Adiabatic Two-Phase Flow and Flow Boiling in Microchannel

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Lecture -05
Criteria for Confinement in Case of Two Phase Flow

Well, hello everybody. Today we are going to the 3rd topic of this particular lecture series on adiabatic 2 phase flow and flow boiling in micro channels, now yesterday what we did we rather in the last class what we did was, we try to find out the importance of micro channel why it is very much use, what are the typical flow pattern that we are encounter there. Now before we do anything else, the1st thing which I think we should be discussing is.

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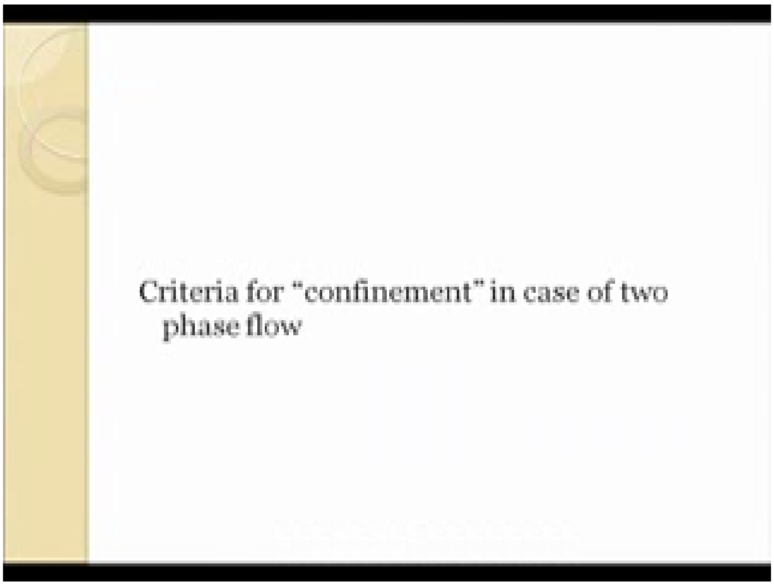

How do we define micro channels; in other words in what condition do we say that, this falls in the criteria of micro channels and this falls in the criteria of mini channels and so on.

Now, let me tell you there has been no define criteria; rather there have been a large number of controversies regarding the classification.

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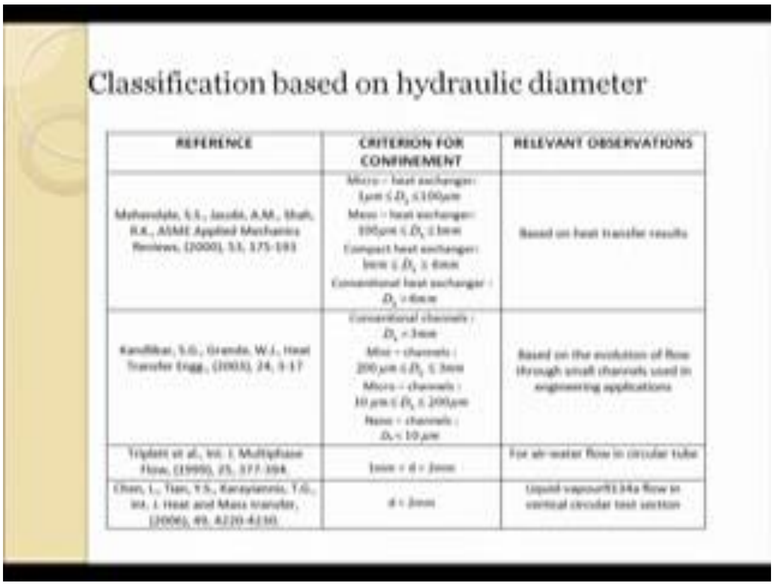

Now the1st thing which was done was; that the classification was done based on simply the diameter for circular pipes and the hydraulic diameter for non circular pipes. Now this was the way which engineer very frequently use to just define this thing; it was thought that well anything which is in the millimeter scale is a mille channel anything which is in the less than that it is a micro channel and then something conventional pipes your ordinary pipes, they refer to the micro system and so on. Therefore, the initial classification was based on hydraulic diameter; you can see that this particular classification have been done both on the bases of compact heat exchanger, as well as for conventional channel.

Now, if you look into that them you will find, that well some particular person, he as a define that Mesoscale for heat exchangers between 100 micro meter to 1 millimeter, while the same thing has been define by someone else based on 200 micro meter to 3 millimeter. We will find there is quite amount of disagreement between these particular and there is no exact definition of or proven criteria available for distinguishing the micro domain, the macro domain and the transition between the 2. Knowing full well that transition does not occur abruptly at on one particular dimension I cannot say that well; above this it was a macro below this is a micro. Therefore, there is a range over which the characteristic of the micro domain; gradually gets transitioned to that of the micro domain.

Now, the initial attempts were just to define it in terms of hydraulic diameter, now in this particular situation for people actually wanted to do was they just wanted to differentiate the studies which are already been reported in micro system and the study which are current been reported in reduce dimensions and which were not tallying with the studies the information already available. This was initial criteria based on which the macro and micro scales have been differentiate and the basic thing as I have already told that, it was just to differentiate the studies which have been performed in conventional pipes and the studies which were are being reported or were being reported in reduce scale and they are not agreeing to information already available. In due course people found that, just the physical dimension is not sufficient. And there should be some sort of the proper coupling between the physical dimensions as well as the local follow variables and the physical properties of the fluid.

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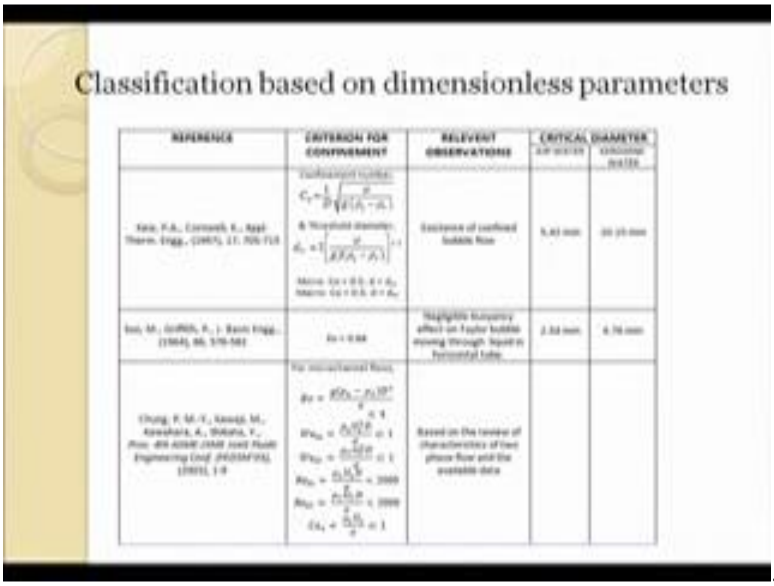

Therefore based on this, people or rather several researchers they had tried to combine the local follow variables and the physical properties of the fluid. And it was backed by numerous flow observation and extensive data bases and along with that there were accurate methods to predict the hydro dynamic and thermal performance both in the macro domain; in the micro range and also in the intermediate domain, which was commonly, refer to as the misoscale or the mille channel. Accordingly we find that, rather several particular criteria of definition came up and as the consequences of which, several dimension parameter had been proposed; now we look into particular presentation we find that, the definition which were proposed they were based on several numbers for example, the confinement number the (Refer Time: 05:26) number the capillary length and so on and so forth.

Now, on this particular stage, I also like to mention one thing that the classification was based on hydraulic diameter; what people found was, they were just defining in terms of the physical dimension. But then they realize that its not the physical dimension which is sufficient, for example, when we work at a high pressure then, suppose boiling is occurring and bubbles are generated; now at this particular high pressure, the bubbles generated will be very small almost on the micro size and under that circumstance a 1 millimeter channel can serve as a micro domain. On the contrary in the same particular tube, if you are working under some atmospheric condition than in that case, it would behave as in the micro scale. Therefore, from here people came to know that, simply defining micro, macro and meso in term of physical dimension are not sufficient; and then rather they started defining several dimension parameters, the different dimensional parameters which used.

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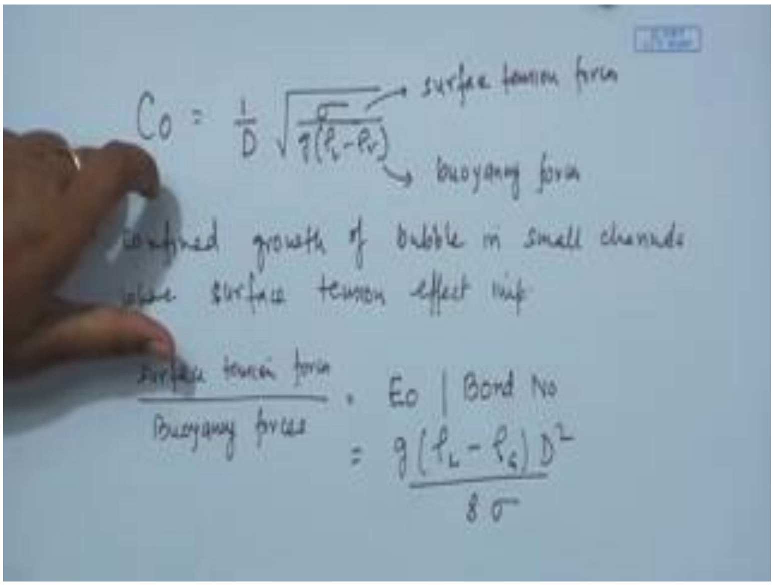

1st was known as the confinement number were this basically what it does is; it is define as 1 by D route over of, sigma by G into rho l minus rho v it is very evidence it give you balance between the surface tension forces and the buoyancy forces.

Now, this number it is based on the confined growth of the bubble; in small channels, where the effect of surface tension was importance. This was primarily practiced for follow boiling situation where we found that, normally what happen in the large channel; a bubble rather it starts forming at the nucleation site and it gradually it becomes larger and larger and at some particular critical diameter it detaches from the site and it start rising due to buoyancy and when there is a follow system, it is also pushed faster due to the follow system therefore, the detachment occur at faster rate. Now in small channel what happens when the bubble start forming into nucleation site; before it can detach from the site, it get confined by the upper volume. As the result of which, it cannot escape from the nucleation site and it start becoming larger and larger.

Now, this is definitely it depends upon the surface forces or depend up the surface tension or the or rather in other words the role of surface tension must be quite important in deciding maximum bubble radius. We know that the maximum bubble radius at detachment, it will decrease at the expense of the gradual separation of the gravity force with channel diameter, so as the channel diameter decreases. The maximum bubble diameter also decreases due to the decrease effect of gravity forces. Based on this we find several researches they have proposed the criteria for example, one particular group of researchers Kew and Cornwell, they suggested that this confinement number should be less then point 5 for macro domain and greater than point 5 for micro domain. The criteria, the observation was that there should be an existence of confined bubble flow in other words; the bubble should be confined between the 2 volts and flow as elongated isolated bubbles. Apart from this, there was another particular important dimension list group which was suggested in order to criteria for micro channels that is also a balance between surface tension forces and buoyancy forces. This particular number is often define as the adverse number or a reciprocal of, it is define as the bond number, different researcher have define it in different particular ways and some have define it as a adverse number and some have define it as a bond number. This actually I have written the reciprocal of it. This is often define as G into rho l minus rho G into d square by 8 sigma and this has been define I believe by Ullmann and Brauner they have define it.

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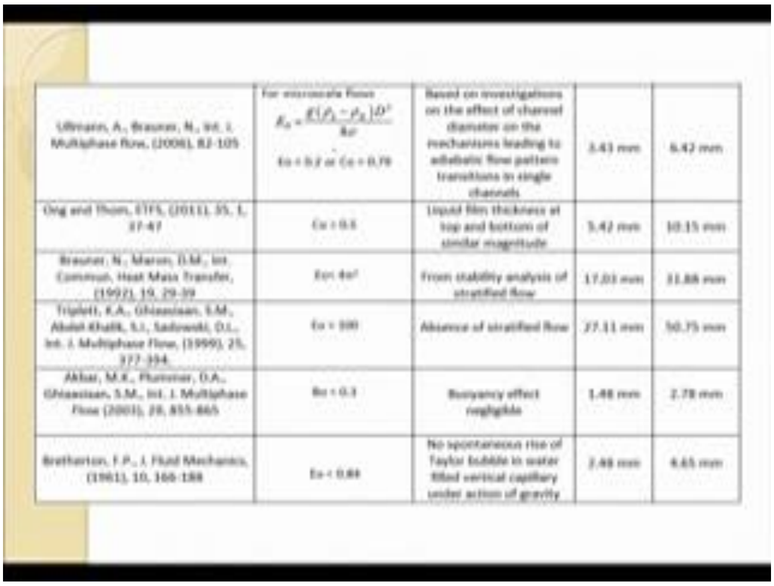

Ullmann, A., Brauner, N., Int. J. Multiphase flow, (2006), 82-105	For microscale flows $E_o = \frac{g(\rho_L - \rho_G)D^2}{8\sigma}$ Eo < 0.2 or Co = 0.79	Based on investigations on the effect of channel diameter on the mechanisms leading to adiabatic flow pattern transitions in single channels	3.43 mm	6.42 mm
Ong and Thome, ETFS, (2011), 35, 1, 37-47	Co ≥ 0.5	Liquid film thickness at top and bottom of similar magnitude	5.42 mm	10.15 mm
Brauner, N., Maron, D.M., Int. Commun. Heat Mass Transfer, (1992), 19, 29-39	Eo< 4π²	From stability analysis of stratified flow	17.03 mm	31.88 mm
Triplett, K.A., Ghiaasiaan, S.M., Abdel-Khalik, S.I., Sadowski, D.L., Int. J. Multiphase Flow, (1999), 25, 377-394	Eo < 100	Absence of stratified flow	27.11 mm	50.75 mm
Akbar, M.K., Plummer, D.A., Ghiaasiaan, S.M., Int. J. Multiphase Flow (2003), 29, 855-865	Bo < 0.3	Buoyancy effect negligible	1.48 mm	2.78 mm
Bretherton, F.P., J. Fluid Mechanics, (1961), 10, 166-188	Eo < 0.84	No spontaneous rise of Taylor bubble in water filled vertical capillary under action of gravity	2.48 mm	4.65 mm

It shows and they have suggested that, the adverse close to point 2 which corresponds to confinement number close to 0.79 is going to decide the criteria between micro and macro channels, on the other hand this Brauner n Maron, they had a slightly different definition of this the adverse number and they propose slightly different criteria for this.

Now, the criteria which was proposed by this Brauner n Maron it read something of this sort, the criteria which they it had a 4 pi square in it. As the result if which the definition was slightly different in this particular case; now they have define some particular criteria and that was co related to some particular physical observation. What were the physical observations; 1st thing is may be stratification is suppressed, all of us know that when stratification get suppressed; it is the termination of micro scale. The other criterion which was suggested was on set of asymmetric face distribution in horizontal pipes. Usually what was thought was that, moment stratification get suppressed it is the termination of the macro scale and when the face distribution becomes symmetric, this is defined as either symmetric plug flow or may be annular flow the film in the upper part and lower part of the channel, they are more or less symmetric by anyone by this criteria it is decided that, the onset of symmetric flow mark the inception of micro channel and the range from where this stratification is suppressed, and symmetric flow is starting; this particular range is define as a isosceles or the mini scale.

It will be interesting if you observe the different criteria; which people have selected and that will explain why they are so much of discrepancies in the criterion for defining the micro channel say for example, one particular research group Kew and Cornwell, they decided on the bases of the confinement number, which marks the existence of confined bubble flow and there are another group Suo and Griffith what they did; they defined in terms of (Refer Time: 14:07) their element of observation was negligible buoyancy effect on Taylor bubble. So, in just as I was telling; the onset of symmetric flow distribution. Then another group they did a very extensive review was the characteristic of 2 phase flow and they suggested the criteria on the bases of 6 dimension list group. They has chosen bond number, this super Fesical weber number of the 2 phases; as I had already mention bond number gives you ratio of the buoyancy to surf extension forces, the weber number of the 2 phases, they give us the ratio of inertial to surf extension forces and both of these are based on inlet input condition, then that also define Reynolds numbers which as you all know is a ratio of inertial to. In fact, this is not properly written, it should have been new. They are the ratio of inertial to viscous forces and the capillary number which is the ratio of viscous to surface forces.

At based on these number, what they did they decided the criteria on the bases of bond number and then fix all the other number to decide the domain of micro channel flow. Here again we have find mostly people have used bond number and the adverse number.

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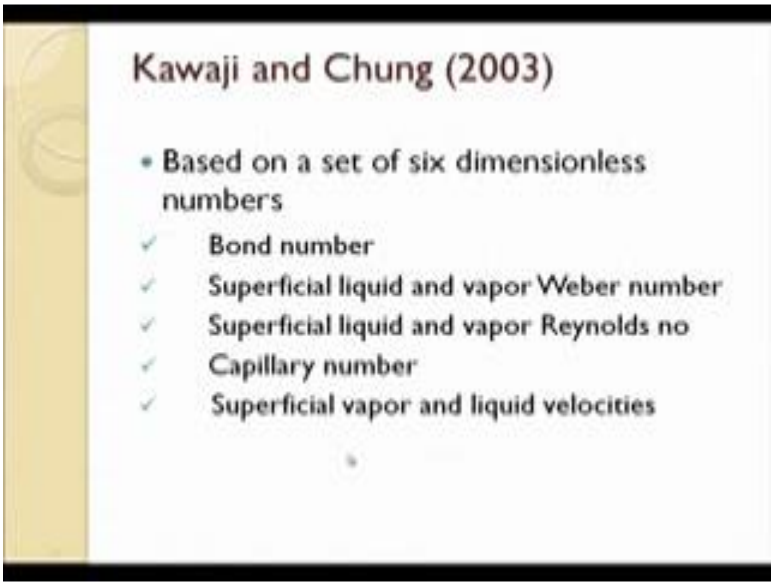

And again just i was telling there was another group who had defined upon the 6 dimension list; 6 groups including superficial vapor and liquid velocities to decide upon the criteria.

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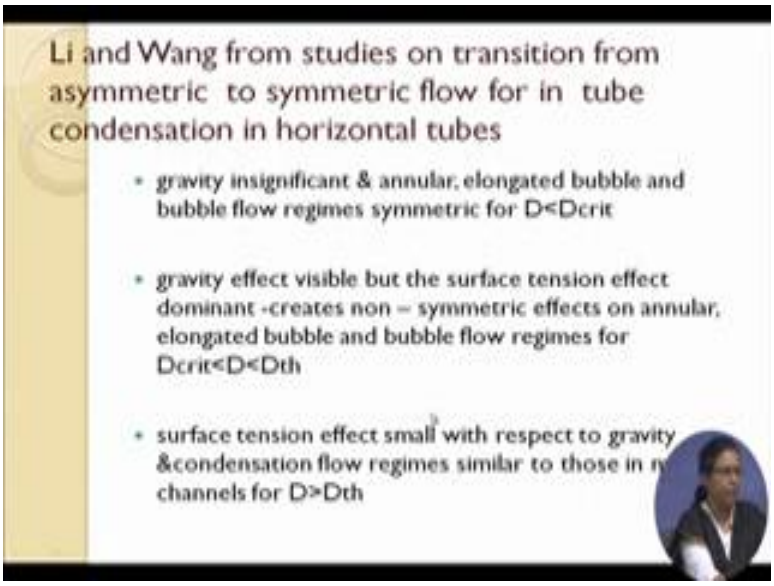

And then was another group what they did was, they defined 2 diameter 1 was the threshold diameter the other was, a critical diameter, now based on this 2 definition of the threshold diameter, and critical diameter.

They define threshold diameter as 1.75 lambda; where this lambda it is the capillary length which I have already define earlier, this is given as sigma by g into rho l minus rho g whole to the power half; now this is known as the capillary length or capillary constant whatever you width you can call it. What this particular Li and Wang group did was, they define 2 diameters; one was define as a threshold diameters, which was 1.75 times lambda, the other was define as a critical diameter which was 0.24 lambda and what they did, they based on these 2 diameters, they found out that

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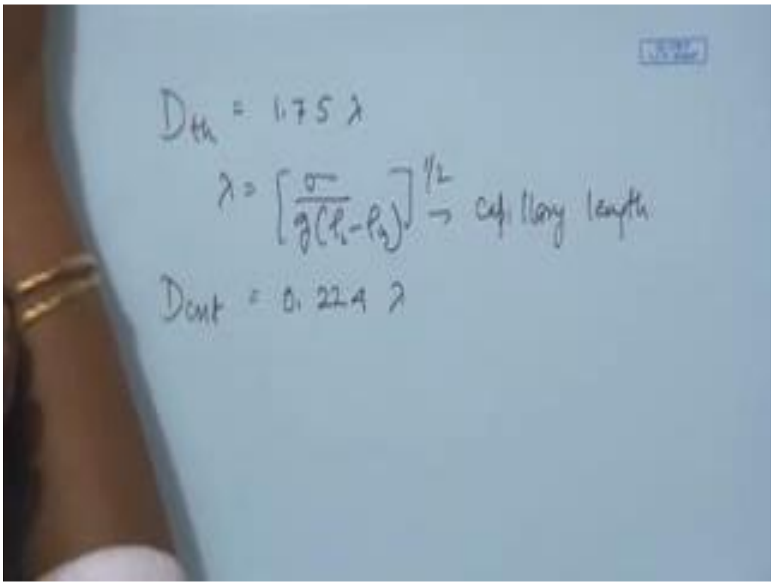

Certain cases for examples; when the contour dimension or the equivalent diameter was less than equal to the critical diameter, they found that gravity effects where insignificant, and annular elongated bubble and bubble flow regimes everything was symmetric. Then again they found when the diameter was in the range of critical and threshold diameter, gravity effect were visible its true, but the surface tension effects were more dominant, as of result of which the stratification was not there, but non symmetric effects on annular elongated bubble and bubble flow regimes were quite evident.

And again when the diameter was greater than equal to the threshold diameter, the effect of surface tension was small with respect to the 2 gravity. And they found out that the condensation flow regimes, was similar those in micro channels. Now 1 thing I just forgot to mention I think this particular researcher group, they determine the effect of conduit size on 2 face flow regimes for incube condensation studies in horizontal cubes. There postulation was based on condensation studies in horizontal pipes and during such studies they try to understand the effect of gravity by investigation, the transition from asymmetric to symmetric flows and did it based on the young la plus equation where the capillary constant was define and 2 dimension were define based on the capillary constant and then the entire range of your macro domain, the micro domain and the

Mesoscale was define very well by them, Well I should say this is possibly the 1st proposition for macro scale or rather macro to micro scale differentiation, which could be applicable to both adiabatic as well as flow boiling or flow condensation system. Previously most of this studies they were confined either to flow boiling were the confinement number etcetera was important or to adiabatic conditions were adverse number was important.

More or less based on what we find is, surface tension is important here. And the balance of surface tension with buoyancy or maybe the confinement or how it effects the confinement of bubble. These things were take as the criteria and the observations which were used to relate this particular translation or other to co relate this particular translation was as I have already mention separation of stratified flow and onset of symmetric flow distribution in bubble plug and annular flow regimes.

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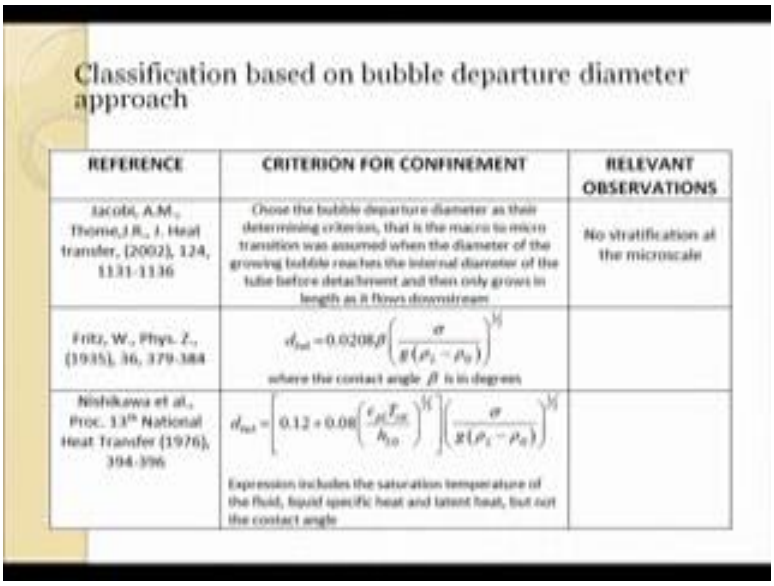

Well this was primary for adiabatic flow conditions, now if you observe that several criteria have been suggested based on flow boiling experiments, now in nuclear pool boiling experiments what we have seen that, in micro scale level there is no stratification why because the bubbles they get formed at nucleation site as I have already mention; for micro system what happen this bubble start growing at a particular critical diameter or where the forces acting on the bubble or more or less balance the bubble get detach due to buoyancy it start rising and when there is a flow occurring, then the flow also access in its detachment from the nucleation site.

Now, in the micro scale we find and this bubble they get accumulated on the top naturally they qualis and form they stratified floor to me and as we all know this stratification does not occur in a micro scale situation. Therefore, the 1st researcher who adopted this concept were jacobi and thome, what they did, they chose the bubble departure diameter as the determining criteria for macro to micro transition. This diameter they postulated was the diameter of the growing bubble, when it reached or it attends the size of the internal diameter of the tube before detachment. Therefore, file it was detachment going, it touched the upper wall its dimension became or diameter became comparable of the diameter of the conduit channel and natural after that there was no question of detachment; it could not rise in the vertical direction it got elongated in the adual direction.

Naturally there was no stratification. This particular criterion was first proposed by Jacobi Thome, as the transition from macro to micro scale for flow boiling experiments. And subsequently we find that, several expression has been proposed for the bubble departure diameter; they have been expressed in term of the contact angel, some researcher they have expressed it in terms of saturation temperature of the fluid, the liquid specific heat and latent heat, but they did not include the contact angel in there expressions.

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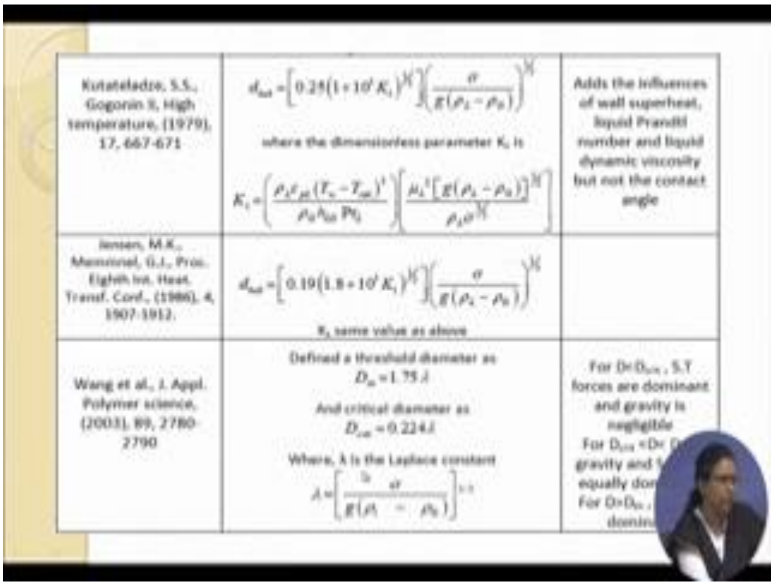

And here also we find that, order to define the departure diameter; another dimensional parameter has been defined, rather we will be discussing this dimensionless parameters; after a few lecture when we discuss the importance of dimension groups in adiabatic 2 phases flow and then later on we will be discussing the same for flow boiling.

Here we find it adds the influences of wall superheat liquid Prandtl number and liquid dynamic viscosity, but not contact angle was included here. Same way based on this particular dimension group K1 a different expression of bubble departure diameter was proposed and yet this I already discussed that, in boiling as well as condensation threshold under critical diameter was discussed and so on. And interestingly before I processed I like would like to show you that, based on the dimension less numbers, when the critical diameter was define; we find that, for air water we have one set of critical diameter, for kerosene water they give another set of critical diameter and even for air water and kerosene water system also, we find that the dimension they are remarkable different. From here we can very well get an idea regarding the discrepancy which are already available in the definition of macro to micro scale and this also suggests that, there is the necessity for further studies in this particular feed.

Now, while we were discussing these things, something became very evident that; this particularly transition as you have already understood this does not occur abruptly, there is a range of dimension which we call as a Mesoscale, were this particular transaction occurs. Now this Mesoscale is very interesting to us. Primarily for 2 reasons, firstly, in this particular scale both surf extension and gravity becomes important. What do we find, we find in micro scale gravity was important inertia was important viscous is important under certain circumstances and we deal with viscous liquid, in the micro scale surf extension become very important, gravity is suppressed. But in the Mesoscale we find, that both surface tension and gravity are important; were a decreasing importance of gravity and increasing importance of surface tension were decrease of conduit dimension.

Naturally the physics of this particular scale is unique and definitely it should be very different and interesting. In the course of lectures while dealing with flow in micro channels, we will also be touching upon or discussing flow in mini channels or in the miso scale. In fact, I have already done it when I was discussing the flow patterns in the previous class, there also several other advantages in this Mesoscale due to which; they are quit they have been in the focus recently.

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The advantages being easy to fabricate naturally, when we discussed macro channel you will be remembering the first thing I told you that, they are expensive and this difficult to fabricate in that way Mesoscale is better. Then rapid prototyping is easier, the problem of channel getting choked that is not happen; on the other hand high specific heat transfer area is also available in this particular channel.

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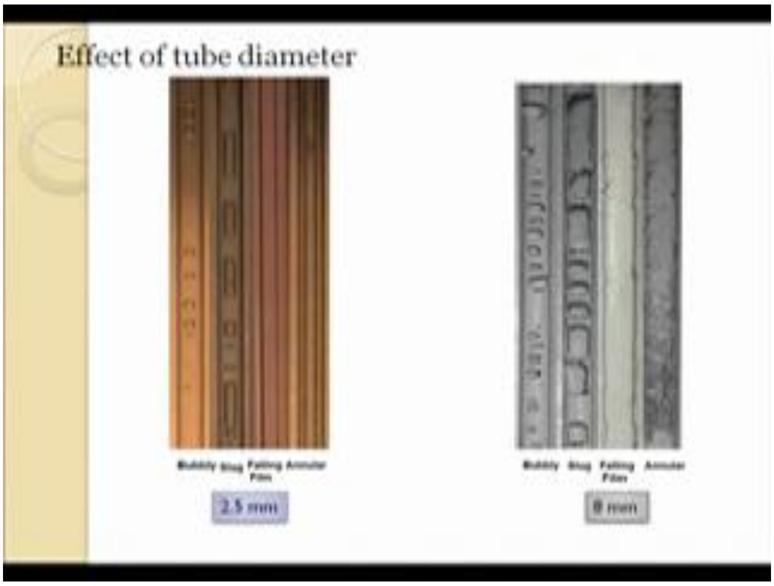

Just to show you the uniqueness of milli channels; I would just show you the flow patterns in a 2.5 and 8 millimeter tubes, they have been recorded in the multi face flow laboratory of chemical engine department, you can see that just for such a small difference in what way the flow patterns have changed you can observe the bubbly flow pattern here, the increase density and size of bubbles here; the regular shape Taylor bubbles for 2.5 and irregular Tyler bubbles for 8 millimeters and you can also observe the smooth interface in the following film flow for 2.5 and the wave interface in this particular case.

Therefore, this shows the effect of 2 diameters in the mille scale.

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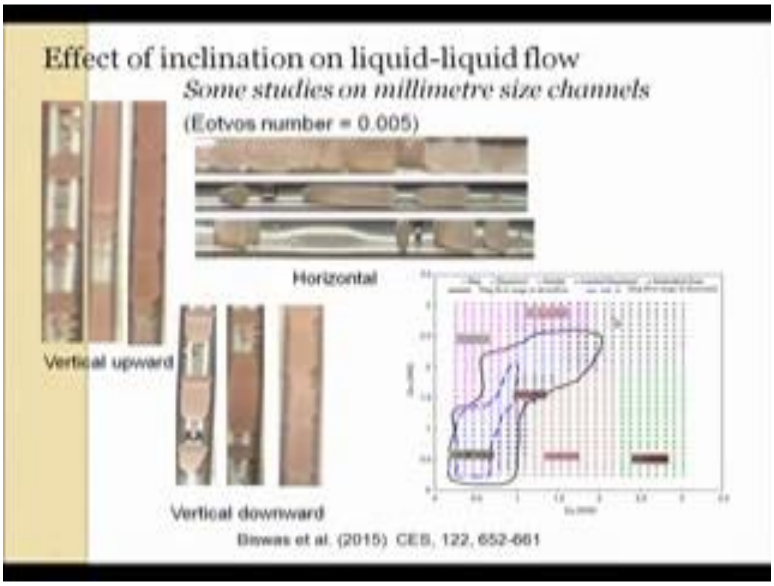

Now, if we go to observe the effect of inclination, we find its true that; in the milli scale there is no effect of orientation that is true. Stratification is suppressed that also true, there is a predominance of slack flow that is also true, but if you observe little more minutely and if you try to observe the range of flow pattern, then we find something very interesting in order to discuss this what we did rather we try to plot the range of slack flow or this 3 orientations in a 2 dimensional plot with the liquid and the water and towline superficial velocity as the 2 access.

And very interestingly we find here that the down flow in the down flow orientation, you can find this show the down flow orientation slack flow range is the maximum and it is the minimum for the horizontal orientation; this shows the horizontal. The black line shows the down flow and the point show the up flow orientation. We find although stratification is suppressed here. the flow patterns appears to be more or less similar morphology appears to be more or less similar with slack flow predominantly and annular flow also, yet we find there is a effect of inclination and this acts the new dimension to the study of 2 face flow in reduce dimension. With this I would like to conclude this lecture session stating that we will be continuing our discussion on mini and micro channels in our subsequent lectures.

Thank you very much.