not saturated a negative super heat, there could be formation of vapor bubble.

Now, actual situation is not shown, there is another physical interpretation that, suppose we have got this kind of an inter phase. The the theta dash is becoming 180 degree, that can be related to the; here, we have got vapour or you can have permanent gas or you can have a mixture and here you are having liquid. So, here you were having liquid.

So it also means, the liquid pressure is more than the pressure of the permanent gas or the mixture of vapor and permanent gas. So, physical meaning one can get, but really will there be any evaporation, if there is theta dash greater than 180 degree. So, that we have to see. And for that, we have to analyze or closely observe the process of vapour nucleation; vapor nucleation act, a particular site of; at a particular site of nucleation or at a particular pore site.

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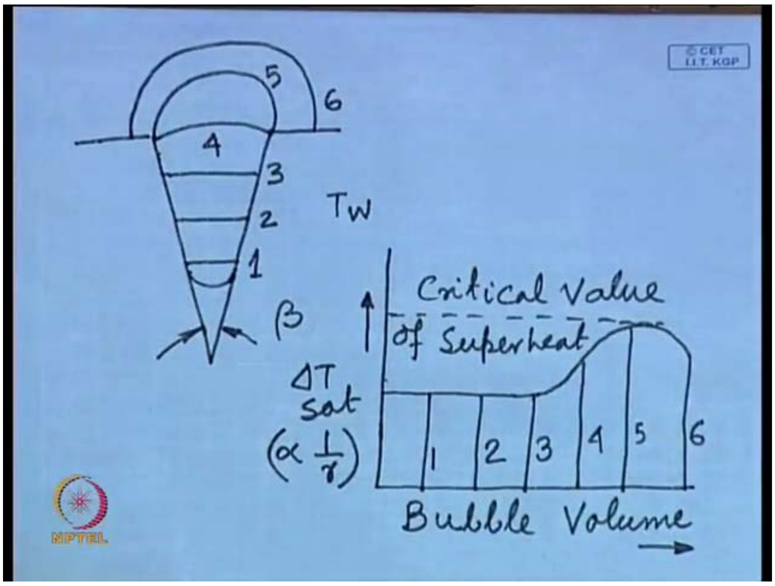

Now, there may be several possibilities, let us examine the possibilities one by one. See, as I have told, some amount of vapor or gas or a mix mixture of vapour and gas, that is interrupt over here and this angle is beta. Now, if this angle beta is very small; very very small, then what will happen, whatever gas or vapour, that is interrupt. And for the vaporization process, we need some amount of heating, so that gas or vapour may diffuse in the crack or in the pore itself; as the temperature is increasing, the diffusion coefficient will also increase and then then the small amount of vapour or gas that may also diffuse. Then what will happen, it will not act as the nucleation sight.

Now, other thing can happen, suppose we have got initial inter phase like this; meniscus like this. So, these will due to heat transfer; this will grow, this can grow by different process, the gas can expand or there could be additional evaporation, the volume is increasing. So, this meniscul meniscus will go off and on.

So, what one can have; one can have, this is location 1; this is location 2; this we can have a location 3; something like that very close, 3; then, one can have something like that, 4; one can have 5, this is 4, this is 5 and also in some cases, it can come out of the vapour cavity, the surface cavity and this we represent as 6. And (( )) when we are doing this, how we are getting this, we are getting this with the increase of temperature; with the increase of temperature means, which temperature is increasing, the solid wall temperature is increasing. Liquid temperature is more or less kept constant. So, if the liquid temperature is more or less kept constant at solid wall temperature, that is increasing. So, what will happen, in an in an essence, the degree of super heat, that is going on increasing.

So, if I make a plot, I will have this kind of a phenomena. This side is bubble volume, which is going on increasing. So, really it cannot be called a bubble volume, but it is the volume of the bubble embryo. So, this is going on increasing and then delta T sat, which is proportional to 1 by r, that is plotted in the; or that is in the other coordinate. So, what we will have; we will have a figure like this. So, 1 there is no change of angle; 2 also, that is the plot inter phase, there is no change of angle; probably 3 is very close to 4, there is a change of angle, slight change of angle, then we have got 4, then we have got 5 and then we have got 6.

So, 1, 2, 3, 4, 5, 6. So, these are; at different position, how there is a change in the radius of curvature, 1 by r, actually it is the radius of curvature. How there is a change in bubble volume and what is the corresponding delta T sat, that we are getting from this particular curve. Now, here we can see that, the curve has got a peak. So, this value is called critical value of super heat. So, basically this is good enough, for the bubble to grow further and ultimately, this is good enough, for the bubble to leave the pore or the cavity.

So this is what, we will have in the actual practice of boiling. So you see, though the included angle beta is important, another important thing is coming, which is the radius at the mouth of the bubble. Because, you see, it is connected to the bubble volume high, which is just at the mouth of the pore and it has got this bubble radius; it has got some sort of a relationship with the radius of the pore mouth.

So, people have done lot of mathematics. So, you will not go into this, but let us keep our physics clear that, when a bubble nucleation will takes place from this pore, this included angle is important and at the same time, the radius of the bubble mouth, that is also important.

Now, with this additional thing which is just an extension of our; of the previous topics which we have learnt. So, now, we go go to the ibolition ibulliton cycle of a bubble.

Now, ibullition cycle of a bubble that means, the cycle of bubble growth and bubble collapse. As I have already told you that, it means the growth and collapse of a bubble. Now, it has got separate; I mean different stages. Now, different stages, if we see, we have to make some sort of idealization and based on this idealization, we will make a phenomenal phenomenological picture of what is happening at a hot surface.

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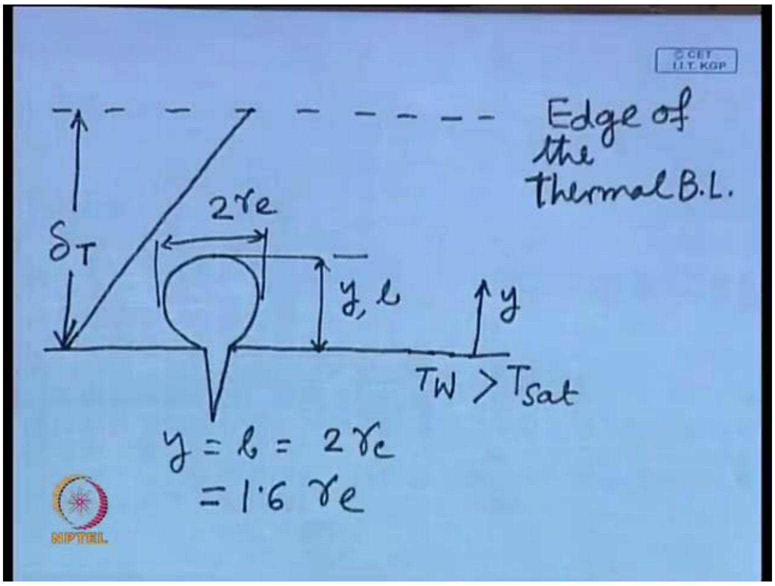

So, what is happening at a hot surface is like this. At the hot surface, let us say, the surface is kept at a temperature T wall, which is greater than T saturated. Unless this condition is made, we will not have boiling. Now, the dotted line what I have drawn, though one may think that, the bulk of the liquid will be at saturation temperature, but very near the wall; as the wall temperature is higher than the saturation temperature, it could be substantially higher (( ))

So, very near the wall, the there is some sort of a temperature continuity between the solid phase and liquid phase. So, we will have the liquid layer at a temperature more than the saturation temperature. Basically, we will have a thermal boundary layer. So, the broken line, whatever I have drawn, that is called edge of the thermal boundary layer; edge of the thermal boundary layer, we are getting. And again, to keep things simple, what has been done that, it has been assumed that the temperature changes here linear. And this one, we can represent by delta T, that is the thickness of the thermal boundary layer.

So, basically we have got our y code in it; in this degree direction. Now, now if I see different dimensions of the bubble, we have got y here; from the top of the bubble. And then, we have got 2 r e or sub e. So, what we are calling this, not as a full, fully fully formed bubble; fully developed bubble, but it is some sort of bubble embryo. So, to mention that, it is embryo, this suffix e has been brought here. So, 2 r e is the bubble diameter or the diameter of the bubble, where it is, I mean where we gave taken the diameter, where it is the largest; it is having the largest value.

So here, two; three parameters are important, this is also denoted; this is also denoted by people as b, the height of the bubble; that is also denoted as b. So, y is equal to b, that is equal to approximately twice r c. What is r c? r c is the cavity radius at the mouth of the cavity. And, by some analysis and observation, people have also got it, as equal to 1.6 r e, where e is the radius of the bubble embryo.

So, this is the picture which we want to have, before we go further for analyzing this particular situation physically and then some amount of mathematics we want to discuss, in connection with this bubble nucleation process.

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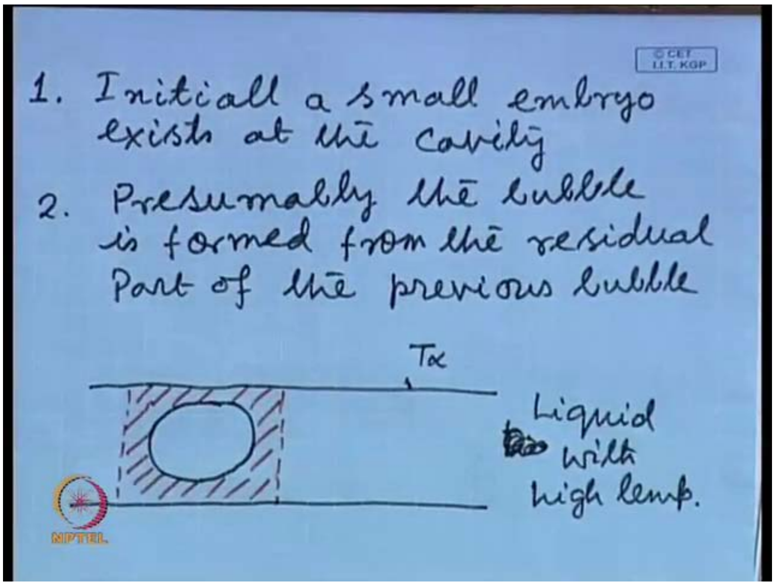

So, if we see these tapes, by which the phenomena is occurring. Initially, a small embryo exists at the cavity, initially this will exists at the cavity. And as I have again talked earlier, this embryo could be; this embryo could be vapour, this embryo could be a mixture of vapour plus the permanent gas. Basically, what people have argued and also seen by from experiments, it is like this; that, presence of permanent gas is very very important. And for the creation of the vapour nucleus, at least a few molecule of the permanent gas is needed initially.

So, the bubble is presumably formed, how it is formed. So, presumably the bubble is formed… from the residual part of the previous bubble. So this is how, this bubble is formed. So initially, there was or previously, there was another bubble. So, from the residual part of this this vapour nucleus or the bubble is formed. The Now, what I have assumed; I have assumed that, the wall is covered with; here it is T infinity, here we have got liquid; we have got liquid with high temperature. Now, when a bubble will leave this surface, so what will happen, let us say this bubble is living this surface. So, when this bubble leave this surface, along with it, it will also take the heated up liquid.

So let us say, this is a particular cell, when the bubble is living, so it is not living without any liquid, it is taking this cell along with it. So, this is also another assumption, which is made that, when this bubble leaves, it will leave with certain amount of liquid surrounding this and this is a common phenomena, it will happen.

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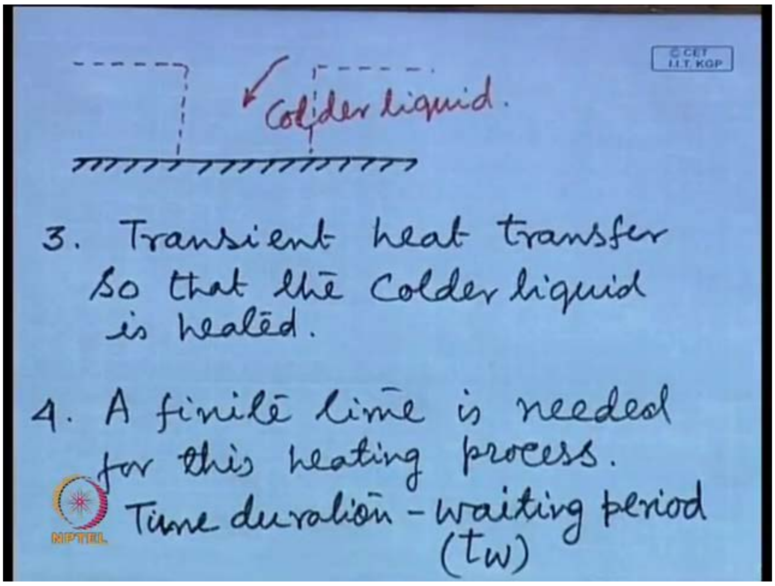

Now, if it leaves then, with some surrounding liquid, then a very simplified mechanical or mechanistic representation of the process will be something. So, this is the hot surface, up to these we have got heated liquid; up to this we have got heated liquid, this place cannot remain back end, so this will be filled up by colder liquid; so this will be filled up by colder liquid. By surrounding colder liquid or from the top, the colder liquid will come and fill up this place. This is a very very simplistic representation of the process.

Now again, if a bubble has to grow, then what will happen, this place has to be filled up or this place, the liquid has to gain a higher temperature. Otherwise, the bubble growth will not take place. So now, up to second stage I have written, third stage will be transient heat transfer.… so that, the colder liquid is heated. So, there will be transient heat transfer and the colder liquid will be heated.

Now, so for this heating process, what will happen, a finite time will will be needed. So, a finite time is needed for this heating process; for this heating process, a finite time is needed. Because, it is a heat transfer process, it is some sort of a transport phenomena, instantaneously it cannot take place.

Now, this time duration is known as waiting period; so this time duration is known as waiting period. So, in the ibullition cycle or bubble growth cycle, the first time duration what we get is known as the waiting period and people have also estimated, what is the time needed for this waiting period. So, this is denoted by T w, this waiting period is also denoted by T w.

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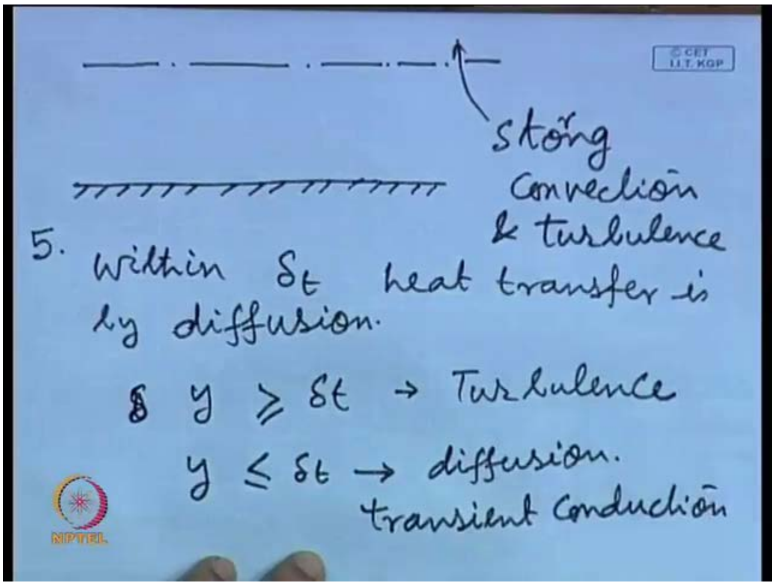

Another postulation is made; another postulation what is made. Next point that, this is the edge of the boundary layer; above this, there could be strong convection and turbulence. But, within the thermal boundary layer, the heat transfer within delta t, heat transfer is by diffusion, molecular diffusion. So, this is also another postulation which has been made that, within the thermal boundary layer, the process is by molecular diffusion.

So basically, then we are having two region, when delta is; y is greater than equal to delta t, so we have got the effect of turbulence, y less than equal to delta t, we have got molecular diffusion, transient conduction is the attribute of that. Now, we can proceed for some sort of analysis. Another thing what has been postulated by people that, basically the conduction is along one direction, what is that direction? This is along the y direction. Because, heat is being transported in that direction.

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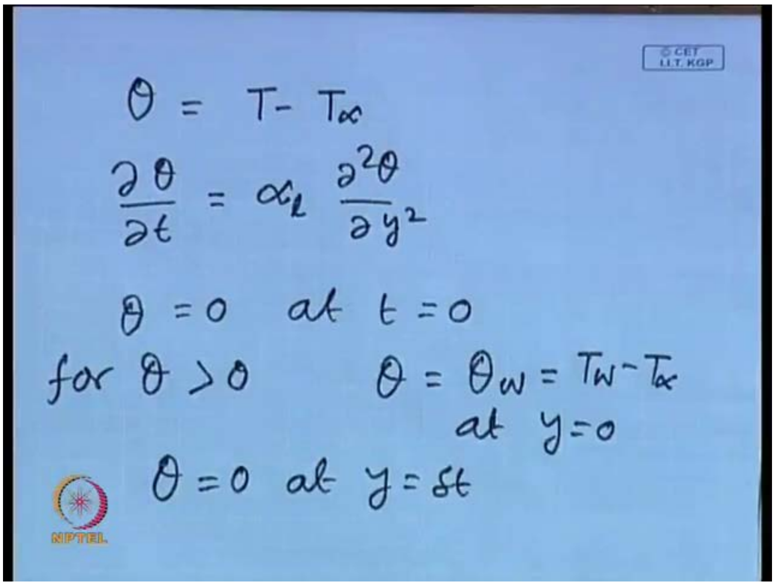

So, we have got one dimensional transient conduction. And if we define theta, that is equal to T minus T infinity. Assuming that, the bulk temperature more or less remains constant. So the equation, which we will get, that is d theta dT, that is equal to alpha l d 2 theta d y 2. So, this is our transient one dimensional conduction equation, which we will get. What are the boundary condition? Theta is equal to zero at t is equal to zero, that is just one bubble have left and that place has been replaced or that vaccum place has been replaced by colder liquid from the top. And the colder liquid is having a temperature of T infinity.

So that is why, the non-dimensional temperature will be zero. For theta greater than zero, what we will get, theta is equal to theta w; that means, it is T w minus T infinity at y is equal to zero and theta is again equal to zero at y is equal to delta T at the edge of the boundary layer. So, these are the boundary conditions we will get for this particular equation. And we can see that, it is; what? It is a equation involving both t and y, first derivative of t is involved and second derivative with respect to y is involved; first derivative with respect to t and second derivative with respect to y. So, accordingly we have to have the boundary conditions.

Now, this is this type of equation is very known kind of equation, what you have done in your heat conduction or heat transfer. So, what will be the solution? There could be different methods of solution, but one can get the solution by separation of variable, there could be other method, but by separation of variable also, one can get the solution.

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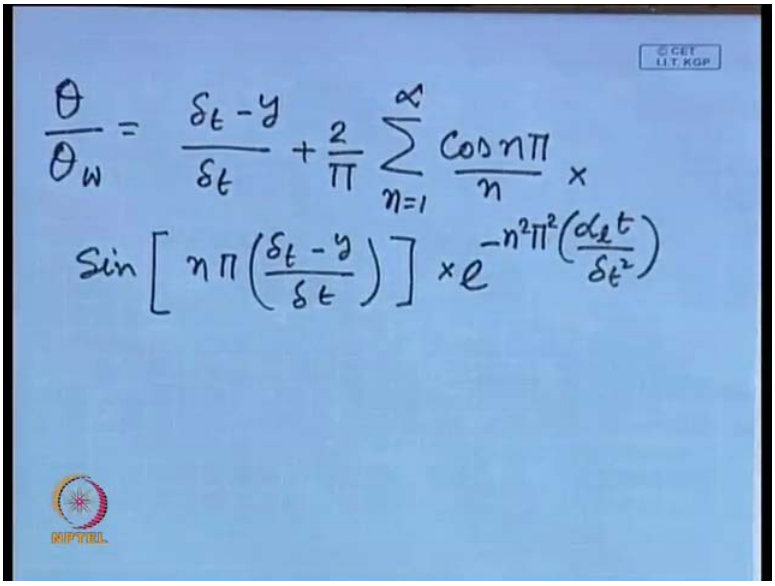

So, if we see any standard reference. So, it will be theta by theta w, that is equal to delta t minus y by delta t plus 2 by pi summation n is equal to 1 to infinity cos of n pi by n sin of n pi delta t minus y by delta t, e to the power minus n squared pi squared alpha l t by delta t squared, so this will be the equation. Obviously, you can see that, up to these it is taking care of the special variation; variation with space and the exponential term, that is taking care up of the variation with time.

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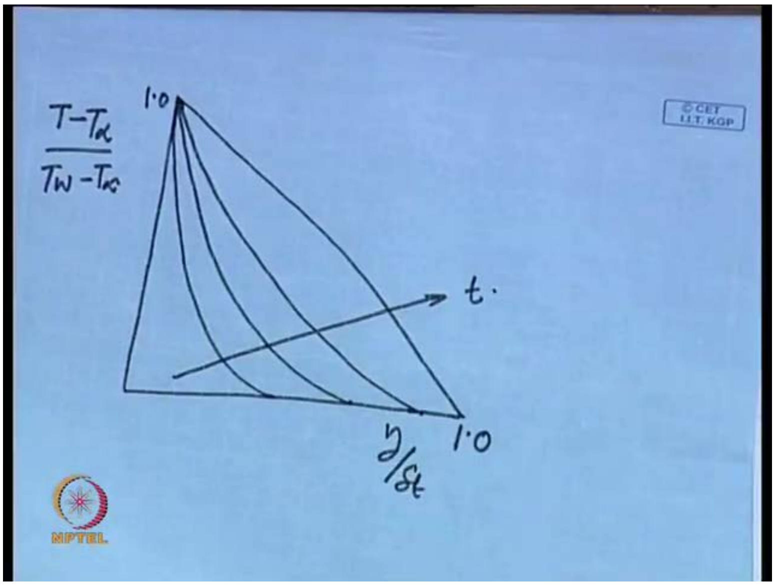

How does this curve look? If we have some sort of a non-dimensional plot, the curve look like this. We have got y by delta t, this is 1.0 and we have got this side as T minus T infinity by T wall minus T infinity, this is also 1.0. So, in steady state, it will have some sort of a linear profile. But otherwise, it will have profiles like this and in this direction, you have got increase in time; time is increasing in this direction. So, we will have a temperature variation inside the thermal boundary layer in this particular for, alright.

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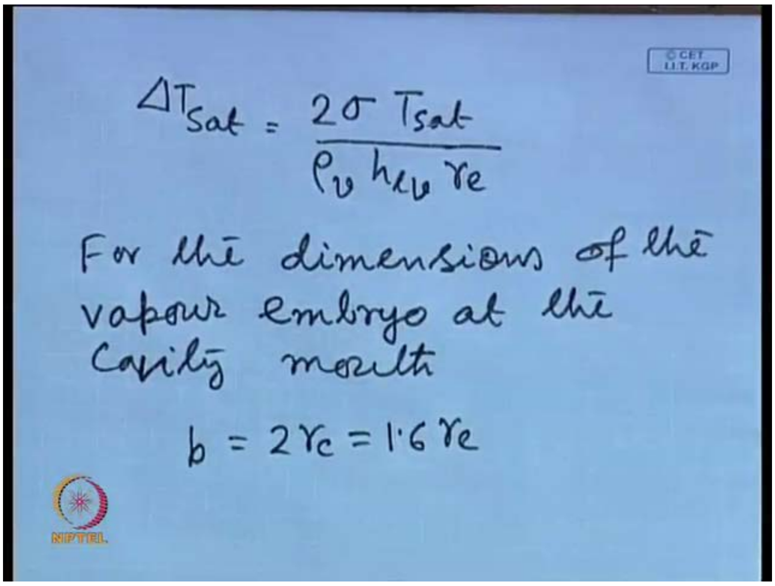

Now, what we can do is that, we have already; we are already familiar with this particular form of equation that, delta T sat that is equal to 2 sigma T sat by rho v h l v r e, r e is the radius of the vapour embryo. Now, here we will replace vapour embryo, we can replace vapour embryo by the radius at the mouth of the conical pore. And the relationship which has been suggested for the dimensions of the vapour embryo at the cavity mouth, what has been suggested, already we have mentioned, that b is equal to twice r c is equal to 1.6 r e, this relationship has been suggested.

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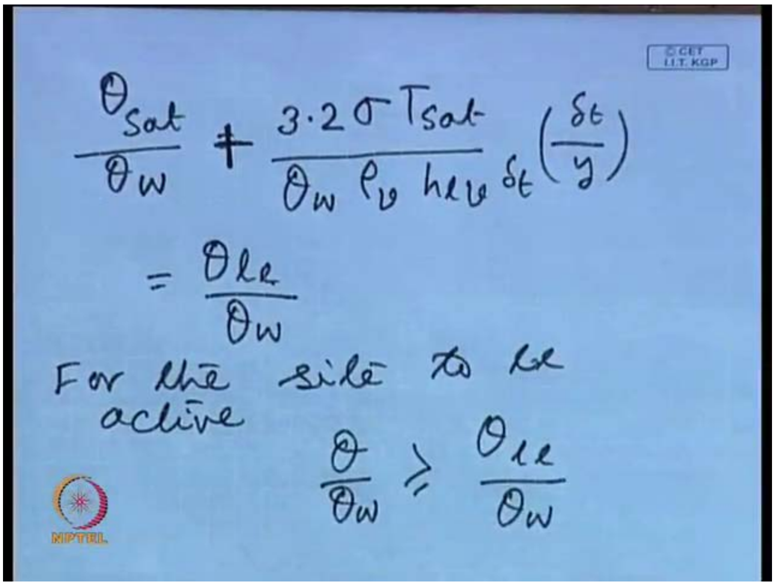

So, if I use this relationship and well; the previous relationship of delta T sat also; if we use and we can make further simplification. So one get, theta sat by theta w is equal to 3.2 sigma T sat by theta w rho v h l v delta t and here, delta t by y. I have made a mistake, so this plus this; this is equal to your theta l e by theta w. So, this this kind of a temperature profile we can get by incorporating the very well known equation, which relates the change in; change in or rather the degree of super heat with the vapour embryo nucleus.

Now, here theta l e is the temperature at the edge of the boundary layer; liquid temperature at the edge of the boundary layer, theta w is the temperature at the wall. Now, if the site is to be active site; if the nucleation sight is to be active site, then for the site to be active, theta by theta w, that should be theta l e by theta w.

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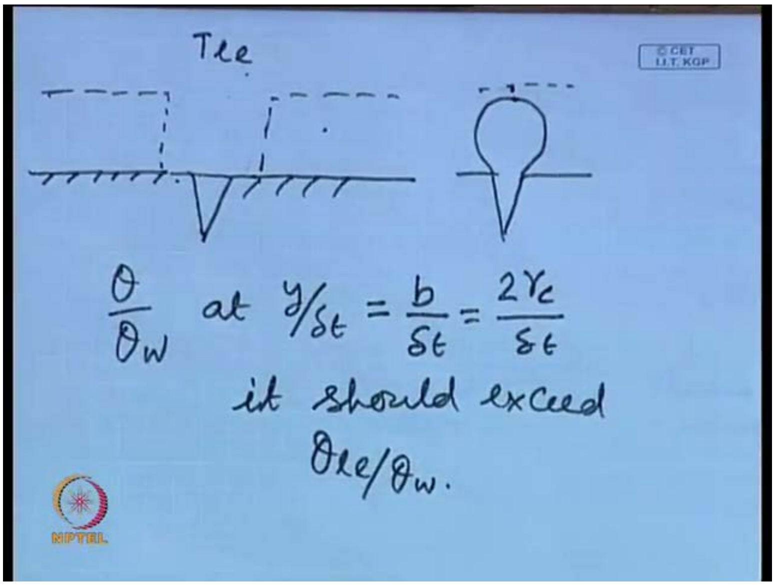

Obvious, this is not a very great thing, what we are telling that you have to remember our earlier phenomenological explanation that, this is your T l e or T infinity. Now, if the site has to be active, then what has to be there, that here; after the bubble has departed, we have got a temperature which is lower compared to the wall temperature, but that could not be too low and here, we should have a higher temperature liquid; this should be replaced by a higher temperature liquid, so that is what has been told.

Now, now if the bubble has to really grow, then what will happen that, we can also write theta by theta w at y by delta t; that means, within the boundary layer. The maximum value with respect to the bubble, it could be b by delta t, because the bubble height, I have represented by b.

So, this b is again related to twice r c by delta t, that should exceeds; that should; it should exceed theta l e by theta w, so this is what I like to tell. That means, the hole in the bubble is growing, bubble embryo is growing, you have got in the top most portion of the bubble embryo, (( )) within a high temperature liquid.

So, the maximum point which can touch the edge of the thermal boundary layer is this, so this point can touch the; atleast at the limiting process, it can touch the with the outer edge of the thermal boundary layer and that has that has been put in the mathematical term in this particular equation. Or in other words, the vapour embryo can grow, only when it is fully surrounded by your super heated liquid, by a hot liquid. Why? why that is needed?

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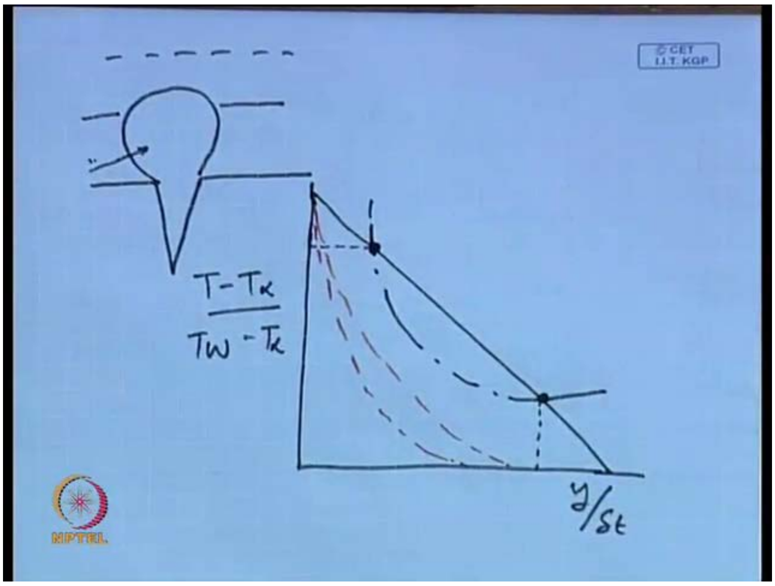

It is needed, because once it comes out of this cavity, one it; once it blossoms outside, then the growth is possible only by further evaporation; further evaporation will be possible, if this temperature is higher. Now at some part, let us say that, this temperature is higher, further evaporation is taking place, but at some part, this temperature is not higher, then a condensation may take place. So, we will not get an effective growth of the vapour embryo.

So, that is why it is postulated that, the entire for the growth to be effective, the entire of the bubble should be should be submerged in a high temperature liquid fluid, that is what, mathematically has been put. Now, now this side is your T minus T infinity by T wall minus T infinity; this side is your y by delta t and we are drawing the temperature profile within the thermal boundary layer. So, this is the linear temperature profile at this steady state.

Over this, if we; and this is the linear temperature of the thermal boundary layer in this steady state means, all the other temperature profiles are below this. So, maximum value which can be reached for the temperature within this thermal boundary layer is giving by this particular straight line, other lines are like this.

Now, what we do, the delta sat equation, what we have written already for the vapour bubble, suppose this equation; this equation which we have written for the vapour bubble; this equation, if I super impose on the this curve. So, what I will find that, this equation is cutting the steady state temperature curve at two points.

So, if it is cutting or intersecting the steady state temperature at two different points. So, these two super heat values are very important. So, these two are the limiting super heat values. And corresponding to these values, we can also calculate; already those equations has been given to you, what is the nucleus, vapour nucleus radius that also, we can calculate. Those equation has already been given to you in our previous class.

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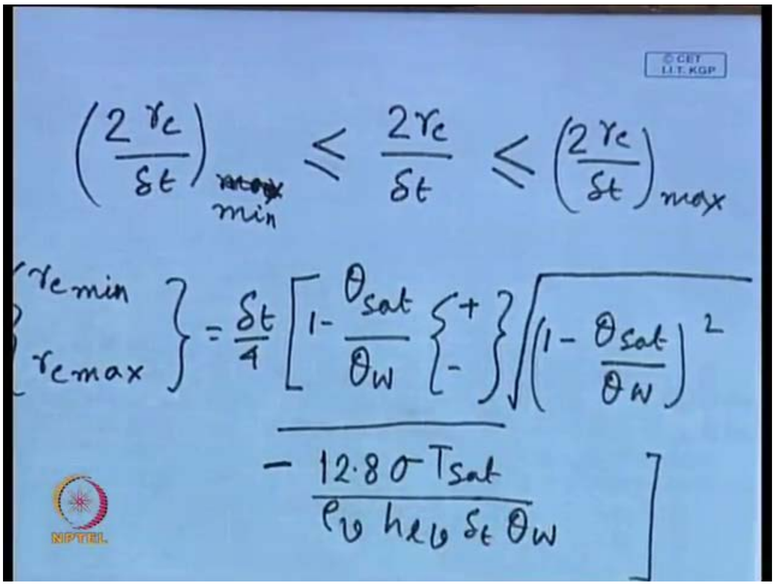

So, what we can get that, suppose the vapour nucleus; corresponding vapor nucleus that is given by r c. So, we will have a situation 2 r c by delta t, there will be a maximum value. This is a typical value of the vapour nucleus and this is your 2 r c. Actually this is minimum; this is minimum, delta t maximum.

That means, what is r c? r c is the radius at the cavity mouth. So, that cavity mouth radius, we can get from this equation that, it can have a maximum value; it can have a minimum value. If some value is more than the maximum value, then it is not operative. If some value is less than the minimum value, then also it is not operative. And any value in between these will be a cavity, which will be operative and which will give us the vapor nucleation. So, that is the information, we can get from here.

Now, another thing we can do; we can calculate; let me write it here r c min and r c max, we will have this one,… delta t by 4 within bracket 1 minus theta sat by theta w, this is plus, this is minus, 1 minus theta sat by theta w whole squared minus, this is within the square root itself, 12.8 sigma T sat by rho v h l v delta t and theta w, so this is within the square root. So, let me put the square root over here.

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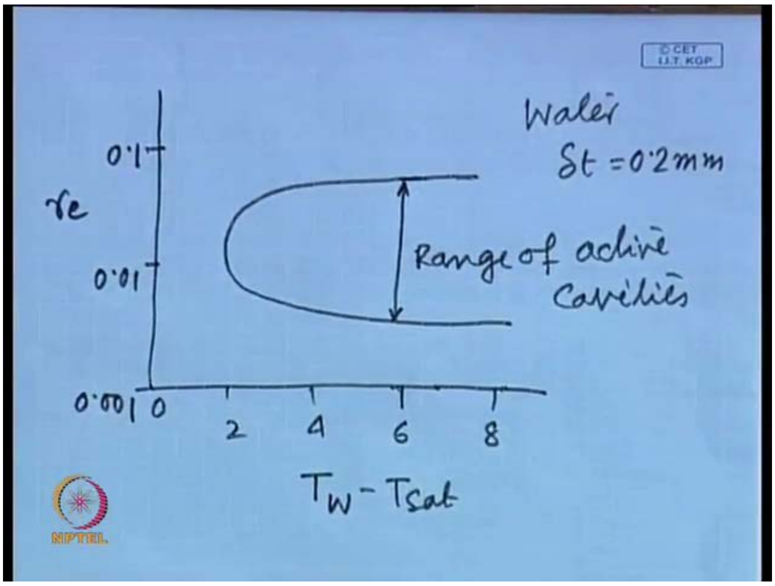

So, you see from this equation, r c min corresponds to the plus; value r c max corresponds to the minus value. So, within this values, we will get the r c minimum and r c maximum. Basically, r c minimum and r c maximum, if we see that, it depends on number of fluid properties, it depends on sigma it, depends on row v; it depends on h l v etc., So, it depends on a number of fluid properties.

It also depends on delta t, the thickness of the thermal boundary layer. And wall temperature, this could be a variable one, but it also depends on the theta saturated, saturation temperature. So, now we can plot curve, how does this curve look for different fluid under different operating condition. Let us consider that, we are having water and under atmospheric pressure and we have estimated delta t is equal to 0.2 millimeter.

Now, this side is your r c and this is a semi log curve. So, we have got 0.01, then we have got 0.1. So, these are different dimensions and this side, you have got, this dimensions are in millimeter and this side we have got, T w minus T sat, so degree of super heat. So zero, we have got 2, 4, 6, 8 like that we have got.

So, the curve which we will have is something like this. So, what does does it mean, this means that, this is the range of active cavities. So active cavity, it will depend on the fluid and delta t as I have told, but it will also depend on T w minus T sat; that means, the degree of super heat. So, at this degree of super heat, let us say, at this degree of super heat, only the cavity pore size or pore radius, because I have pore radius at the mouth I have taken, so that is the value of r c, so only these cavities will be activated.

So, this curve is clearing out. So, you will have higher degree of super heat, so a larger number of cavities will be activated. So, that is why we get, as we have I mean, we can relate it to a, to our day to day experience that, as we increase the temperature; let us say on a container boiling is taking place, as we increase the temperature, we see more vapour bubble formation, because the more number of cavities are getting activated.

Now, what happens this side and this side? See, below this, it is very easier to tell, so below this what will happen that, it will not; I mean this cavity is so small, that it is not activated and it will not act as a bubble nucleation size. Above this what is happening? See, this line is more or less a straight line; more or less a straight line, this line is clearing, above this what is happening? Above this, the cavity I mean the vapour bubble does not identify it as a cavity, it is identified as if it is a flat surface.

So, this is how your vapor nucleation is taking place and range of active cavities are increasing. But what I like to tell you that, these calculation, you can also appreciate that these calculations; this analysis has been done based on a large number of assumptions, very very simplified model, only to give some overview of the physics what can happen, this model has been proposed.

So, actual practice there could be lot of differences. In actual practice, the process of vapour nucleation form a small cavity could be a physico-chemical process also, what I mean to say? Suppose, there is a very hot surface and we are looking into the boiling process in a liquid metal. So, what will happen, the liquid metal may has has some reaction with the hot surface, some oxide formation could be there or with some previous oxide layer, it can have some reaction. So, it could be a physico-chemical process also. So, based on very simplified approaches and assumptions, this has been described more or less the physics is like this. But obviously, the model has got lot of loop holes, in then it can justify, whatever is observed experimentally quite well.

So I think, I will stop here. Next day, from this point we will start again.