Multiphase Microfluidics
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Lecture - 18
Flow Boiling in Microchannels Contd.

Hello. So, in this lecture we will continue our discussion on Flow Boiling in Micro Channels. So, in the previous lecture we looked at the fundamentals of boiling nucleate boiling and convective boiling and their contribution in general in conventional channels. Then we looked at the different criteria that have been proposed especially with respect to the boiling in small diameter channels where the physics of boiling is going to change because of the confinement of the flow.

So, in this lecture we will look at some of the flow regimes or flow regime maps that are there in the literature for boiling in micro channels and then we will discuss a bit about the mechanisms of boiling in micro channel and some model. So, as we have been doing in the entire course to get some prior information or took in order to start with we have looked at what is happening in the conventional channels.

So, same goes for the flow regime maps in micro channels for boiling. So, people have tried to compare the flow regime maps for micro channels with those in the boiling in conventional channels and there does not seem to be the maps or the criteria proposed in the conventional channel they does not fit well for the data obtained for micro channels.

Then we have also seen two phase air water flow or two phase gas liquid flow in micro channels for adiabatic conditions where there is no heat transferred and in such cases we have obtained different flow regimes predominantly slug bubbly churn annular and slug annular.

So, people have also try to compare the two things, but the difference in the two is that the flow rates of the gas and liquid are constant in the adiabatic case whereas, in the case of boiling the evaporation is happening. So, the gas flow rate or the vapour quality increase continuously and the liquid flow rate keep decreasing.

So, along the channel length if the channel is sufficiently long one see different flow regimes in the channel length itself, but one do not see the fully developed flow. So, for example, one may not be able to see the regular periodic Taylor flow; that is observed in case of adiabatic flow where as in a boiling one might say that these bubbles there are a number of long bubbles, but they will have different sizes and they will grow in size and they move along in the channel they will even coiners with each other.

So, the flow regimes will depend on the channel size on the gas and liquid superficial velocities. So, here the gas and liquid superficial velocities we can have as say vapour quality with will which can represent or which is a measure of gas flow rate and the total mass flux that can represent the liquid or total mass flux multiplied by 1 minus x, where x is the quality can represent the liquid flow rate.

Apart from this the wall heat flux can also play a major role in the occurrence of the flow regimes.

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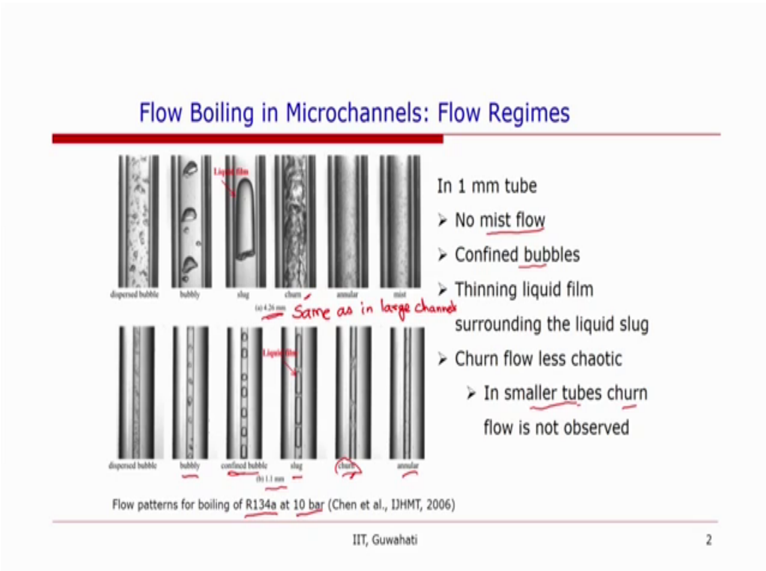

What we have in this slide is; the experiments that have been performed in two different channel sizes: one is 4.26 mm and the other one is 1.1 mm and this is for boiling of R 134 a at 10 bar pressure and they observed that while the boiling regimes in 4.26 in mm channel they looked like conventional channel whereas, there was significant difference in the flow regime maps that were observed in the millimeter or 11 millimeter size channel.

So, the first thing they suggested that they have not observed any mist flow. So, you can see the mist flow is determined or is characterized as the droplets dispersed as mist in the almost dry wall. So, where there is the when almost all the liquid has dried up vapour has become saturated or maybe superheated in this vapour there are small liquid droplets there which are dispersed.

So, they did not see any such thing and flow regime was annular and then probably dry out regime whereas, the confined bubbles. So, here they have seen bubbles which are confined in the channel and there it was a liquid slugs kind of thing and even the image in the bubbly flow when there are bubbles which are confined. So, this bubbles, when after nucleus and they did not departed; before departure the bubbles elongated.

And then they also suggested that the liquid film surrounding the slug or the liquid film thinning liquid film. So, the liquid film surrounding the liquid slug that started thinning or liquid. So, that is another characteristic and then they saw that the churn flow, whereas, in the large channels it was very chaotic the chaotic nature of the churn flow decreased at the channel size decreased and it has been observed in other experiments that in smaller channels the churn flow is not even observed ok.

So, these are some of the differences that has been noticed we had presence of similar flow regimes as we discussed in gas liquid adiabatic flow in micro channels we had a bubbly flow confined bubbles slug annular flow and then this churn or depending on the condition slug annular condition.

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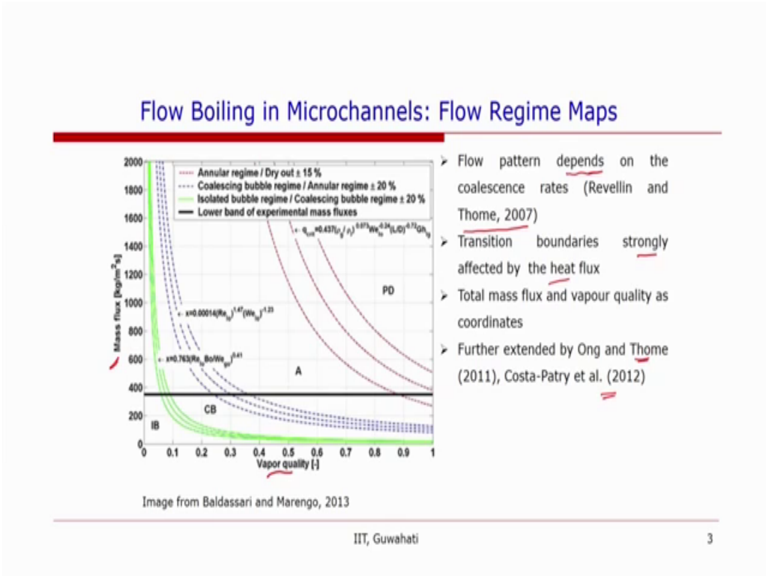

So, a flow map has been proposed by Thomas group and they looked at the flow regime on the coordinates where mass flux is on the y axis and the vapour quality is on the x axis and then they identify it or found that, because the flow pattern it depends strongly on the coalescence rate on the bubbles are generated they grow and then they leave the wall and these bubbles may coilers. So, the bubble generation rate and coalescence rate that is a determining factor that this flow regime may occur. And it is strongly dependent on the heat flux and this flow regime was further map was further extended by further experiments by their group.

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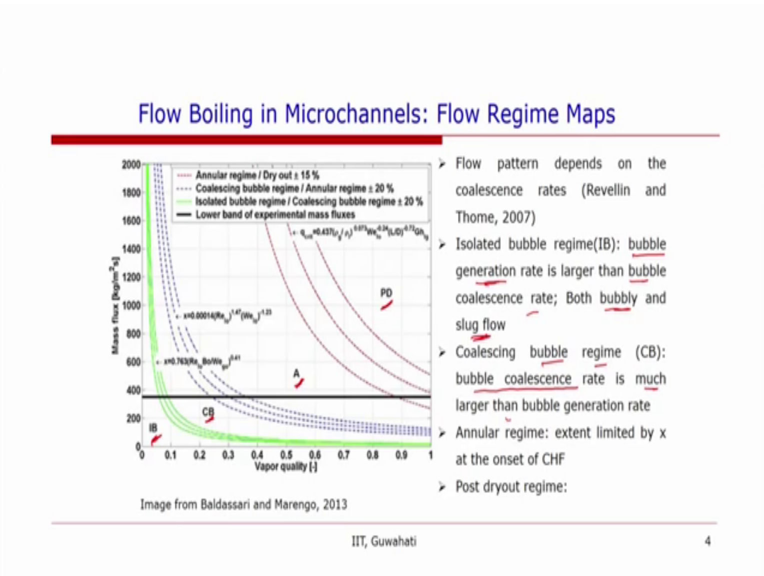

So looking at the 4 flow regimes that they identified IB which is isolated bubble regime, so this is characterized by that the generation bubble generation rate is larger than the coalescence rate of the bubbles and in this case they saw both bubbly and the slug flow.

The next flow regime is comes coalescence coalescing bubble regime. So, in this case in this regime the bubble coalescence rate is significantly larger than the bubble generation rate. So, isolated bubble regime and then coalescing bubble regime when the bubbles have coalesced of course, we will get an annular flow regime. So, the next provision was the annular flow regime and then it was observed until a dry out occurred on the channel wall. So, the next regime was post dry out regime they have also given expressions for the different transitions.

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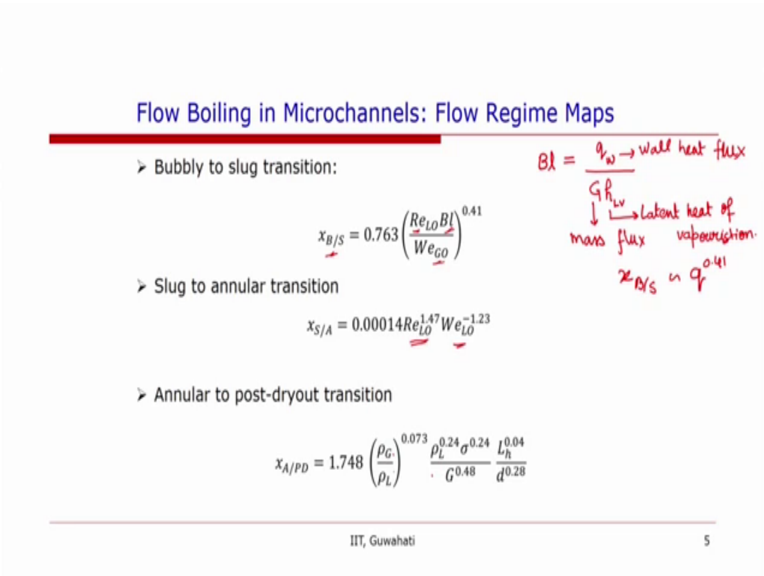

So, the transition from bubble to slug regime it depends on liquid only Reynolds number and this is gas only waiver number boiling number. So, boiling number which we have not seen until now is defined as Q wall G h Lv. So, Q wall is wall heat flux G is mass flux and hLv is latent heat of vaporization.

So, from this one can observe that x from boiling to slug regime it depends on q raised to the power 0.41. So, it is dependent on q and then slug to annular transition it depends on liquid only Reynolds number and liquid only waiver number and then annular to post dry out transition is dependent on the ratio of the density of the two phases and rho L sigma over g and l h over d.

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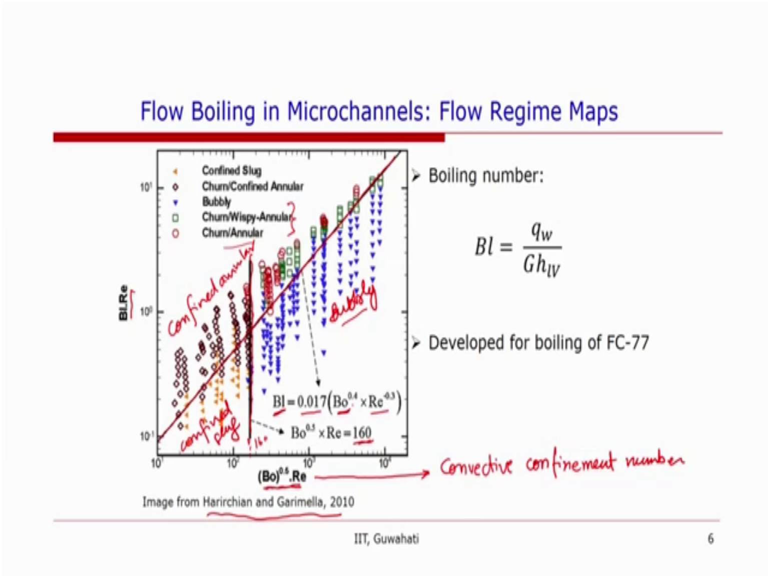

So, another flow regime that has been given by Harirchian and Garimella they showed it on two different non dimensional numbers as coordinates on the x axis is bond number raised to the power 0.6 into Re on and the y axis boiling number into Re. So, boiling number is same that we have defined in the previous slide and you might remember from the previous class that this is called confinement number convective confinement number here Bo is the bond number and Re is the liquid only Reynolds number.

So, they identified a two different transitions here one is the vertical line as we see here this vertical line corresponds to Bo 0.5 into Re. So, the x axis is equal to 160 this point is 160 and that suggests that bellow this one get the two flow regimes that we get here is this is confined annular and the other one here is confined slug. So, the flow regimes below this are confined above this one get either bubbly flow regime or churn wispy annular or churn annular flow regime.

So, the vertical line separates the confined annular or slug flow regime with the bubbly or churn annular flow regimes. Now the other line that separates is the slanted line which is given by this expression and that the boiling number is 0.017 bond number raised to the power 0.4 and Reynolds number raised to the power minus 0.3.

So, in this case we see that below the line the flow regime is either bubbly or slug and above it the confined annular. So, this represents the that the bubbles have coalesced and they have made a continuous vapour stream or they have depending on the surface tense and they have the circular regimes or bubbly regime in the bubbly regime there will be bubbles will be circular or will have a curvature where as a in the annular flow the bubbles have collaged on may and have made a continuous gas stream ok.

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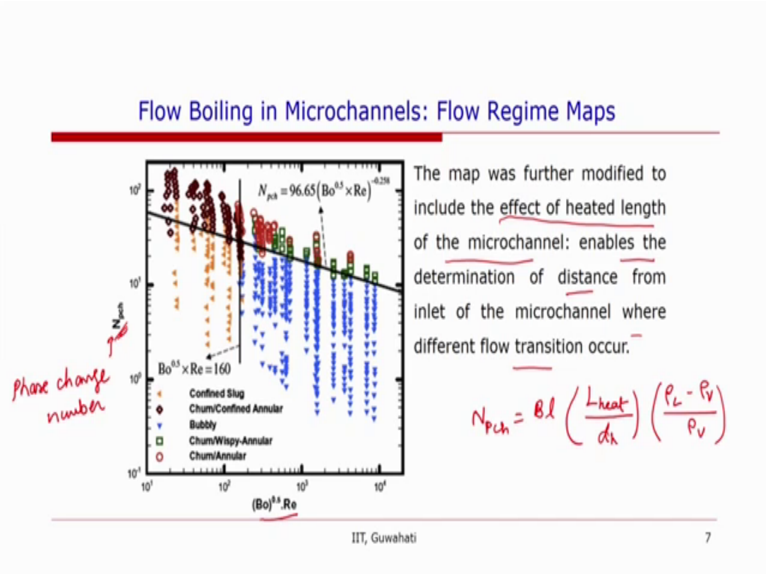

So, these are the two flow regimes that has been suggested and then Harirchian Garimella they improved upon their flow regime maps and represented it based on NPch or phase change number. So, this is called phase change number while the x axis regiment same and this phase change number is equal to boiling number into l heated divided by d h into rho L minus rho V divided by rho V. So, this takes into account the effect of the heated length of the micro channel. So, such a flow regime this also enables to predict or determine the distance from the inlet where different flow transition can occur.

So, in this case also the same data has been presented, but it has a different ordinate ok. So, as we discussed.

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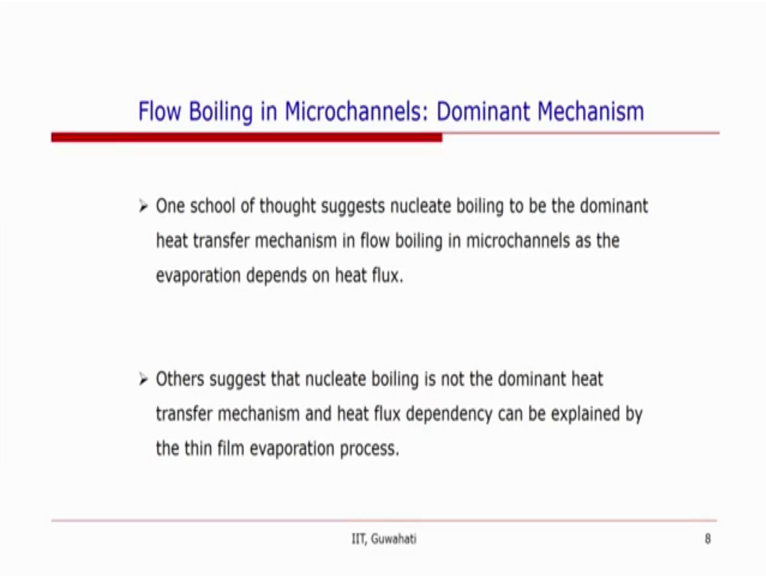

In the last class that there are two different views on the dominant mechanism of flow boiling in micro channels on the one hand people suggest that nucleate boiling is the dominant mechanism of flow boiling in micro channel others suggests that it is not the nucleate boiling a, but the evaporation or the convective boiling or the thin film evaporation that occurred in the slug flow that is the dominant mechanism of boiling.

So, let us look at where does this these belief comes from.

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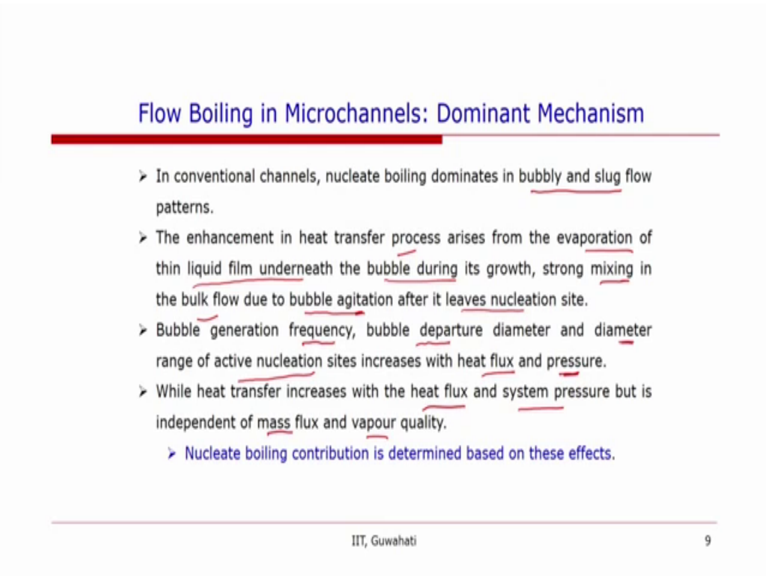

Now, in conventional channels the nucleate boiling it dominates in bubbly and slug flow patterns and the enhancement in heat transfer occur from different physical phenomena such as evaporation of the liquid film that is near the bubble and the bubble growth and then this causes strong mixing in the bulk flow because of the bubble agitation when it leaves the nucleation site. So, that is the enhancements or those are the factors which causes the enhancement of heat flux during nucleate boiling.

So, the nucleate boiling it depends on the bubble generation frequency the bubble departure diameter and diameter range of active nucleation site and all this increase with heat flux and pressure. So, as a result the heat transfer in the nucleate boiling in conventional channels it is a function of heat flux and system pressure, but it is independent of mass flux and vapour quality.

So, this particular observation that if the heat transfer coefficient is proportional to or is a function of wall heat flux and system pressure and it is independent of mass flux and vapour quality then it has been concluded for the experiments in flow boiling in micro channel that the nucleate boiling is the dominant mechanism. So, that is the region so; that means, the number of experiments suggest that the heat transfer coefficient in flow boiling in micro channel is dependent on wall heat flux and that is the region that people have concluded that nucleate boiling is the dominant flow mechanism

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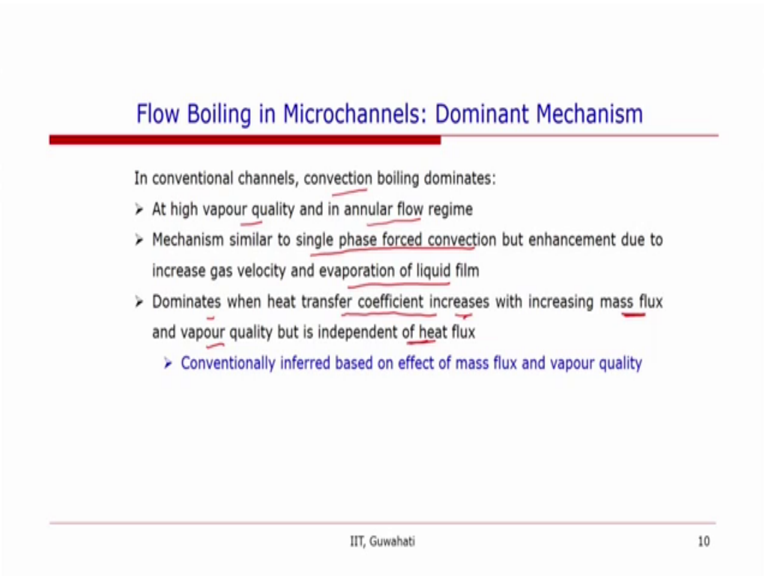

On the other hand, in the convection boiling of which occur at high vapour quality and the flow regime is annular flow regime nucleate boiling is almost suppressed there is less number of bubbles and the mechanism of heat transfer in this case is similar to single phase forced convection and the enhancement occurs, because of evaporation of liquid film and the increased gas velocity.

So, in this case; when the heat transfer coefficient increases with the mass flux; so when the convective boiling is dominant then the mass flux the heat transfer coefficient is dependent on mass flux and vapour quality, but it is independent of heat flux. So, if this is, so then one in first that the flow boiling in micro channel is dependent on the convective boiling.

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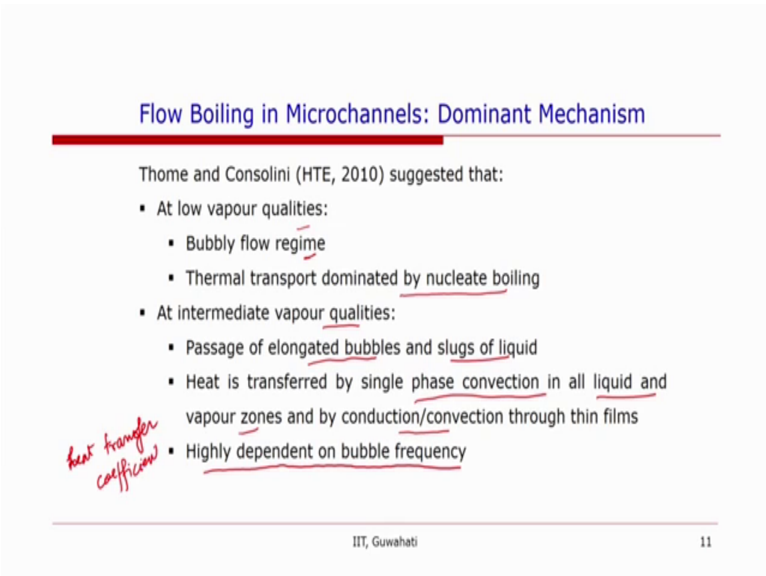

So, now this was the principal region for belief that flow boiling in micro channel is nucleate boiling as most of the experiments showed a strong dependency of the wall heat flux or the strong dependency of the heat transfer coefficient on the wall heat flux and it can be a for a number of regions; because depending on the flow conditions depending on the heat flux conditions one can have, one might be operating in the regime where nucleate boiling is dominated or when might be operating where other mechanisms such as convective boiling or thin film evaporations are dominating.

So, based on their experiments and analysis Thomas group suggested that at low vapour quality the bubbly flow regime occurs and in this case the thermal transport is dominated by nucleate boiling; however, at the intermediate vapour qualities the bubbles elongate and elongated bubbles and slug of liquid. So, Taylor flow kind of flow regime is observed and then in such case the heat is transferred by the single phase convection in the all liquid and vapour zones and in the film a conduction or convection occurs through the thin films.

So, in this case the heat transfer coefficient is highly dependent on the bubble frequency.

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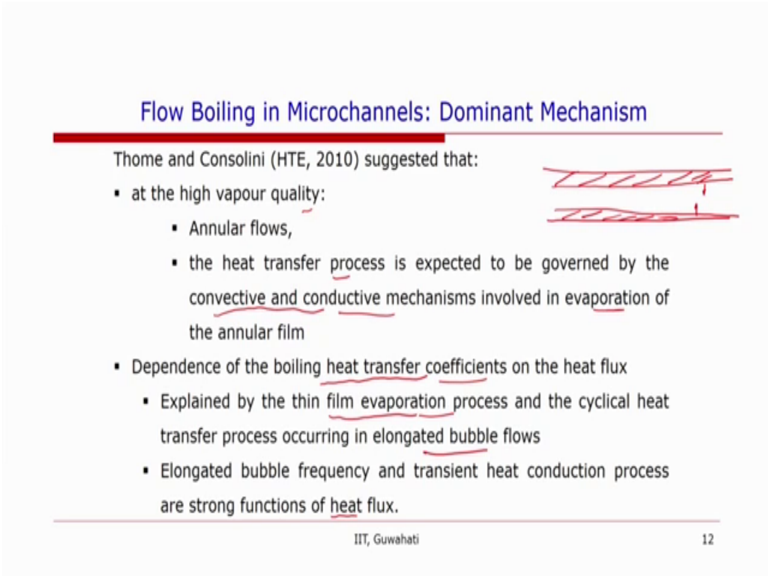

Now, when the vapour quality is high then the flow regime is annular flow regime and or in such case the heat transfer is expected to govern by the convection and conduction in the evaporation of thin film. So, in the annular flow there is a thin film that will reduce in the thickness because of the evaporation of the thin film. So, the conduction through the film and the evaporation will be the; dominant mechanism.

Now, they suggested that the dependence of boiling heat transfer coefficient on the heat flux it can be explained by thin film evaporation process in the elongated bubbly flow and elongated bubble frequency and transient heat conduction processes both are strong functions of heat flux. So, they developed a model for this.

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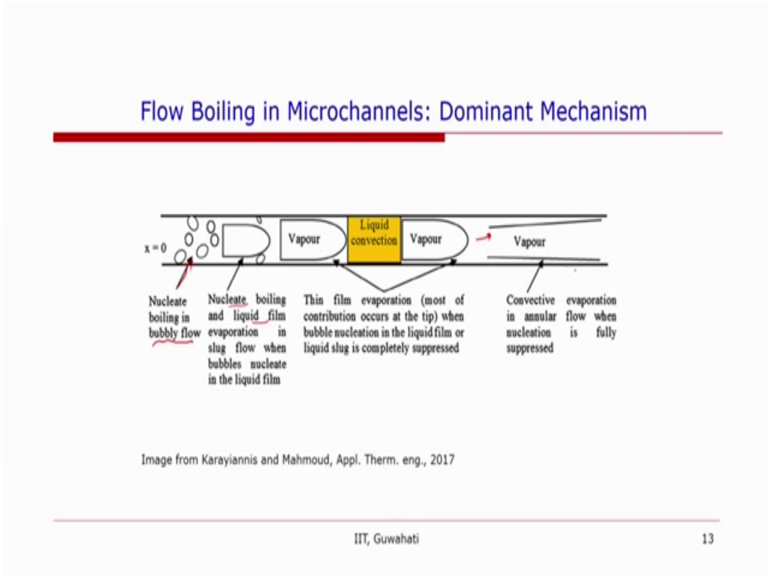

This is a visual picture of such that at low when the vapour quality is low, then bubbly flow occurs and the nucleate boiling is observed at higher vapour quality nucleate boiling as well as liquid film evaporation in slug flow both occurs even bubbles also nucleate in the liquid film. Further, on the evaporation in the thin film occurs and most of this contribution comes at the tip of the bubble and as the quality is increase the annular flow is observed.

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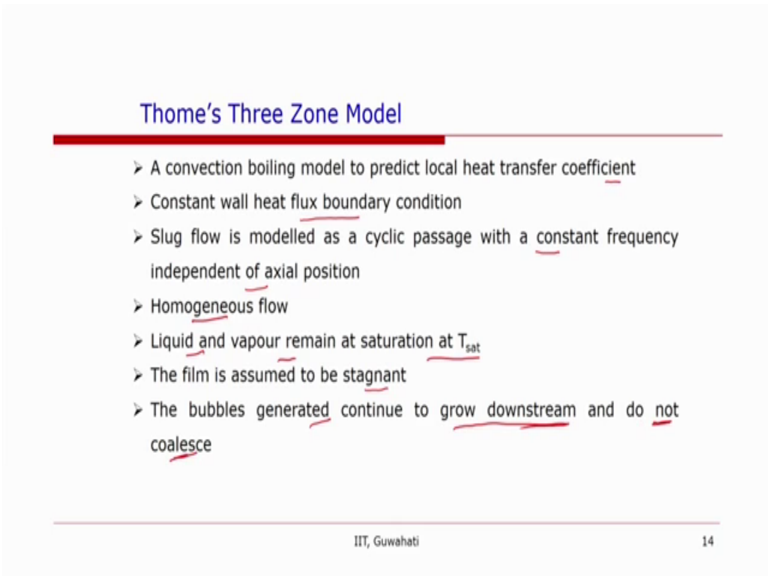

So, now based on he is under physical understanding develop from the experiments and cfd simulations Thome's he proposed a three zone model to explain the boiling in the slug flow regime and he had the following assumptions that the wall the boundary condition on the wall was a constant wall heat flux boundary condition and slug was considered as a cyclic path passage.

So, slug flow was modelled as a cyclic passage with the constant frequency independent of the axial position and the flow was considered as a homogeneous flow; that means, the gas and liquid phases had the same velocity there was no slip between the gas and liquid phases.

So, it was homogeneous flow both the phases were considered to be liquid and vapour they were considered to be at the saturation temperature the film that surround the slug it is considered to be stagnant and they also assumed that the bubbles which are generated they continue to grow downstream and do not coalescence do not coalesce. So, the coalescence has not been taken into account in their model.

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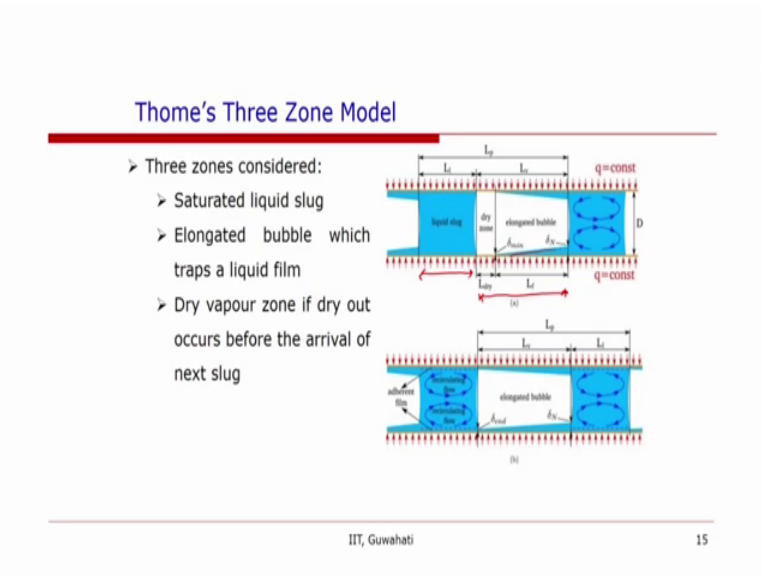

So, this is a visual picture of their model they considered three zone the liquid slug and the bubble which evaporates. Now depending on the length of the bubble and the velocity and wall heat flux there may be 2 or 1 region. So, as we see in the upper image there are two regions that the bubble the film surrounding the bubble has dried out; where as in the image below the film remains always surrounding the bubble. So, one can have two zone or three zones depending on if they dry out of the film occurs in the bubble or does not it does not occur.

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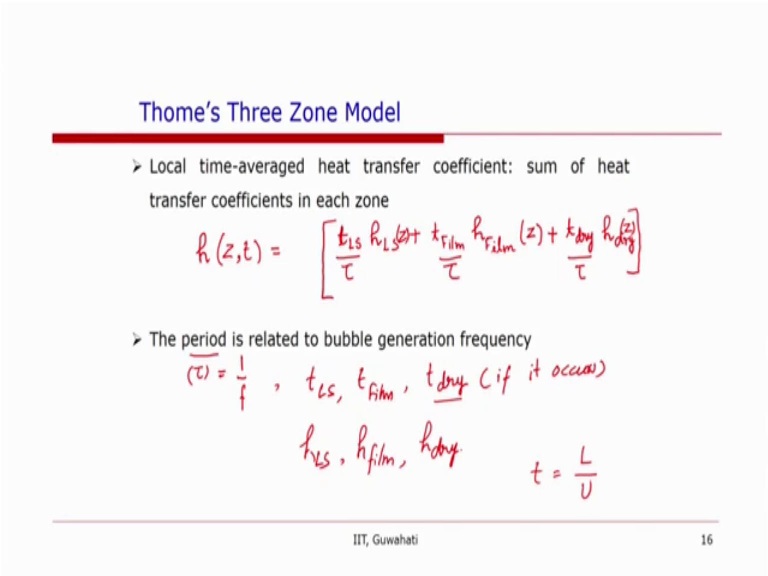

So, they considered the heat transfer for such a case and calculated that the heat transfer or the local heat transfer at is equal to sum on the heat transfer coefficients in each of these three zones. So, 1 over tau t of liquid slug h liquid slug plus t of film h of film z plus t of dry zone into h of dry

So, basically one can also write this in terms of the fractions of time; so tau. So, they consider tau as the period this period is tau; so when one bubble is generated and after that another bubble is generated. So, this bubble generation process has been assumed to be periodic and tau is the time period or between that two bubble generation. So, that will be equal to one over f or bubble generation frequency.

Now, as we can see that this model all of these are function of z and this is time averaged heat transfer coefficient. So, now, we need to get the heat transfer coefficient in the liquid slug we need tau and we need three times t L s t film t dry zone if it occurs and the expressions for heat transfer coefficient in the liquid slug heat transfer coefficient in the film and heat transfer coefficient in the dry zone

So, the flow velocity we can calculate the times based on the length divided by the velocity.

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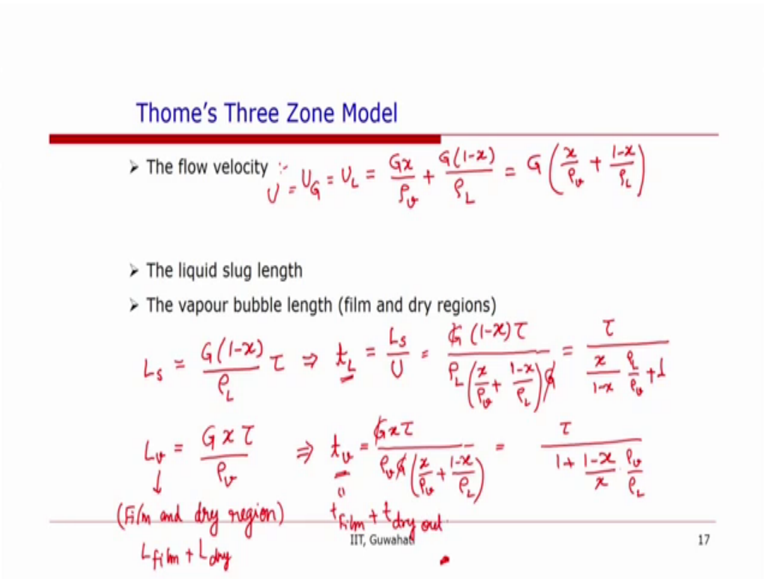

So, we need the flow velocity as we discussed earlier that the flow velocity is obtained by assuming flow to be homogeneous. So, the flow velocity is assume that U gas is equal to u liquid that will be equal to G x over rho v. So, gas flow rate divided by the or gas flux divided by the gas density plus G 1 minus x divided by rho L or we can write this as a G x over rho v plus 1 minus x over rho l.

Now, the liquid slug length or l slug can be obtained as g into 1 minus x divided by rho L into tau. So, that is the liquid slug length and similarly the liquid vapour length is g into x tau by rho v

Now, from this we can find out note that this includes film and dry regions. So, this is l film plus l dry. So, from this we can find out t in the liquid that is equal to L s over u let us say this is U. So, this will be equal to G 1 minus x tau over rho L into x over rho v plus 1 minus x rho L into G. So, G and G cancel out now what we have is or we can just write G here and now we can divide by a x. So, we will have tau divided by x over 1 minus x rho L over rho v plus one

Similarly, t vapour can be obtained as tau g x tau divided by rho v into g x over rho v plus one minus x over rho L G and G cancel out here and we have tau divided by x rho v over x over 1 plus 1 minus x over x into rho v over rho L. So, these are the expressions for t L and tv.

Now, we are not going to discuss the criteria for the film dry out here I mean we are not going to develop the criteria for the film dry out here, but we will look at briefly that. So, what we have here is we have been able to obtain t L and t v which is t film plus t dry out ok.

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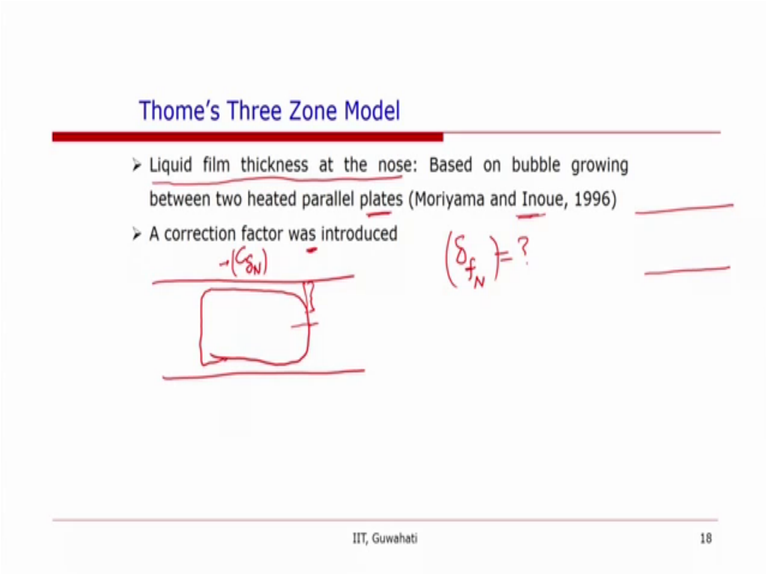

So, now the next question is that we need to find out the film thickness and from that we can obtain a relationship for the rate of evaporation of the film or the decrease of the thickness of the film with time using energy balance. So, first thing is that we need an expression for the liquid film thickness at the no jump the bubble. So, if this is our slug zone then what is the thickness of the liquid film at this point.

So, based on the experiments and the analytical model or the semi empirical model proposed by Moriyama and Inoue for a bubble which is confined between two parallel heated plates and it is growth they developed a relationship for the liquid film and the nose. So, let us call that delta f n, which is the thickness of the liquid film at start

Now, to utilize this they introduce a correction factor of which is called let us say c delta n. So, this was a model parameter and this depends on the. So, they obtained a expression for the film thickness at the nose which we are not going to discuss in detail.

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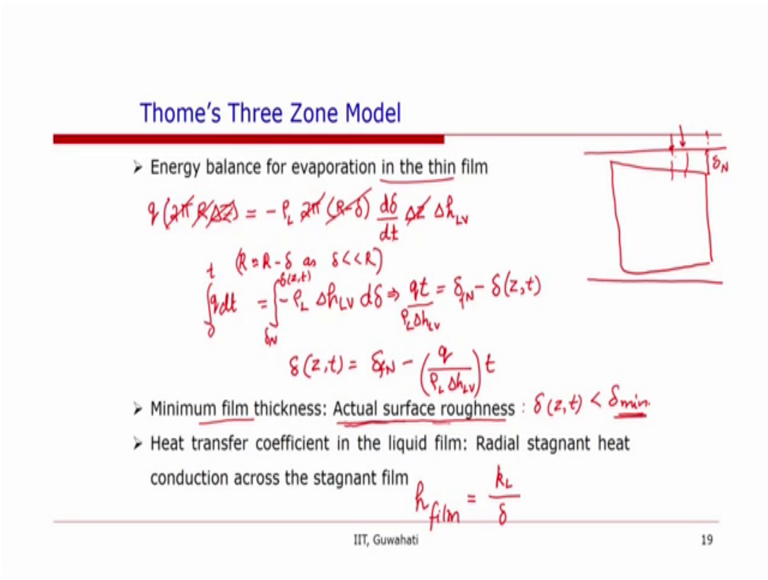

Now, based on the energy balance and expression was obtained for the evaporation in the thin film. So, for the bubble region we have the film thickness here as delta n and when it passes through the thickness of the film keep decreasing. So, if we consider a delta Z length of the film then we can apply a heat balance that q 1 pi r where r is the radius of the channel delta z.

So, this is the heat incoming from the wall in this delta Z thickness 2 pi R delta Z this is equal to minus rho L 2 pi R minus delta, where delta is the thickness of the film d delta over dt delta Z into delta h of vaporisation.

So, this is the heat coming from the wall and this is the heat required for the evaporation of the d delta thickness of the film. So, we can cancel out these two terms and delta Z can also be cancelled out and we assume that R is equal to R minus delta as delta is small negligible with respect to R.

So, we get from here q is equal to this R and R minus delta can be cancelled out. So, we get q is equal to minus rho L q dt is equal to minus rho L delta h L v into d delta. So, if we integrate this from 0 to t and at t is equal to 0. We will have delta n is the thickness of the film and delta is the thickness of the film at an arbitrary time.

So, we will have this will give us q t is equal to delta qt divided by rho L delta h L v is equal to delta n minus delta Z t or we can get the film thickness delta Z t is equal to delta n or delta f N minus q over rho L delta h L v into t. So, this is an expression for the thickness of the film.

Now when the film thickness becomes less than a delta minimum; then a dry out region occurs. So, in the first model that term developed one of the parameters was or one of the fitting parameters was this minimum film thickness. However, later on with the experiments and comparison with the experiment others experimental data they suggested that the actual surface roughness can be taken as the minimum film thickness that is where the dry out start occurring. So, this is not a fitting parameter anymore and it can be taken as an input in the model depending on the or based on the roughness of the surface

Now, heat transfer in the liquid film, because the film is considered to be stagnant. So, and for a thin film one can consider as film is equal to conductivity of the liquid divided by the delta. So, that will give the heat transfer in the liquid film.

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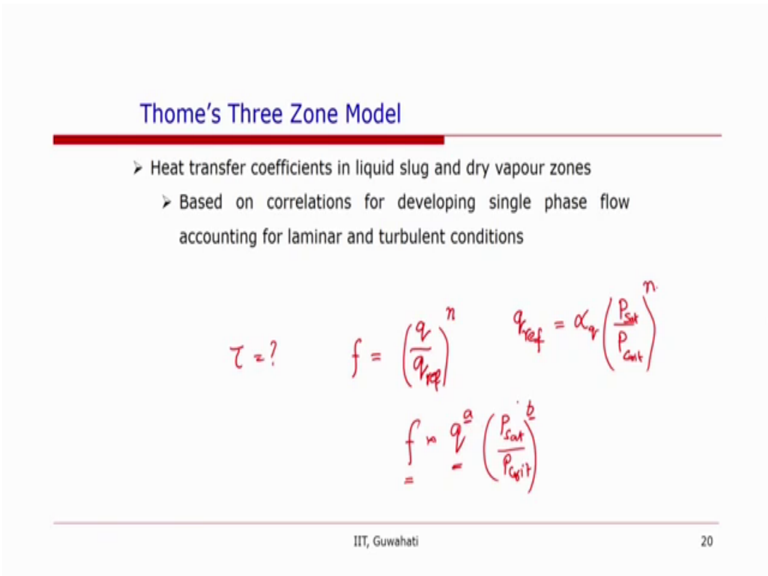

Now if we go back to our original model, then what we required is the bubble frequency or tau which is the period the time periods and heat transfer coefficients. So, we have already looked at the time periods for liquid slug and vapour we have also looked at the expression which gives us that when the dry out will occur. So, we can find out t film and t drive. So, we can get the three times we have also discussed the heat transfer coefficient on the film.

Now, in the liquid slug; because, it is a single phase liquid; so one can use the expression for single phase developing flow in the single phase developing flow in a channel depending on or one can calculate the Reynolds number and find out if it is a laminar flow or turbulent flow and calculate the expression accordingly.

Similarly, for the dry region one can calculate the heat transfer coefficient based on the gas properties again for the single phase vapour flow. So, one can take into account the laminar and turbulent regime and to find out if the flow is turbulent or laminar and get the expressions. So, we have this model develop except that the frequency or the tau is not there.

So, what they have shown that the frequency is a function of q over q reference raised to the power n. Now this q reference is again a function of alpha or a alpha q and reduced pressure. So, P over P critical and this is saturation pressure raised to the power n. So, that suggests that f is proportional to q raised to the power a into this reduced pressure or P saturation divided by P critical raised to the power say b. So, f is are the frequency of the bubble generation is proportional to q raised to power a. So, from this one can see that the bubble generation frequency and therefore, the heat transfer coefficient is overall heat transfer coefficient is a function of the wall heat flux.

In the model they had three different adjustable parameters one is bubble frequency and we have seen to give bubble frequency they need to provide one constant and two parameters here and the nose film thickness correction factor c delta n.

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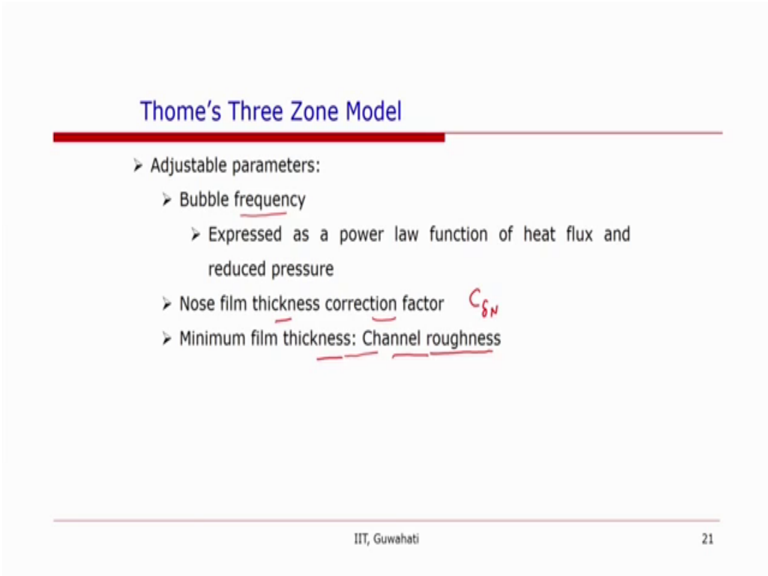

And the minimum film thickness. So, they were able to eliminate one of the fitting parameters channel roughness or based on the channel roughness. So, this is not arbitrary anymore. However, the parameters for the bubble frequency and the film thickness correction factor. So, there are four parameters that needed to be determined from the experimental data.

So, based on the parameters that they have determined they have obtained the fitness of the model. So, this model is based on the assumption that the evaporation in the liquid film is the dominant mechanism of flow boiling in micro channels; however, several experiments have shown or in recent times that there might be the presence of small bubbles in the liquid film region in the liquid slug or in the liquid film. So, if this is the case the nucleate boiling can also be important.

So, in my opinion it has not been yet the final verdict is not out yet what is the dominant mechanism of flow boiling in micro channels there is still needs to be a lot of experiment to be done specially look at the flow pattern for different channel roughness for different liquids for different channel cross sections at different mass flux and identify the flow patterns and corresponding a flow regime flow regimes and related to the related to at the mechanism of flow boiling in micro channels ok.

So, in summary what we have discussed today is that flow regime maps the two flow regime maps one is by professor Thome's group and another one is professor Garimellas group professor Thome's groups model was based on the mass flux and vapour quality as the coordinates whereas, professor Garimella he had the two non dimensional numbers as the coordinates on the y axis he had a bl into re boiling number into liquid only Reynolds number and on the x axis the convective confinement number which is bond number raised to be power 0.5 into Reynolds number and based on that they suggested the occurrence of different flow regimes.

Then, we discussed the possible regions why people think that nucleate boiling is dominant and why people think that convective boiling may be dominant and then we have discussed briefly the model by Professor Thome's groups where he has considered the slug boiling in slug flow regime in micro channels. So, he basically in the model identified the three zones the liquid slug zone the film zone and the drive vapour zone in the liquid slug zone and in this model the heat transfer coefficient is the time averaged heat transfer coefficient. So, one look at the heat transfer coefficient at one particular location and some it for the entire time period.

Now, in the liquid slug zone the heat transfer coefficient can be dif determined from the single phase correlations for developing or fully developed regions depending on the length and the developing length etcetera same is true for dry vapour zones for the dry regions, because there is only vapour present in this region for the film region the because the film is stagnant. So, the heat transfer coefficient is k over delta and because the now we had to obtain three times t film t dry zone and t slug zone. So, for the t slug we can calculate the length of the slug divided by the two phase velocity or divided by the homogeneous velocity.

Then similarly we could calculate the t film plus t dry the length of the vapour zone divided by the velocity and then we calculated an expression for the evaporation in the film based on the energy balance in the film the heat coming in from the wall and heat being utilized for the evaporation. So, from that we could calculate the evaporation rate in the film and so, the thickness of the film or rate of decrease of the thickness of the film.

So, from that we can also calculate the time at which the dry out will occur the initial thickness of the film can be obtained they have developed a correlation based on the literature data available in the literature for a bubble growing between two parallel plates which are being heated. So, then the last parameter was the bubble frequency or the bubble period which is a function of q over q reference and it is there is a power law.

So, the bubble frequency is a function of q. So, that is where the dependence of the heat transfer coefficient or the overall heat transfer coefficient in the slug flow regime is observed which explains the dependency of the heat transfer coefficient on wall heat flux even in the thin film evaporation models ok. So, that is all for this lecture.

Thank you.