**Multiphase Flow**
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**Module No. # 01**
**Lecture No. # 35**
**Heat Transfer in Different Regimes of Boiling (contd.)**

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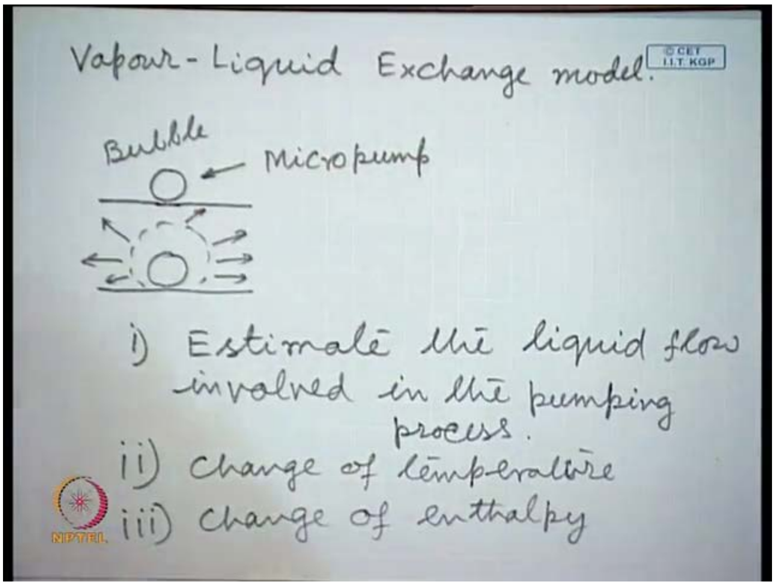


Welcome back. So, we will continue with our previous discussion and we are we were discussing different models of heat transfer during nucleate boiling. So, the present model which in which we are interested in is vapor liquid exchange model. So, as the mechanism has been described to you a bubble as it changes it is shape and size it is acts as a micro pan when it expands it pushes fluid when it contracts or leaves the surface. So, it induces fluid motion towards the center of the bubble.

So, with this we can have as I have told that we can estimate the liquid flow involved in the pumping process, and what is the change of temperature this liquid will undergo then the change of enthalpy and heat transfer we can calculate. Assuming that the bubble is a hemispherical bubble and the fluid movement associated with this is also, hemispherical is also of the same volume as of the bubble. So, we can write the equation for heat transfer.

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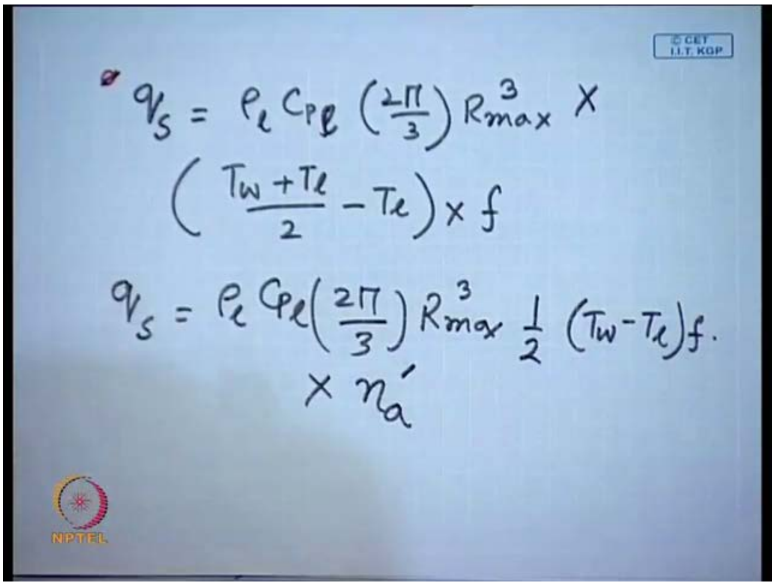


See the equation for heat transfer will be. So, this is q s is equal to rho l C p l T w p pi by three R max q multiplied by your T w plus T l by two minus T l multiplied by f. So, this is the heat flux q s is the heat flux rho l is the density of the liquid C p l is the specific heat, this is coming from the bubble volume r max is the radius of the bubble at it is departure, T wall T w is the T wall temperature of the wall T l is the bulk liquid temperature and a is the frequency of this bubble departure. So, with this we will simplify it to get rho l C p l two pi by three half of T w minus T l into f. So, this is what we will get? Now, this gives the heat transfer due to one bubble, if there is one bubble the volume of one bubble we have considered.

So, this gives the heat transfer due to one bubble. Now, if there are number of bubble and the number of bubble from where I will get we will get it from the number density of the nucleation site. So, with some sort of a factor like that we can multiply to get it over the entire surface in a dash that is that gives us the density of the nucleation site. So, with this then we will have an estimate of the heat flux due to boiling. Now, this expression you please see with bit carefully, first thing here no latent heat is involved this is one way of looking into the problem I am not telling that this is the correct way of looking into the problem, but no latent heat is involved. So, basically this is some sort of a single phase correlation applied for boiling process.

Second thing there is a very important observation this we have already mentioned and again I am mentioning, that q s is directly proportional to T w minus T l. So, it is directly proportional to T w minus T l that is the temperature difference between the wall and the bulk of the fluid, but all the experiment shows that this relationship is not reflected by the experimental data. One example, can be given that let is say there is a three hundred percent increase in T w minus T l the heat flux that increases, merely by fifteen to twenty percent. So, that does not reflect the way the formula has been made whether it is correct or not that is not reflected by the experimental observation.

Then people could see that as T w minus T l increases or rather as T w increases degree of super heat or rather degree of sub cooling that increases. So, a few phenomena occurs which is not visible from this equation at the first glance. What happens? As the degree of sub cooling increases as the liquid bulk is more sub cooled we will have the departure diameter of the bubble smaller and smaller. This experience we are having in any in any case of boiling. So, even if you heat oil over a heat water over a pan you will find that it is when it is sub cooled the bubbles are living the pan surface heated pan surface at a smaller diameter.

As the pan surface temperature increases and the sub cooling of the bulk of the liquid decreases, then only you get bigger and bigger bubble as you go towards the saturation we will get bigger and bigger bubble. So, this is increasing, but R max will decrease and also, what has been found that frequency changes the bubble release frequency changes we the temperature defines. So, something is increasing other factors are decreasing so, they compensate each other. So, that is why we do not get a direct increase of q s as T w minus T l is increasing.

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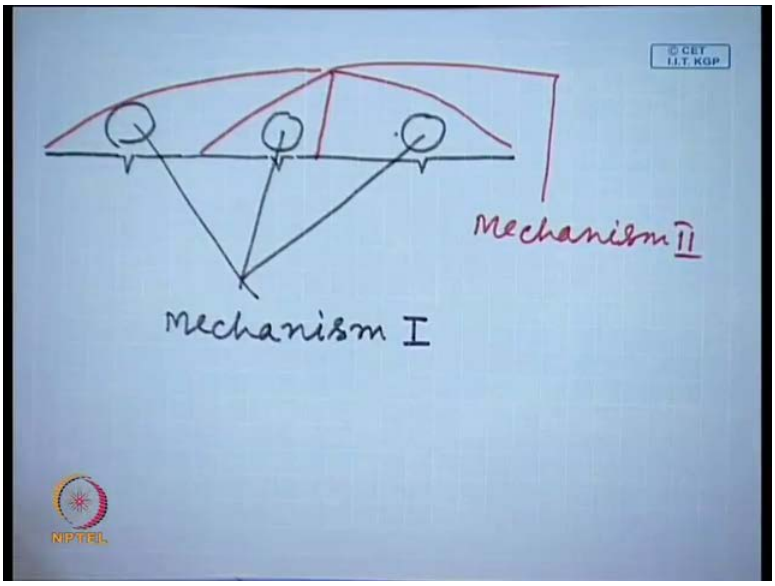


So, this is one of the reason another thing as I had already mentioned as I have already mentioned that this is also important. So far we are looking into the bubbles let us say there is one nucleation site we are looking into bubbles and the mechanism of heat transfer due to the movement of the bubble that we are concentrating. So, basically this is mechanism one for heat transfer and so far what we have done we have concentrated on that. But between the bubble there are spaces where also, the heat hot surface is in contact with fluid. So, there will be some other mechanism of heat transfer, which we are not bothering at all.

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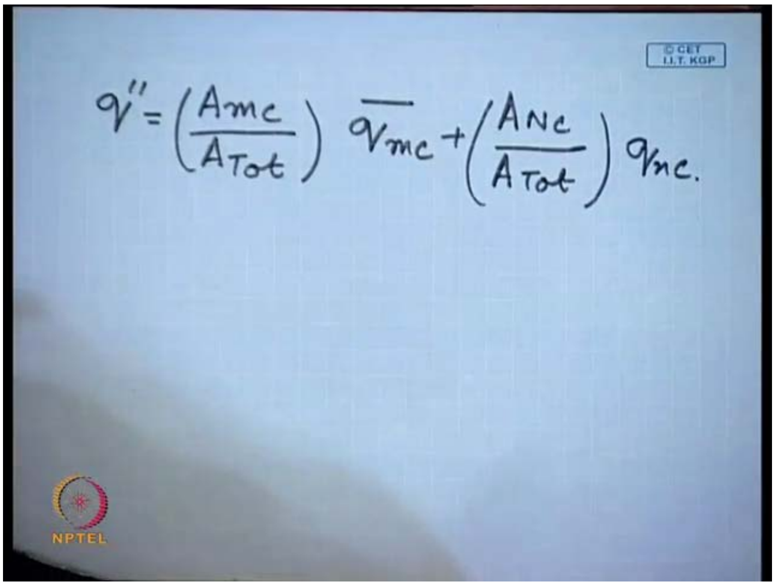

So, these we can call mechanism two. So, some people have also suggested that let us consider these two and then make some sort of a improve. So, if I try to do that what we will have is this heat flux that is equal to A m c by a total q m c plus A N c by total q n c.

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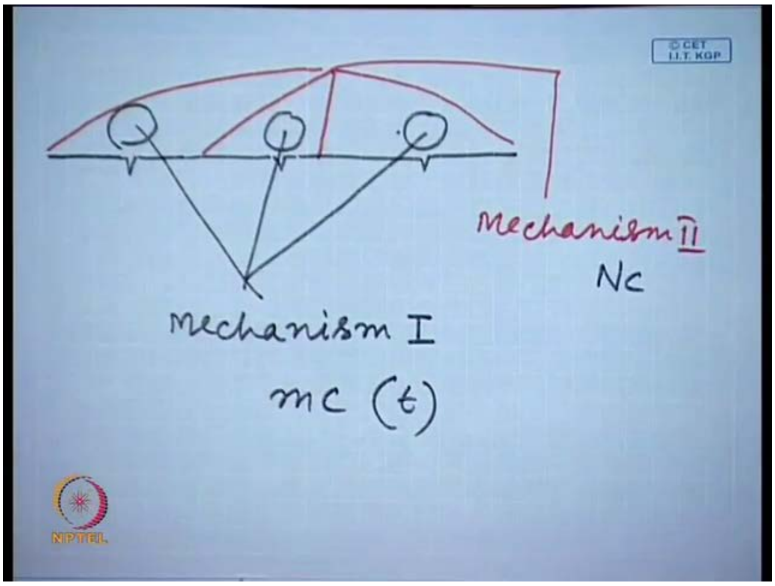


Let me explain what it is? People are we can assume that there are two mechanisms working side by side. One is micro convection which I have called the mechanism one see the bubble are moving bubbles are moving so, there is some sort of micro convection, even one can involve the critic latent heat of vaporization in this mode of heat transfer. And then in between the bubble there is a solid area, which is in contact with liquid so, their natural convection will take place. So, one is micro convection and one is natural convection now, natural convection this is more or less constant because of the temperature difference remains constant then what is the heat transfer due to natural convection that is also constant, but micro convection a bubble grows then departs.

So, there is a cycle. So, micro convection this is dependent on time. So, micro convection if I want to calculate the rate of heat transfer. So, we have to do it by integrating over the entire period of cycle natural convection rather is straight forward. So, with this particular with this assumption this particular formula has been written. So, total amount of heat transfer is the average heat transfer during I mean due to micro convection multiplied by area, which is responsible for micro convection and this has been divided by the total area plus, there is another model of heat transfer by natural convection the area, which is involved in natural convection heat transfer divided by the total area. So, this is how we will get the heat transfer from a boiling surface? So, this of course, is not a typical model, but it gives an a corrective measure suppose we want to do the boiling heat transfer prediction it gives some sort of a corrective measure.

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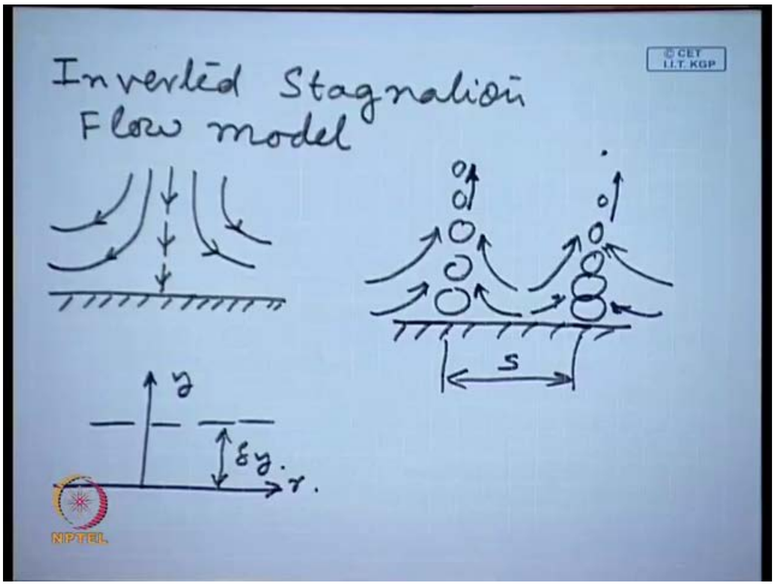


As I have told that there are many models of boiling heat transfer another model I like to discuss, which is bit interesting may not be very successful in predicting boiling heat transfer. But it is bit interesting that is known as inverted stagnation flow model. What is inverted stagnation flow model? Let us say there is a surface now, stagnation flow means if the flow is directed towards it. So, if the flow is directed towards it then what will happen? This stream lines will be like this, if we reverse the direction of the stream lines we will get inverted stagnation flow model this is a stagnation flow.

Why we are considering inverted stagnation flow model? It is like this that a bubble column is there. So, bubbles are living like this there is another bubble column. So, bubbles are living like this. So, as the bubbles are living like this as I have told that it will drop fluid so; it will drop fluid like this. So, you can see that this is reverse of stagnation flow and we can assume that this is your s the distance between this two are s. So, we can we can think of some sort of idealization this is your y this is your r direction and this is your delta y, delta y is the outer edge of the thermal boundary layer.

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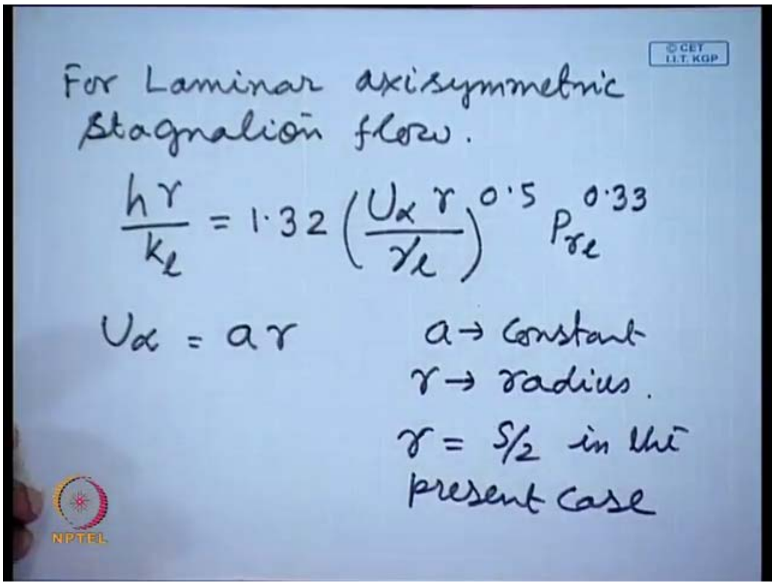


So, with this for laminar axi symmetric stagnation flow for laminar axi symmetric stagnation flow we are having, h r k l liquid conductivity is equal to1.32 U infinity r by mu l to the power 0.5 p r l to the power 0.33. So, this is your correlation for laminar axis symmetric stagnation flow. And then U infinity is equal to a r, a is a constant and r is your radius and here, we are assuming that the bubble columns are distributed in regular array and the radius of this one the zone which is affected by a bubble column. So, that is given by s by two so; that means, r is equal to s by two in the present case.

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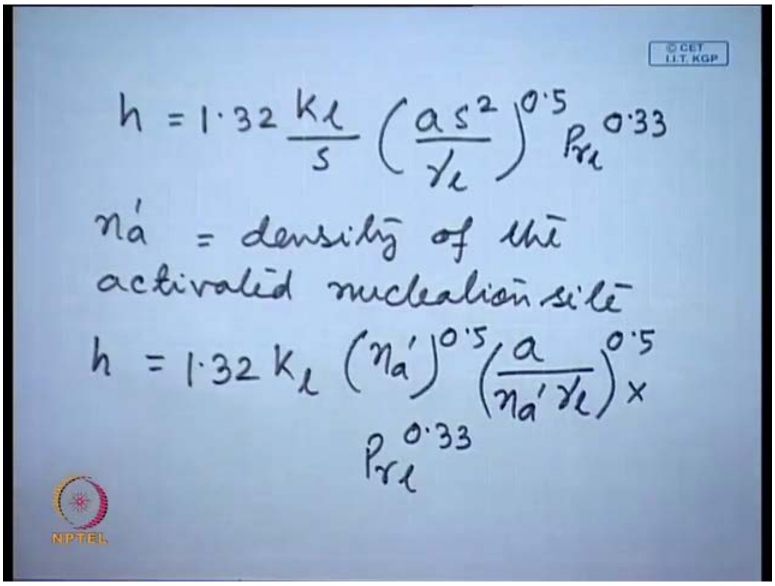

So, what we will get from this particular equation? We will get from this particular equation h is equal to 1.32 K l by s a s square by mu l to the power 0.5 and p r l to the power 0.33. So, this is what I will get now, what again one can do one can bring n a dash, which is the density of the of the activated nucleation site and with that one can write h is equal to 1.32 K l n a dash to the power 0.5 a by n a dash multiplied by p r l to the power 0.33.

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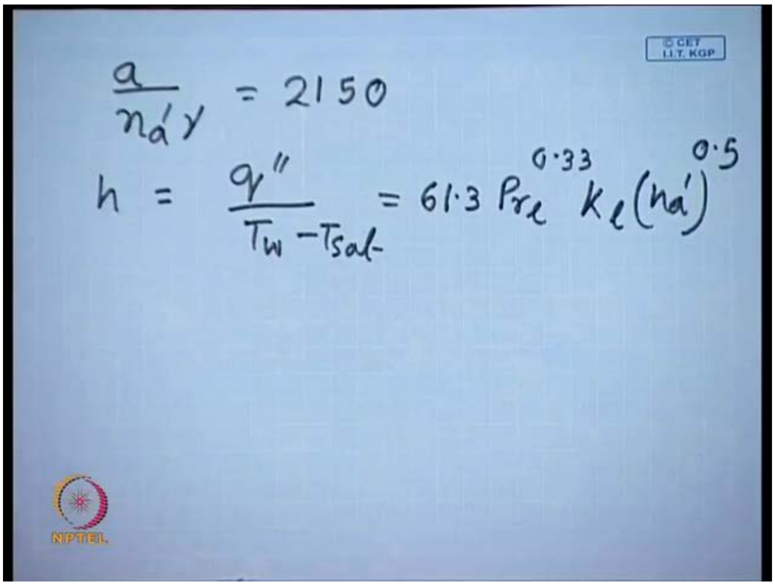


Now, based on some experimental data a by n a dash. So, ultimately h is equal to q T w minus T sat saturated is equal to 61.3 p r l 0.33 K l n a dash to the power 0.5. So, this kind of a relationship has been given. So, this is one model again a different kind of approach has been taken for analyzing boiling heat transfer. Now, let me tell you a few things of course, another model let me discuss without any mathematics and then we will go back for a general discussion of all the models, which I have described so far. See, so far whatever model we have described all of them assume that some sort of a I mean many of them assume that some sort of mass exchange is their along the interphase, but the exact way the mass transfer is taking place mass evaporation is taking place none of these models they concentrate on it.

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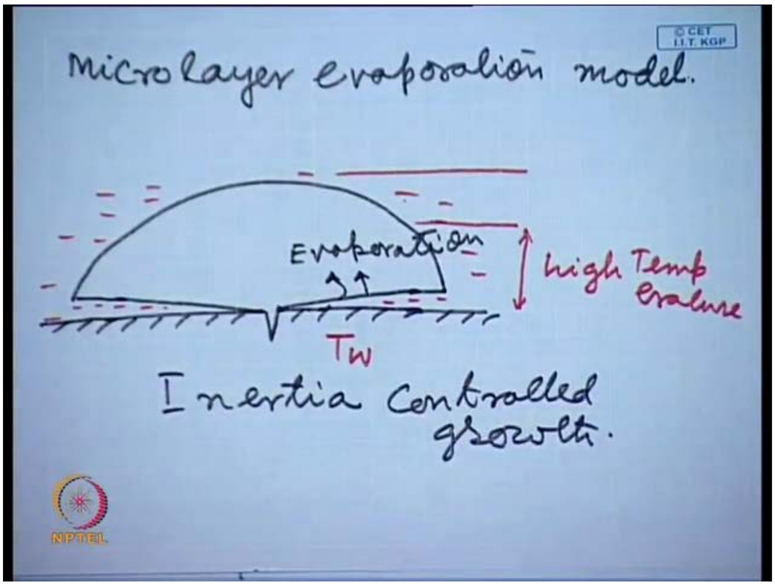


There is another class of model those are known as micro layer evaporation models. So, in the micro layer evaporation model sometimes I have discussed this also, but let us recapitulate. The vapor is assumed to have some sort of hemi hemispherical shape like this the vapor is assumed to have some sort of an hemi spherical shape like this and here we are having liquid. But the liquid here near the vapor base or up to this point or up to this point depending on the depending on the size of the vapor bubble is high temperature and here of course, T w is the highest temperature.

So, from this T wall heat will be transferred and due to conductionally. So, through this through this micro layer and as heat is transferring so, from here your evaporation will take place this is your evaporation. So, that is why this is called a micro layer evaporation model and the bubble will grow large enough and then it will live the surface. So, this is basically, valid for inertial controlled growth and a full bubble cycle can be described based on this micro layer evaporation and then what can be done? That the entire amount of heat transfer by some integration process one can also find out from this micro layer evaporation.

So, there are model based on this micro layer evaporation and part of the I mean some experimental data can be predicted very well by this micro layer evaporation model also. This is bit recent model all the models, which I have described those are bit earlier model this is bit recent model so, this model is also applicable. Now, let me tell you let me have so, many models I have told so, let me have a some sort of over view of the models. Now, one thing we have to understand that none of these models are some sort of a master key that for all situations of boiling we will have a good result or good prediction from these models.

So, this is first thing we have to remember that none, of not a single model will predict all the boiling data very effectively. There are certain models which predict the boiling data of water or aqua's fluid very well there are certain other models, which predict the data for the dilected fluid like (( )).

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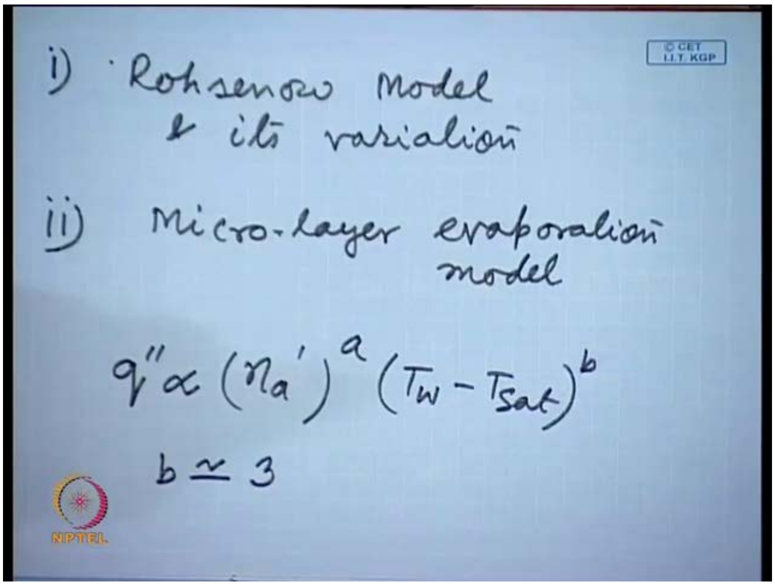


Now, in general the Rohsenow correlation and the variation Rohsenow correlation that gives a good prediction. So, one model which I can recommend is that the first correlation your Rohsenow correlation first correlation what I have told. So, that is the model, which I can recommend to start with I can recommend Rohsenow model and it is variations there are certain variation of this model. Second type of model which are also, very showing which are also showing good predictability that is your micro layer evaporation model, again if we make a comparison between these two model Rohsenow model is much simpler.

This involves number of steps, but even then the micro layer evaporation model is good. The experimental evidence which shows, that this is proportional to prove very important parameters n a dash to the power a and T w minus T saturated to the power b. There will be of course, some numerical constant etcetera, but for any boiling experiment this type of relationship is obtained. Out of this it is very difficult to predict n a dash that is the nucleation site density nucleation site density it is very difficult, because it is a material property I mean it cannot be determined so, easily.

Some people have suggested that T w minus T sat with heat flux there could be a good estimate if we take b is equal to 3, but again these are not universally applicable in some experiment we will see that these are applicable in some other experiment this is not applicable. Then the final what can we say? The final message which I like you to take that boiling heat transfer it is so, complex phenomena that none of the models, which we have developed, which we have been developed. So far are very suitable if known fluid known surface conditions are their then it is better to apply the rohsenow model if you can give more time for the calculation etcetera then micro layer evaporation model is also good.

Otherwise if it is a totally, unknown kind of fluid the surface is non waiting it is not a very good waiting surface see in those cases probably the experimental result one has to relay on. If we want to do if we want to apply any kind of prediction, we should be ready that there should be a very large amount of factor of C F D or factor of ignorance for any design calculation.

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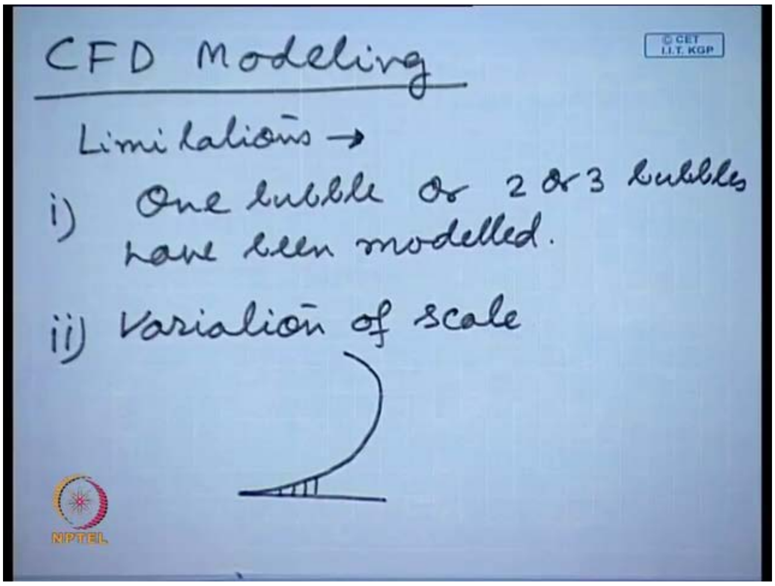

Then lastly what I can tell that C F D modeling are becoming important tool for the prediction of boiling heat transfer particularly, nucleate boiling heat transfer. Now, the limitation of C F D modeling C F D modeling is becoming important, but the limitations are let me tell you limitations what are the limitations. First limitation is that so far only one bubble or two or three bubbles have been modeled, because of restriction of the computational time. So, we cannot model very large number of bubble that is one restriction, second restriction is that that variation of scale variation of scale means, as I have told that we have got a bubble.

So, here if we see the liquid layer is very very thin and even it can go to the molecular level and then from the molecular level we have to go to the level of the bubble and not only bubble we have to take a some amount of surrounding fluid. So, there is a there is a variation of scale so, unless we take the multi scale approach this simulation cannot be done properly.

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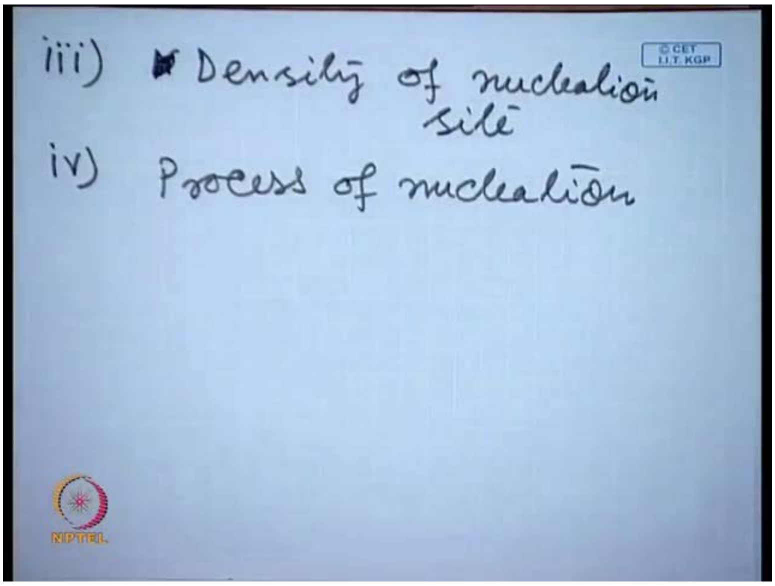


And last, but not the least is that certain issues for which the physics is not known like your density of nucleation site. So, we do not know how this can be this can be fixed or this can be assigned to your simulation model. Then the process of nucleation this physics is also, not known fully. So, that is why the if we want to do C F D we have got large number of limitations and we are handicapped with that, but it is showing some sort of promise may be in coming future one can have more success, with C F D modeling.

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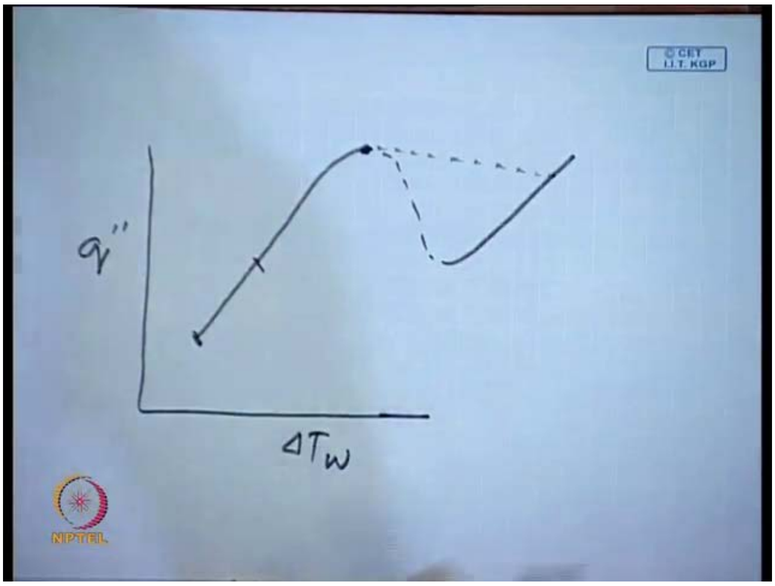


So, this brings us to the end if we again look back that we were in the boiling curve delta T w. So, somehow this portion we have done relatively with ease the portion where you are having fully developed nucleate boiling we cannot do much, but probably with some correlation we can tackle it.

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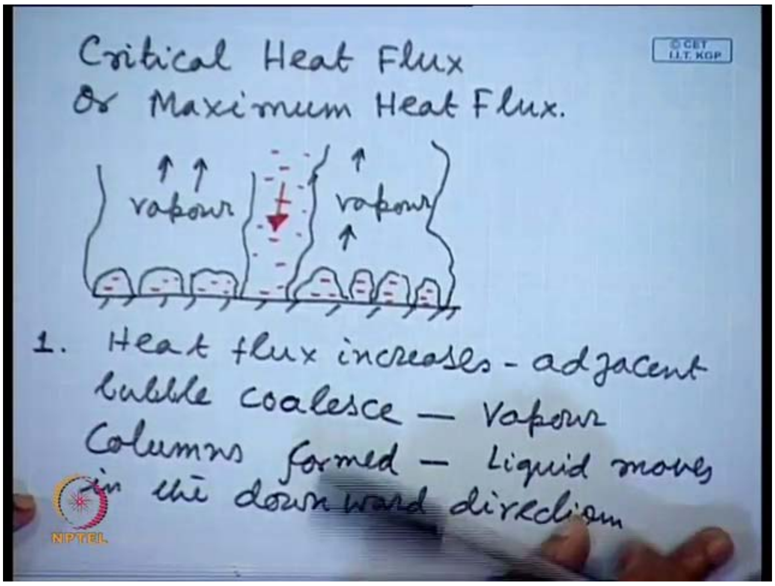

So, we have come to this point this is your critical heat flux point or maximum heat flux point. The critical heat flux point or maximum heat flux point is very important because in most of the industrial situation we operate only on the nucleate boiling regime. So, in the nucleate boiling regime if we operate, then we have to know where we have to terminate and we have to terminate at your critical heat flux. So, the maximum amount of heat flux to, which your boiling system can be subjected to, is your critical heat flux. So, this has to be known and if we valid this then we there is a possibility that we may go directly here and there will be a high rise of temperature.

So, people have spent lot of time in the determination of critical heat flux or maximum heat flux so, critical heat flux or maximum heat flux. Now, critical heat flux or maximum heat flux if we see that the physical mechanism. So, physical mechanism is something like this, there is a heated surface first we will see isolated bubble then what will happen? As the as the heat flux is increasing so, what will happen? The there will be large number of nucleation sites and neighboring bubble they will if will come very closer so, ultimately you can get this kind of things.

So, lest say this is your liquid and this is some sort of a vapor column or this is your vapor. So, this is some sort of a vapor column or vapor jet we will get this one so, we will get also, something like this side by side. So, this is also vapor and here you will have the liquid and also, you will have liquid somewhere over here so, this is your liquid. Now, certain thing we will find out now, if I the physical observation if I summarize it, it will be like this first what we will find out? The as the heat flux increases heat flux increases adjacent bubbles will coalesce.

Then we will get vapor columns formed vapor columns had formed. So, the vapor column we can see the vapor is moving in the downward direction, vapor is moving in the upward direction as it is a lighter fluid then the liquid that has to come in the downward direction, the liquid will be coming in between two vapor columns let us say the liquid has to come in the downward direction.

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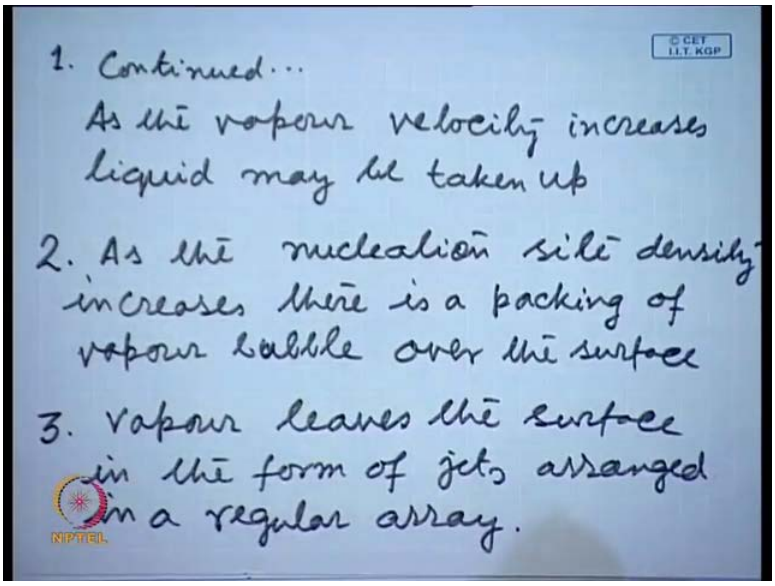


So, vapor column formed liquid moves in the downward direction then what we will find? As the liquid moves in the downward direction and vapor moves in the upward direction, as the vapor velocity increases liquid may be taken up. So, instead of moving in the downward direction the liquid may be taken up, if this happens then what if this happens liquid is taken up then the surface is not getting a replenishment of the liquid then; obviously, the heat transfer rate will fall.

So, the second phase what we can write? As the nucleation site density increases there is a packing of vapor bubble over the surface over the surface there is a packing of vapor bubble earlier isolated bubbles were generating their living now, there will be a packing of vapor bubble over the surface. Now, the vapor leaves the surface in the form of jets arranged in a regular array.

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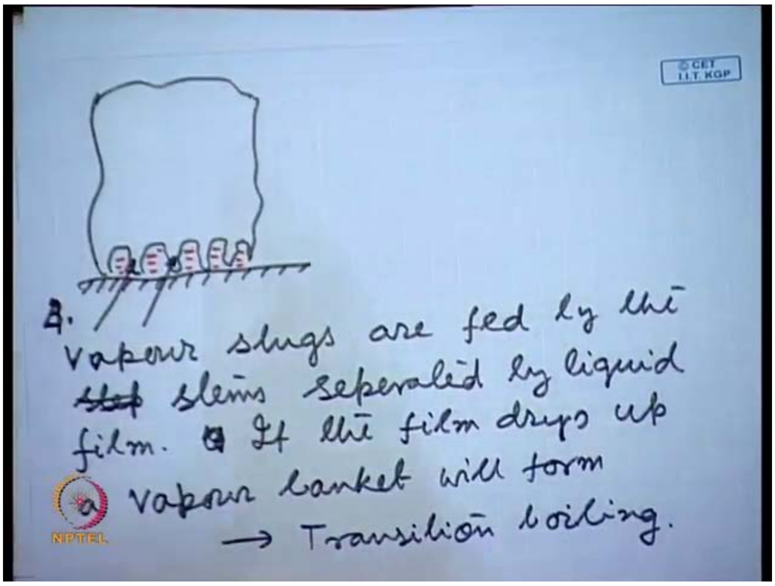


Now, let us think of slightly different figure so, this is some sort of a vapor jet or vapor slug let us say. So, how it is sustained? This is sustained by the evaporation, which is coming from here because that is the place where it is having connection with liquid. Now, this vapor jet it cannot grow infinitely somewhere this vapor slug will break and live the surface. Now, what is happening? T lit lives the surface it is getting the supply of vapor from the liquid. Now, before it reaches the critical mass for living the surface if the liquid shown over here by this red dot they are dried up. Then what will happen? A vapor patch will fall suppose in this o a it this vapor slug lives another vapor slug grows then there is no dry patch's there are number of stems vapor stems that is true, but even then the surface is having some contact with liquid.

But before this vapor slug leaves if this liquid dries up liquid film dries up then what happening? The formation of a vapor patch or vapor blanket. So, this will give rise to your transition boiling, this will give rise a shift from the nucleate boiling to the transition boiling and this is known as where it will happen this is known as critical heat flux. So, let me tell so number four vapor slugs are fed by the stems separated by liquid film, if the film dries up a vapor blanket will form so, we will go to transition boiling. So, this could be also a mechanism for your critical heat flux to take place.

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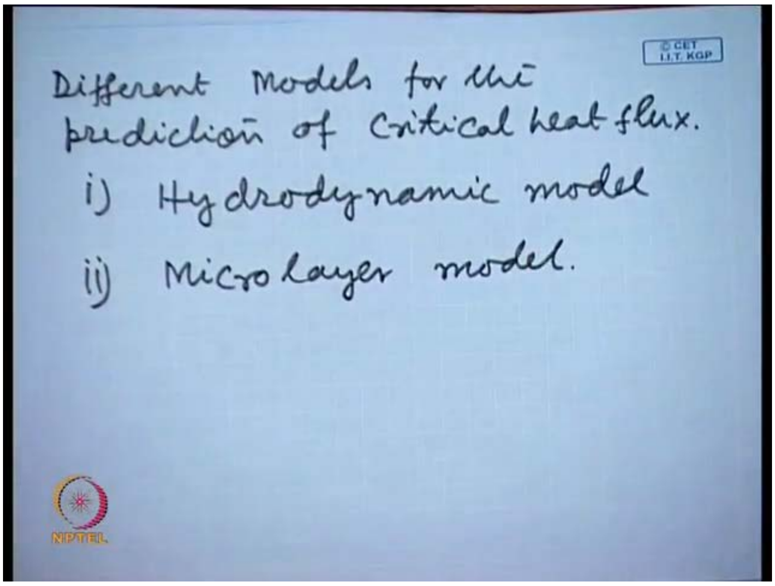


Now, there are different models for prediction of critical heat flux so, different models for the prediction of critical heat flux. First one is known as hydrodynamic model and second one the micro layer model of course, the result of both the models there are lot of similarities.

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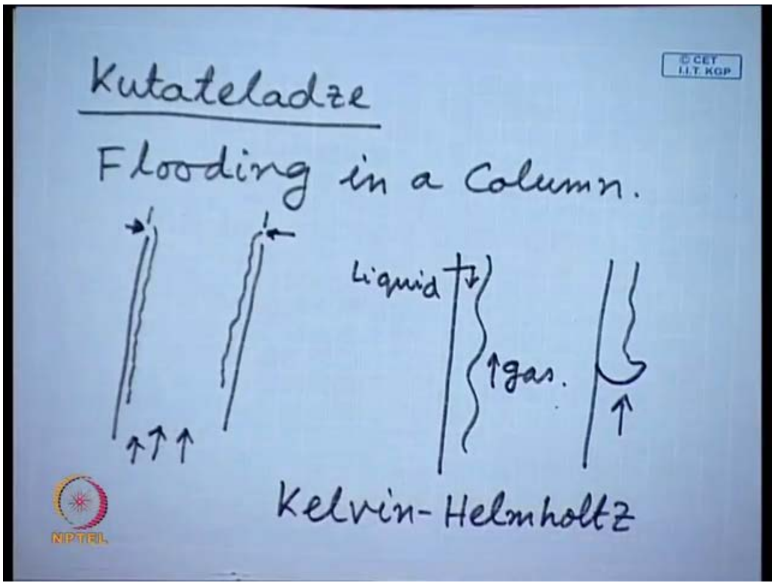


So, let me explain what is micro layer model and what is first let us start with the hydrodynamic model, hydrodynamic model boiling heat transfer the contribution of this Russian scientist Kutateladze his contribution is are many. So, he has first postulated certain thing drawing the similarity between some phenomena in chemical engineering and this critical heat flux. Now, so what he has told that flooding in a column. What is flooding in a column? So, suppose we have got a tube so in this tube we have got liquid injection from this side. So, if you got liquid injection from this side liquid will fall to the over the wall liquid will fall like this and then from the bottom you are supplying a gas. So, the gas will move in the upward direction.

So, now what we are getting? We are getting the liquid flow is there in the downward direction and side by side gas flow is there in the upward direction. So, if the gas velocity is small then, we will have a smooth liquid film, but if the gas velocity is high then you will have some sort of an undulation or repel on the liquid film. So, this is your liquid and this is your gas. So, you will have some sort of a undulation in the liquid film and when the gas velocity is very high then what will happen? The gas will try to push the liquid in the opposite direction so; this phenomenon is known as flooding.

And this is due to some instability, which is known as Kelvin Helmholtz instability this is due to Kelvin Helmholtz instability. So, Kutateladze he could see or he could postulate that the critical heat flux phenomena and the flooding phenomena it has got certain similarity. And he has first given some sort of relationship not based on very rigorous mathematics, but based on some sort of logic the logic which I have told already. So, based on this logic he could give some relationship.

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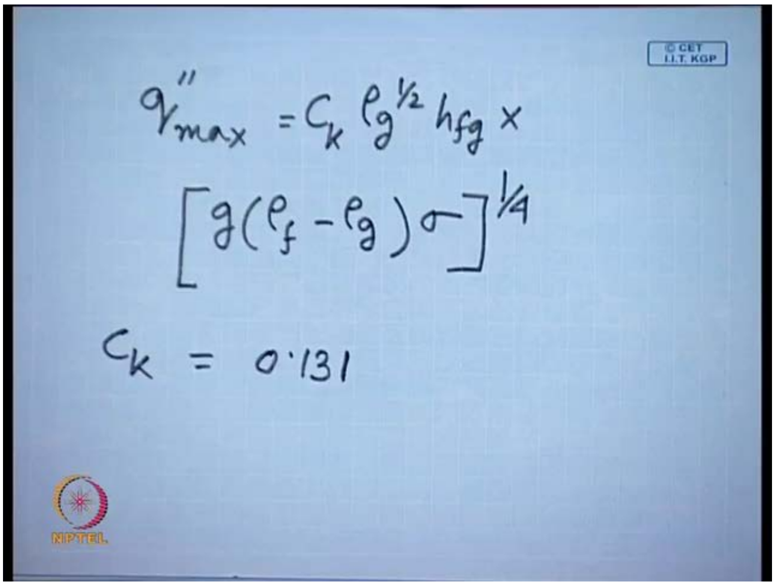

The relationship which he has given is this, q max that is equal to C k rho g to the power half h f g multiplied by g rho f minus rho g to sigma to the power one forth so, this is the relationship which he has given. And c k; obviously, this is an empirical constant so, C k I 0.131 and this has been not obtained by any theory this has been obtained by filling the data. So, Kutateladze was the first person then to establish some sort of a similarity or to point out some sort of a similarity between, the flooding phenomena and the phenomena of critical heat flux.

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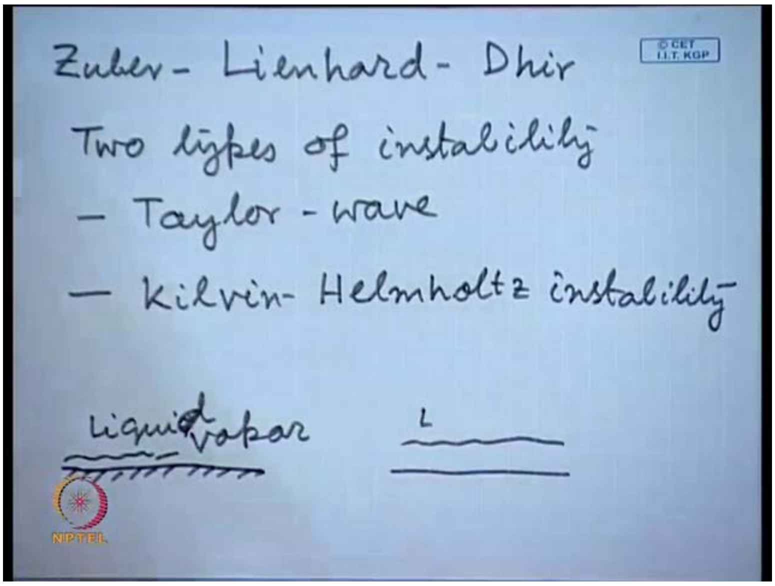


Then latter on work done by Zuber and after that Lienhard and Dhir, Zuber is again very very famous for his contribution in boiling heat transfer and Lienhard is also, very famous for his contribution in boiling heat transfer Dhir is of Indian origin d k Dhir he is also, he is he has also contributed very substantially for the theory of boiling heat transfer he is of Indian origin. So, Kutateladze theory then Zuber's modification and then again the work of Lienhard and Dhir both are on the same line. So, all these are for the development of your hydrodynamic theory of critical heat flux.

Now, this hydrodynamic theory of critical heat flux it depends on two kinds of instabilities. (No audio from 51:21 to 51:28) One is a Taylor wave type phenomena another is your Kelvin Helmholtz instability. Now, what is Taylor instability or Taylor sometimes it is also called rally Taylor type of instability it is like this that, there are two fluids from the stability criteria always, the heavier fluid tries to be at the bottom and the lighter fluid tries to be at the top. But in case of a boiling process what is happening? Suppose, this is a horizontal surface this is a horizontal surface here the bubbles are forming bubble are bubble bubbles are forming.

But let us say somehow they cannot immediately live the surface. Then what is happening? We are having some sort of a vapor and at the top we are having liquid. So, we are having a lighter liquid below and a heavier liquid at the top so; obviously, it is an unstable situation. Unstable situation means, what we will get? Suppose, we have got some sort of a vapor layer and some sort of a liquid so; obviously, we will not get a smooth surface we will get undulated surface, I think time is up. So, we have to continue next day so, next day we will continue from this point.