Multiphase Microfluidics
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Lecture – 17
Flow Boiling in Microchannels

Hello in this lecture we are going to discuss Flow Boiling in Microchannels. You know flow boiling in microchannels is probably one of the earliest applications of flow in microchannels because it has applications in refrigeration and compact heat exchangers. So, in the earlier lectures we have looked at the heat transfer without phase change, specifically in the Taylor flow or slug flow regime.

Now, we will try to look at how the flow boiling in microchannels is different from that in conventional channels and what are the different effects, what is the mechanism of heat transfer. So, in the last 20-30 years there have been lot of research specifically using experiments or experimental research, where people have looked at the flow boiling in microchannels.

Now, there are two different viewpoints: one group of researchers say that nuclear boiling is the dominant mechanism of heat transfer during flow boiling in microchannels. On the other hand another group of researchers they say that the evaporative heat transfer or forced convective heat transfer is the dominant mechanism of flow boiling in microchannels. So, in this and the subsequent lecture we will try to address some of those questions and look at the state of the art of flow boiling in microchannels briefly. If you Google the review articles on flow boiling in microchannels, you will find at least about 10 or more articles on review of flow boiling in microchannels they might differ in aspects. So, this is a very at a area of research recently.

Now before we start discussing a flow boiling in microchannels, it is a good idea to remind ourselves or to get familiarized with different terminology or some basic fundamentals of boiling in channels or boiling in general. So, boiling generally refers to the heat transfer by evaporation over a heated surface. Now there can be the boiling is categorized in two different categories: one is Pool Boiling and another is Forced Convective Boiling.

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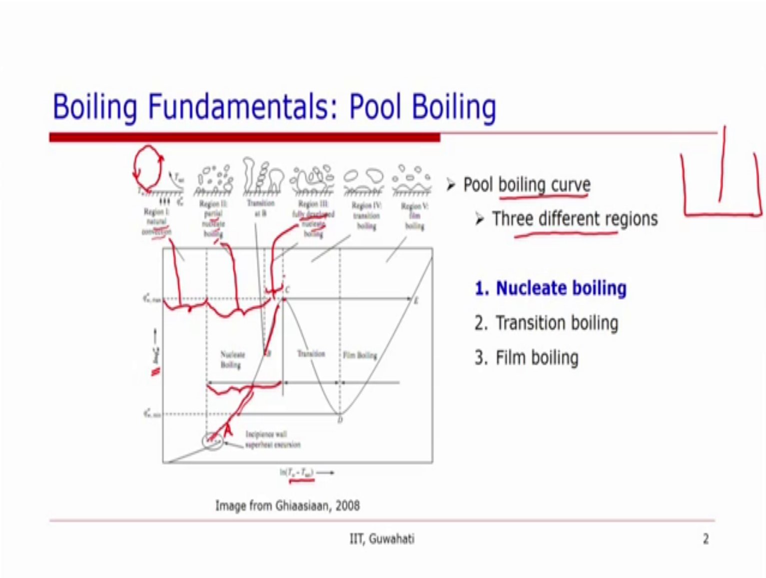

So, the pool boiling refers or the this categorization is based on the if the liquid is static, if the liquid is not flowing then it is pool boiling, a general example of boiling in the cattle or boiling in the pan that we are do every day in our kitchens. The other example or the other and the other end we have forced convective boiling; which is boiling of liquid flowing in a heated channel. So, looking at the first at pool boiling what we have here is a boiling curve for pool boiling and these curves have been obtained by Nukiyama and then researchers later on and a the results have been presented in form say in the form of a boiling curve.

So, what the experiments generally involved that in a pool of liquid, a heated wire is inserted and then either the heat flux is maintained constant and the wall temperature and the or the superheated temperature is measured or the wall temperature is increase slowly and the heat wall heat flux is measured, one of those can be done. So, this result they have been presented in terms of wall heat flux versus superheat which is in terms of T wall minus saturation temperature at a constant tracer.

So, as you can see that this graph is a log-log plot. So, it is between and the log of wall heat flux and log of the superheat. Now initially when the surface is heated and the wall heat flux is increased, there is no two phase flow, natural convection adds up in the liquid and the hot liquid which is closer to the wall goes up and then it cools down and come back again, so these natural convection is set up. And as the wall heat flux is increase, this keep increasing; at its certain point which is called onset of nucleate boiling; let us call this point as point A. There as you can see there is a small cage in T wall minus T saturation and then so in this case the boiling starts from here and you can see that this is called partial nuclear boiling what happens that bubbles start forming. So, the phase change starts happening in the cavities that might exist or that generally exist cavities or grooves or crevices in the wall. So, there some air might be trapped and those cavity is the air trapped in those cavities grow with the liquid phase changing to the vapor phase and as those bubbles grow at a particular diameter the bubbles leap the wall and then again another set of bubbles are realized.

So, there are two mechanisms that play here; the natural convection which was occurring and there was only liquid phase present plus the boiling caused by the nucleus on a bubble. So, that is why it is called partial nucleate boiling and you might see here that the slope of this curve increases because the contribution of nucleus and boiling keep increasing with the increase in wall heat flux. At point B onwards we see that the curve becomes straight or a linear curve.

So, and this is called fully developed nucleate boiling. So, this region is natural convection as you can see from here. The second region which has been marked here refers to partial nucleate boiling, this region and the third region which is marked by fully developed nucleate boiling. So, in this case the nucleate boiling is the dominant mechanism of heat transfer and the natural convection is almost negligible and we compare it with the nuclear boiling.

Close to the maxima we see that there is a decrease in the heat flux. So, the slope of this line keeps decreasing and then we get a maxima at point C which is called critical heat flux. So, in this region the nucleate boiling start decreasing because the number of bubbles that are there they keep increasing and the continual supply of bubbles becomes difficult. Now so, as we have seen that the pool boiling curve there are three different region. The first region is referred to after the onset of boiling nucleate boiling and in the nucleate boiling we have two regions; the partial nucleate boiling and fully developed nucleate boiling.

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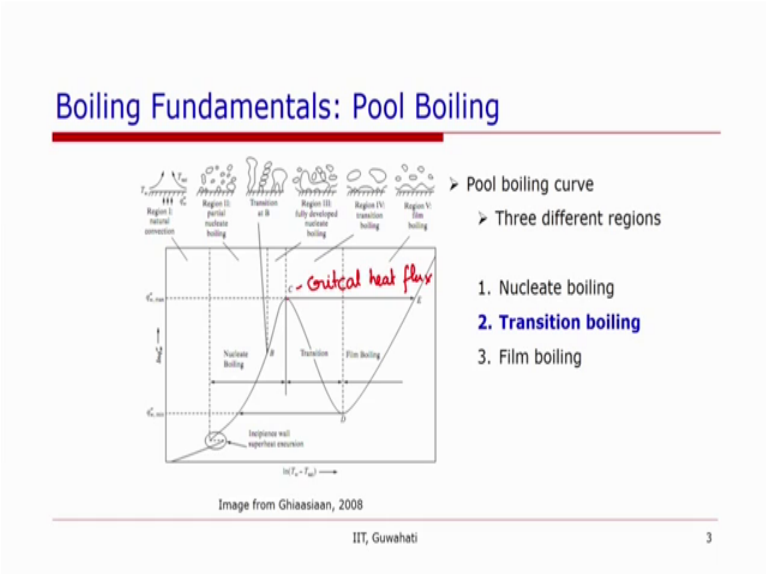

Now, moving on after the nucleate boiling at this maxima point C is called where what we have is critical heat flux. So, at this heat flux the surface is intermittently covered by vapor. So, most of the surface is covered by the vapor phase and the conductivity of vapor is smaller than that of liquid and then so we have very little heat transfer when you compare with the nucleate boiling region.

So, that is why there is a certain decrease in the wall heat flux and the when this heat flux decreases then this is disastrous for a number of applications because the temperature of the surface might shoot up or it will shoot up. So, then there is a problem. Ah So, in this case in the transition boiling the solid surface is partially covered by the vapor and the then the vapor bubbles they keep going up and then some boiling happens, but this is decreased significantly when they compare with the nuclear boiling.

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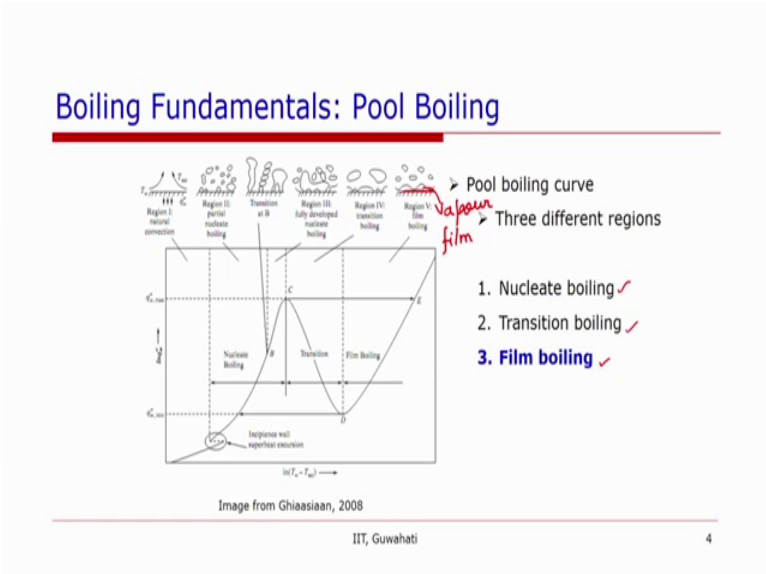

Now all the heat flux is increased further the film boiling happens. So, in this case a continuous film of vapor separates the solid wall. So, this is a vapor film; this separates the solid wall from the liquid region. So, the heat transfer is decreased further and then with the increase further increase in the wall heat flux this increases because there is always a thin film of vapor here and then the heat transfer happens accordingly ok. So in the pool boiling there are three different regions; nucleate boiling, transition boiling and film boiling.

So, while the transition boiling is the transition from the nucleate boiling to film boiling. In the nucleate boiling what we have? The bubbles nucleate or the bubbles form at the solid surface, if it is heterogeneous nucleation and these bubbles will grow and release from the surface. Whereas in the film boiling the entire solid surface is covered by the by a layer of vapor and the heat transfer is significantly reduced.

We might see some examples of film boiling in our day today life. If you have a hot pan if you and throw some droplets of water on it, then we see the these droplets start dancing over it, with really almost no contact between the solid surface and the droplets because there is a thin film of vapor over it and this effect is also known as leading frost effect.

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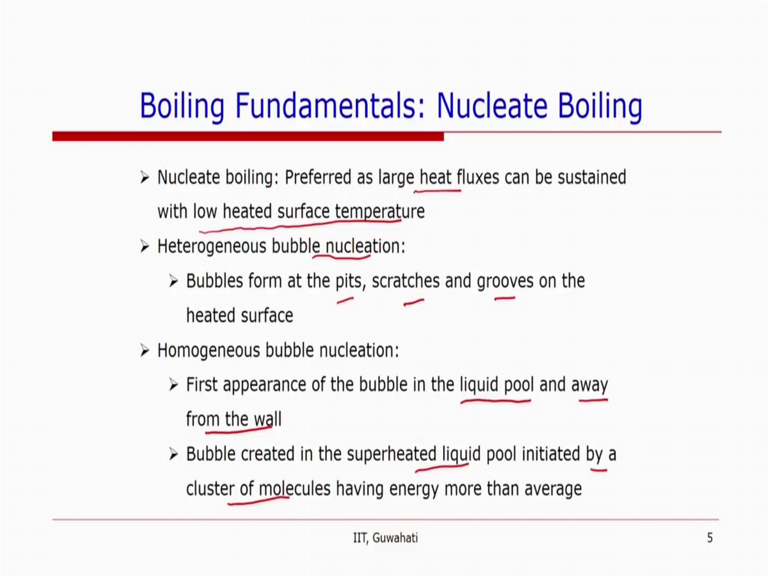

So, nucleate boiling is the preferred mode of boiling heat transfer as large heat fluxes can be sustained while maintaining low heated surface temperatures. So, we can see when we go to transition boiling regime that the heat flux decreases, but delta T or T wall minus T saturation keep increasing. So, the wall temperatures keep increasing in this case. Now the bubble nucleation can be by two mechanisms; one is homogeneous bubble nucleation which refers that the nucleation can happen anywhere in the liquid.

So, this is defined as the appearance of the bubble in the liquid pool and away from the wall straight in the liquid. Now these bubbles are created when the liquid is superheated and this is initiated by a cluster of molecules of liquid which have energy higher than the average energy of the molecules in the pool of liquid. But in this case the super heat or super heating the amount of superheating of liquid can be very high. On the other hand the heterogeneous bubble nucleation happens at the pits, scratches or grooves.

So, basically no surface is perfectly smooth. There are always micron size or smaller cavities or scratches or grooves present on the surface and when the liquid is dropped on it, there might be some air trapped on it and then when the nucleation happens or when the heats heat is given to this these the air trap will grow with the liquid converting to vapor and the bubble bubbles groove in it. We are not going to the details of this bubble ah bubble nucleation, but in any standard boiling book you can find the different relations for bubble nucleation and further details of heterogeneous bubble nucleation as well as homogeneous bubble nucleation.

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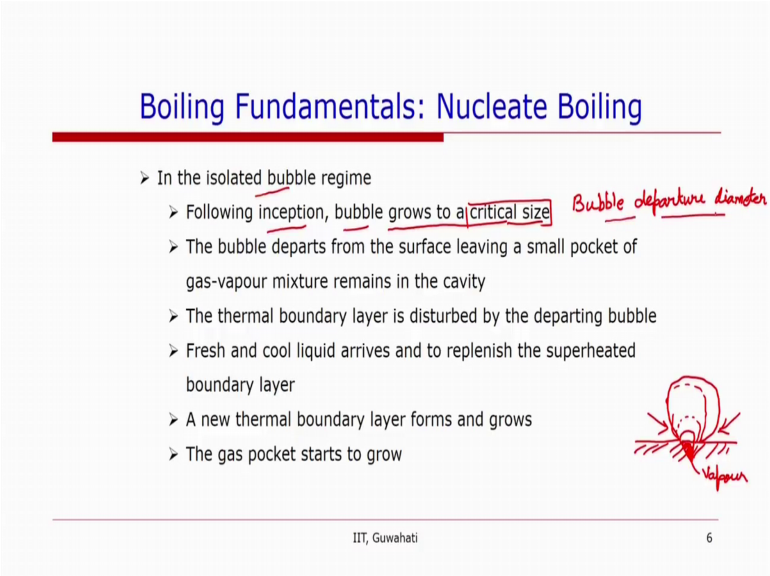

So, when there is one isolated bubble what happens that in the, in during the heterogeneous bubble nucleation after the boiling inception the bubble start growing and then it grows to a critical size; which is generally called the bubble departure diameter. So, this critical size is known as. Then when the bubble has grown to a sufficient size the bubble departs from the surface. So, it leads the solid surface with so if we have a picture of a nucleation site.

So, this might be a cavity or groove on which the bubble which starts growing then this might grow further and then it might lead at a particular size and then once it leaves, the bubble leaves the surface, a small amount of liquid, a small amount of vapor it is still present and when the bubble leaves the thermal boundary layer that was growing around the bubble that is disrupted and the bubble leaves and then they reach phrase liquid or the cooled liquid that comes in and replenish the superheated boundary layer or again.

And then again a new thermal boundary layer grows, the bubble grows and then gas pocket starts to grow and so on and further again the same process is repeated almost periodically if you keep the heat flux constant. You can observe this ah if you keep the heat flux constant in a pan or water boiling in a pan open to atmosphere. So, the diameter at which this bubble starts leaving surface is called bubble departure diameter

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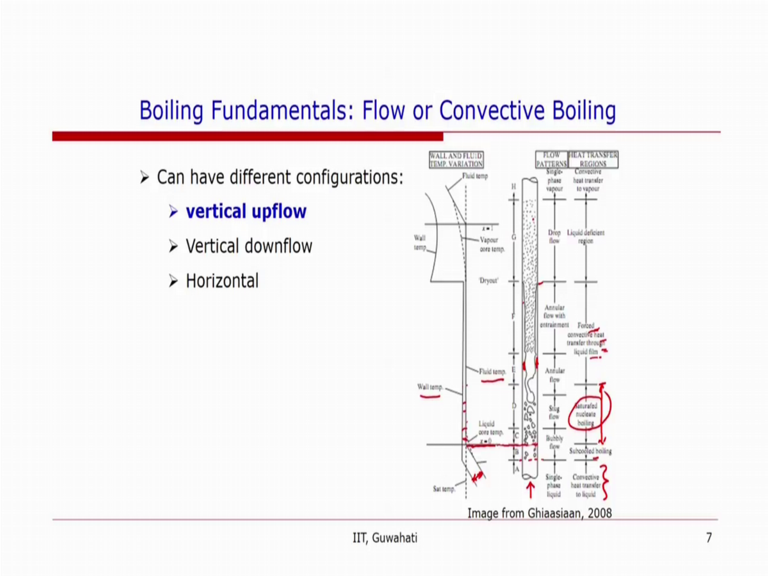

So, that was about the pool boiling and in the pool boiling we have seen two mechanisms of heat transfer at low heat fluxes what we have is nucleate boiling which is called by the nucleation of bubbles and at high heat fluxes the film boiling takes place. Now the other form of boiling which is known as flow or convective boiling it refers to the boiling in a channel. Now, in an environment when gravity is present, the orientation of the channel is going to matter because in the presence of gravity buoyancy forced will be there as the liquid and vapor phase has different have a very different densities.

So, the boiling in the vertically upward channel, vertically downward channel and horizontal channel are going to be different. Generally the orientation of the channel is preferred to be vertically upward; nevertheless in a number of applications the channel orientation might be vertically downward or horizontal or where the boiling is not the intended application there when the boiling occurs; it may occur in a vertically downward or horizontal orientation.

So, this image shows a lot of information about flow boiling in a in a conventional channel, in the vertically upward where channel orientation is vertically upward or the flow is happening in the vertically upward direction. So, as you can see in this case up to point A, this is only single phase liquid. So, the line on the left hand side represents the wall temperature and line on the right hand side represents the temperature of the fluid.

So, for the single phase liquid as the wall heat flux is increased, the wall temperature keep increasing, as well as the liquid phase temperature also keep increasing. Further on h near the wall, the temperature reaches a particular point the wall temperature is above slightly above a saturation slightly above the saturation temperature, then the wall temperature becomes constant and bubbles start growing near the wall or bubbles start being generated near the wall. However, the bulk of the liquid is still sub cooled. So, in this case what we have the liquid is sub cooled, but the liquid near the wall may be superheated because of a temperature profile in the channel.

So, when if you remember the single phase flow heat transfer in a channel the liquid that is near the hot wall that will be at higher temperature than the liquid at the center. So, when the liquid near the wall is at higher temperature it starts growing bubbles and then these bubbles will leave the wall and move towards the center. They might condense depending on the flow conditions and so, overall slightly above this one start looking at or the quality becomes 0 or the quality starts growing more than 0, slightly after when this sub cool boiling starts.

And once so, just at the sub cool boiling liquid quotient. So, at this place you can see that there is the liquid, if you look at the liquid in an average sense then the temperature of the liquid is sub cooled. So, that is why we have and the sub cool boiling the quality to be 0 here, but there are small amount of bubbles present plus there is some amount of liquid which is sub cooled.

So, that is why the quality is shown to be 0 here. As we increase the heat transfer, now we can see that the wall temperature and the fluid temperature both of them have become constant and so, the difference between the wall temperature and the fluid temperature is a constant and at a particular point until a certain length while we observe is what is called saturated nucleate boiling.

So, in this case the mechanism of boiling is still nucleate boiling. So, bubble nucleation happens and then the quality is smaller so that means, the vapor fraction it is smaller. Now you can see that in the sub cooled boiling and saturated nucleate boiling the bubbles are smaller. So, if you refer to the discussion of flow regimes that we had for adiabatic flow where there was no heat transfer then at low gas flow rates the flow regime was bubbly flow regime. So, here we see the appearance of the bubbly flow regime at low at the entrance of the channel and because the quality is low here, as we move further down the channel these bubbles coalesce and big grow and the occurrence of slug flow or the large bubbles happen.

Further down we see the occurrence of annular flow. So, because the quality has increased sufficiently and the as the quality increases you know the volume fraction of gas becomes very high because the density of gas is very small when compared with that of the liquid.

So, at a certain distance annular flow starts setting up; so that means, there is a continuous film of liquid and gas is there in the core. So, no more nucleate boiling is the dominant mechanism that the bubbles are the heat that is being coming in it is being transferred from the film and then the evaporation happens and the nucleate boiling does not happen in this case. So, this is called forced convective heat transfer through the liquid film and in this case the convective heat transfer through the liquid film is happening.

And after that you might see some of the, that the annular flow has some drops of liquid dispersed in the gas core. Eventually as we move further down the film thickness keep decreasing and at a certain point the dry out will happen. So that means there is no liquid film in contact with the wall and vapor is directly in contact with the wall. So, as you can see here the wall temperature suits up and then that as heat transfer is very inefficient in the in this region and then finally, there is only vapor phase present and one will have only the single phase vapor present in the channel .

So, we have different flow regimes in terms of heat transfer or boiling heat transfer the first being the convective heat transfer for liquid just single phase. Then the bubbly flow is start during the sub cool boiling and as the boiling increases further we have saturated nucleate boiling and this happens of the nuclear boiling happens generally for slug flow and bubbly flow regime. In the annular flow regime what is observed is force convective heat transfer to the liquid film and then when the dispersed droplet flow or mist flow happens and then and the finally, only vapor phase is present in the channel ok.

So, as you can see the heat transfer coefficient will be a constant in the single phase liquid flow. Further up here we can see that the delta T is constant and so, the heat transfer will be a constant in the or heat transfer will be dependent on Q wall over delta T and this delta T is a constant in this case. Now this delta T even though the temperatures are increasing, but delta T is constant so heat transfer is constant here. In this case delta T is a constant and over temperature and this bulk flow temperature is also constant. Remember that the heat transfer coefficient is defined as Q wall divided by T wall minus T bulk where the T bulk its same at the saturation temperature in the saturated nucleate boiling region or in the forced convective region, but in the single phase liquid region the liquid will be sub cooled. So, the saturate saturation temperature and bulk flow temperature will be different.

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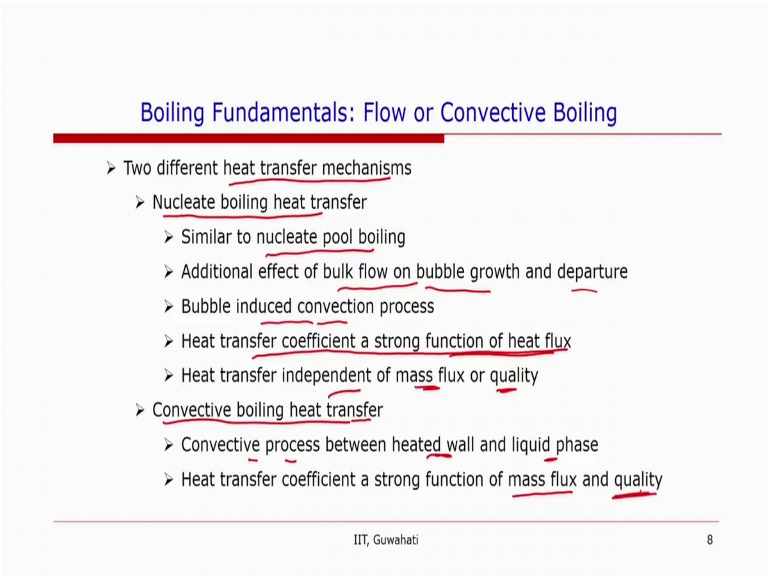

So, in the flow or convective boiling there are two different mechanisms of heat transfer that are in play; one is nucleate boiling heat transfer, another is convective boiling heat transfer as we have just seen. So, the nucleate boiling heat transfer it is similar to the mechanism is similar to nucleate pool boiling. The only difference is that the bubble departure will be affected by the flow patterns or the departure of the bubble or the religion of the bubble is going to affect the flow behavior in the channel. So, the interaction between the flow and the bubble departure is an additional factor when we consider nucleate boiling in the flow or convective boiling as a mechanism.

So, in this case one should remember that the bulk flow might affect the growth of the bubble and departure of the bubble and bubble induced convection process. So, bubble might induce some convection which can add to the already existing the convection process.

What is observed that in the nucleate boiling heat transfer, the heat transfer coefficient is a function of strong function of heat flux? But it is independent of the mass flux or the vapor quality. So, vapor quality you might remember is the mass fraction of the vapor present in the channel. Now for the case of convective boiling heat transfer or the for convective boiling heat transfer mechanism the dominant mechanism is the convection process between a heated wall and the liquid phase and in this case the heat transfer coefficient is almost independent of the wall heat flux and it is a strong function of mass flux and the quality.

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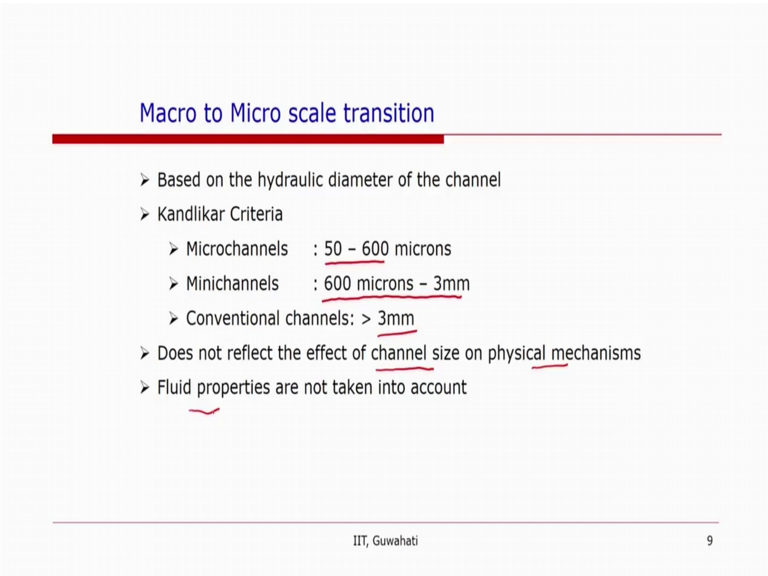

Now, what we have looked at is two different mechanisms of boiling in conventional channels; pool boiling and two different modes of boiling, pool boiling and forced or flow boiling. In the pool boiling where the heat transfer is happening in a stagnant liquid over a surface two mechanisms can exist depending on the heat flux, at low heat flux, at low wall heat flux and at low super heat what we have is nucleus and boiling and at high heat fluxes above a critical heat flux, transition boiling and then finally, film boiling happens. Whereas, in the post convective boiling, nucleate boiling happens predominantly in the bubbly and slug flow regimes and the post convective boiling happens in the annular flow regime.

So, there is a difference when we talk about the flow regimes in during the phase change process and flow regimes during the adiabatic flow, there is a an important difference between the two. When we talk about the adiabatic flow, the flow of gas and liquid the flow rates of gas and liquid phases are constant. So that means, the flow after some distance the flow becomes fully developed or a flow achieve is steady state.

Whereas, during the boiling as we move along the channel the liquid flow rate or the fraction of liquid decreases whereas, the fraction of the vapor phase keep increasing. So, the void fraction or fraction of the gas or volume fraction of the gas, keep increasing and as a result we have different flow regime along the length of the channel. This will also depend on the volume flux.

For example, the case that we have discussed is at low or moderate heat flux in a sufficiently long channel. If we have a very high heat flux applied on the channel wall then one will have a very high degree of superheat near the wall. And the bubbles start, bubbles will start growing and one can see that there might be film boiling, starting near the wall which is detrimental for a number of applications because the heat transfer in this case will be very poor and the wall temperature will shoot up to very high values.

Now, with this information or let us think about the boiling in microchannels. So, first thing to think about is that what is so different that the boiling will be different in microchannels? Then the second question or a related question comes. So, what is the channel size at which these micro effects if any start to come into play? So, there are different criteria a number of criteria have been suggested by researchers.

One of them by professor Kandlikar and he suggested that for channel size between 50 to 600 microns they can be termed as microchannels and between 600 microns to 3000 micron or 3mm, they can be termed as mini channels and channels above 3mm, they can be termed as conventional channels. However this classification seems to a bit arbitrary because it does not take into account any physical mechanisms and the effect of the properties of the fluid that are flowing in the channel.

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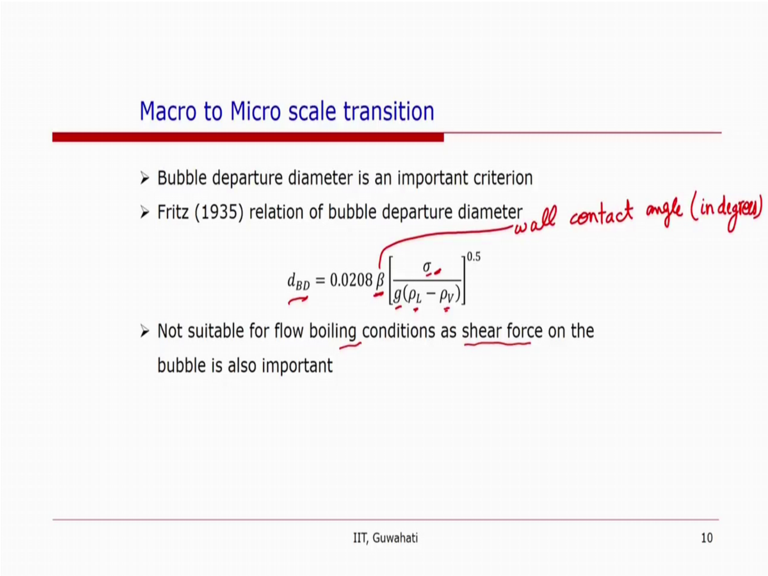

So, another criteria or a number of criteria have been suggested based on the bubble departure diameter. Because what can happen that when the pool boiling or the when the nucleate boiling occurs in microchannels the bubble departure diameter probably one of the criteria can be; when the bubble departure diameter is equal to the size of the channel or is compeller comparable to the size of the channel, then the flow mechanism is not going to remain same as one will see in as one will see in the conventional channels. Because in the conventional channels there is sufficient space for the bubble to move towards the center, whereas in a micro channel or in a mini channel or in a millimeter size channel the bubble departure diameter may be of the same size as the size of the channel or even bigger than the channel size.

So, in this case the bubble will not grow in the radial direction it will have to grow in the axial direction when the bubble departure diameter is larger than the channel size and one will have Taylor flow kind of flow regime in this case. Moreover even if the size of the, bubbles are smaller they can easily called as and make a bigger bubble and then so some of these micron size effects. So, bubble departure diameter seems to be an important parameter or important criteria which can determine that when the channel size should be considered to be micro or micron size channel or or smaller channel.

So, this correlation, given by Fritz for pool nucleates boiling. During pool boiling he has this, the bubble departure diameter as a function of wall contact angle. So, beta is wall contact angle, sigma is surface tension and this wall contact angle is in degrees. Sigma is surface tension g is gravity and rho L minus rho V. So, rho L is the density of liquid phase and rho V is the density of the vapor phase. However, when it comes to the flow boiling as one can see this is only the ratio of buoyancy forced and surface tension. So, it does not take into account the shear forced that may act or that acts on the bubble steering bubble departure. So, it remain on be very suitable for flow boiling conditions..

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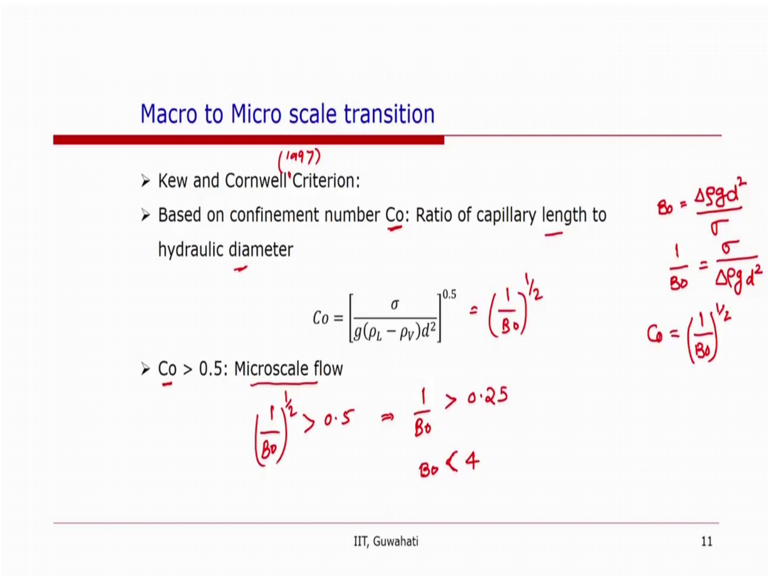

So, using this bubble departure diameter a criteria Kew and Cornwell they give a correlation based on a non-dimensional number this we termed as confinement number, which is a ratio of capillary length and hydraulic diameter and one can relate this with say bond number. So, this is bond number one can see is delta rho g d square over sigma. So, if one look at this then this becomes 1 over bond number is equal to sigma over delta rho g d square. So, confinement number is 1 over bond number raise to the power half. So, this is sigma over g delta rho d square.

So, this confinement number is nothing, but inverse of this square root of bond number. So, Kew and Cornwell this suggested that when the confinement number is greater than 0.5, then the flow can be term to be Microscale. So, if you look this in bond terms of bond number so 1 of bond number is greater than 0.5 or sorry 1 over bond number square root. So that means, 1 over bond number is greater than 0.25 or when bond number is less than 4, it one over point two five is four. So, a bond number is less than four then the flow can be termed as microscale. So, this means and the bond number is less than 4; that means, the surface tension starts becoming important when compared with the buoyancy forced.

So, this criteria is based on if you look at the bubble departure diameter is comparison in this case is a comparison of surface tension force and the buoyancy force. So, this is one criteria that the suggested by Kew and Cornwell.

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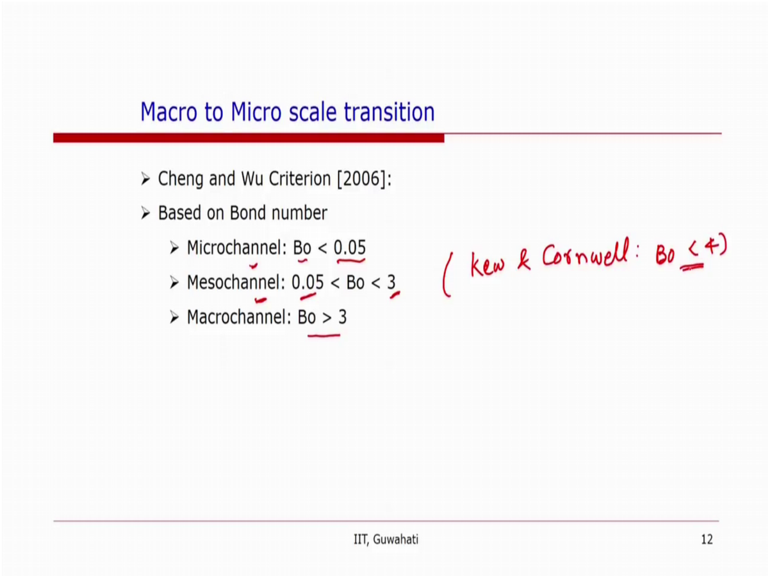

Then another criteria based on the bond number was suggested by Cheng and Wu. So, that was based upon the bond number itself and the bond number if it is less than 0.05 then the termed it has microchannel and between 0.05 to 3 it was termed as mesochannel and bond number greater than 3, this was termed as microchannel. So if we look at the Kew and Cornwell they had bond number less than 4 for the microscale effect to assume importance.

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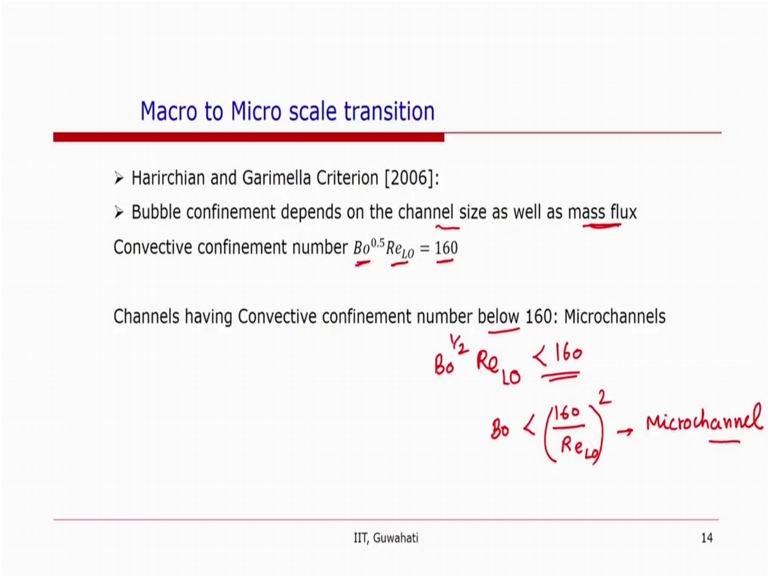

Now, another criteria that has been suggested by Harirchian and Garimella; They suggested that not only the effect of bond number, but the effect of mass flux or the flow rate of the liquid is also an important criteria to determine if the microchannel effects are going to be important. And they suggested a that the root of bond number multiplied by the Reynolds number when it is equal to 60, below 60 if bond number raise to the half into liquid only Reynolds number if it is less than 160 then they termed is as flow to be microchannel or when the bond number is less than 160 Reynolds number is square then, then the channel can be considered to be microchannel.

So, these are different criteria, that has been suggested. The latest one in which they have also shown they have also considered the effect of not only the properties of the liquid, but also the flow behavior, so which can take into account probably the shear forces.

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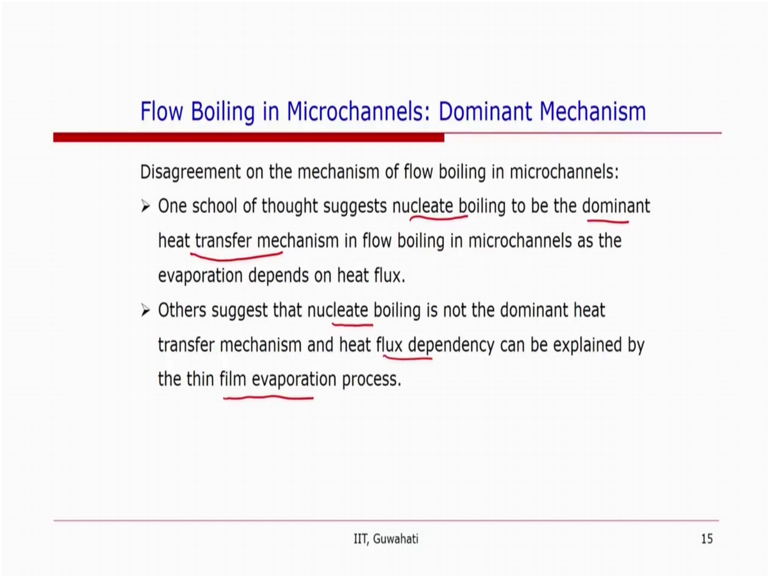

So, now coming to the dominant mechanism flow boiling in microchannels, there are two different school of thought and in the recent years there has been a lot of research to identify that which of the mechanism of what is the dominant mechanism boiling. In one is school of thought it is suggested that nucleate boiling is the dominant heat transfer mechanism. And this assumption or this comes from the observation that the heat transfer coefficient is a function of heat flux, but not a function of mass flux and vapor quality. And based on this it has been suggested that nucleate boiling is the dominant mechanism of heat transfer.

On the other hand researchers have suggested that it is not the nucleate boiling, but the evaporation process or the convective flow boiling or convective evaporation is the dominant mechanism of boiling and it has been shown by in developing some models, some mechanistic models that the heat flux dependency can be explained by this thin film evaporation process. So, we will further look at into this the models that has been developed till date and a bit more into detail about the discussion on dominant mechanism in flow boiling in microchannel in the next lecture.

So, to sum up in this lecture we have looked at some fundamentals of boiling in microchannels in general; the pool boiling and forced convective boiling and in the pool boiling there are two different mechanisms nucleate boiling and film boiling and the transition between the two. So, there are three different regimes that are generally shown on a pool boiling curve. Then for the forced convective boiling there are two different regimes or two different mechanisms; a nucleate boiling which is dominant in the slug flow and the bubbly flow regime and the annular flow boiling or the or the convective forced boiling which is dominant in the annular flow regime. Then we have looked at some of the criteria's that have been suggested, some of the criteria in the literature that have been suggested for ah from macro scale or from large channel to micro scale transition. And it appears that most of these criteria are based on bond number which is responsible to determine the bubble departure diameter. One of the recent criteria includes the bond number as well as the mass flux in terms of the Reynolds number of the liquid.

So, the discussion on the mechanism of heat transfer in microchannels; there are two different schools of thought one suggests that the nucleate boiling is the dominant mechanism and the other suggests that the forced convex to boiling is the dominant mechanism. So, we will look at further on these both, the discussion or both the point in the next lecture.

Thank you.