Adiabatic Two – Phase Flow and Flow Boiling in Microchannel
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Lecture - 12
Influence of Operating Parameter on Flow Patterns

Hello everybody. Today after a lot of discussions regarding two phase flow 2 phase Microchannels flow patterns, how to detect flow patterns and void fraction. Today the topic which we are going to discuss today and few subsequent lectures also is the effect of operating parameters. In this particular case the primary operating parameters which we see they are the effect of phase superficial velocities then, conduit dimension, conduit geometry and since it is a micro channel definitely wall properties will have a say in it.

Gradually we proceed and we find out what are these specific rather some interesting applications or some interesting inference of operating parameters on two phase flow through micro channels, which to some extent can be counter intuitive as well and I will also be discussing a few salient features of macro channel flow.

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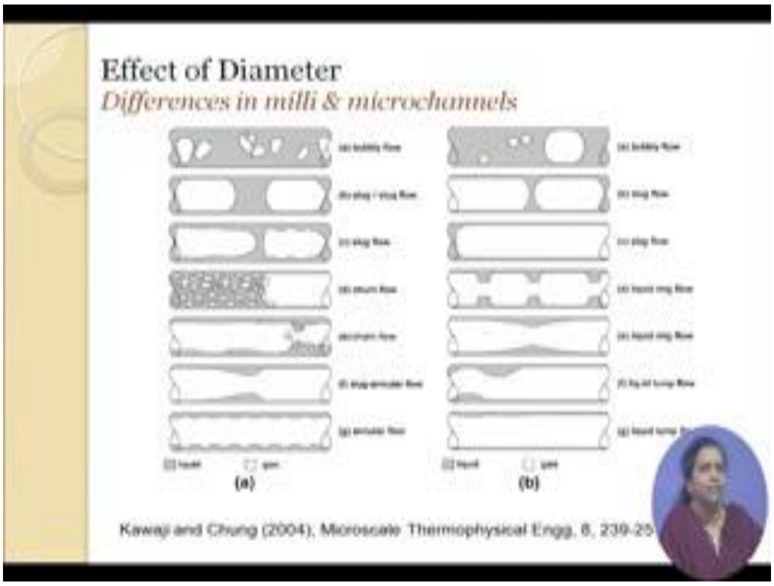

As I find it is relevant to this particular case. Now as far as the effect of diameter is concerned we have already had a lot of discussions regarding it.

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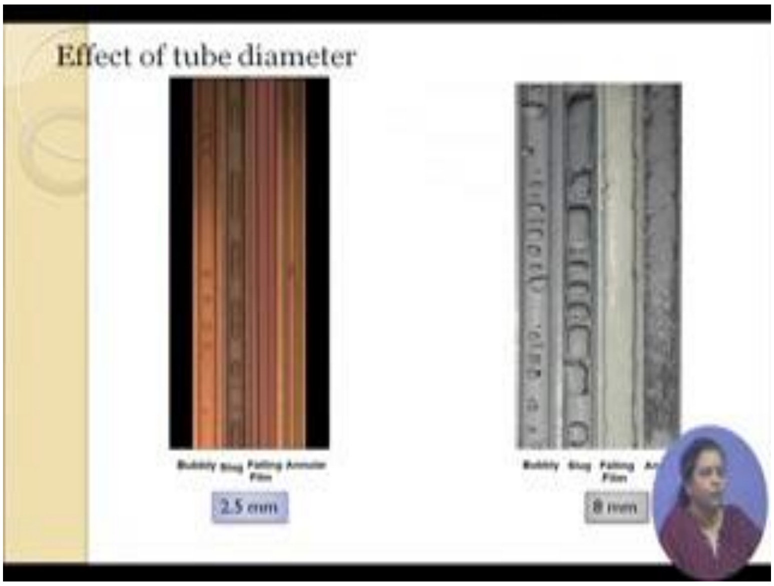

I will not be going into the details of this particular discussion anymore and I have also discussed in the Mesoscale, the diameter effect is more significant as I have said and this slide also I have shown earlier which tells you the shape of the bubbles, the difference in the nature of the bubble flows, slug flow these smoothness of the following film in 2.5 milli meters as compared to the wavy film in 8 milli meters and so on and so forth.

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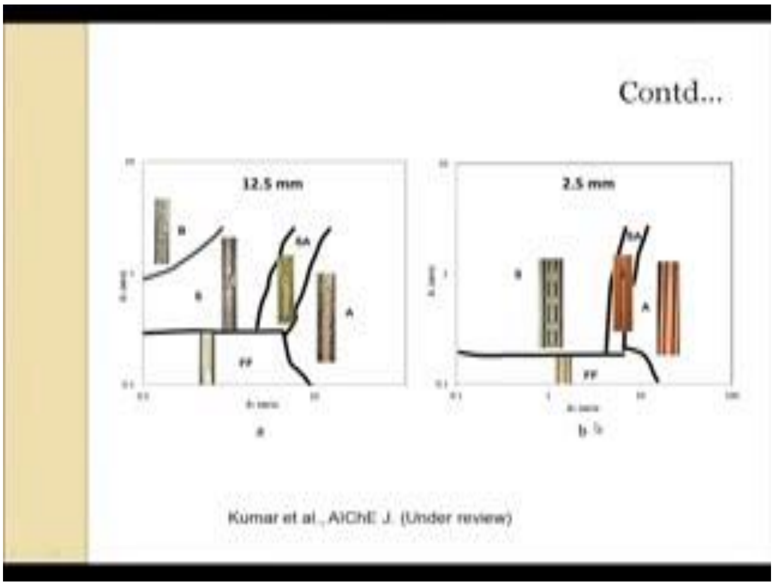

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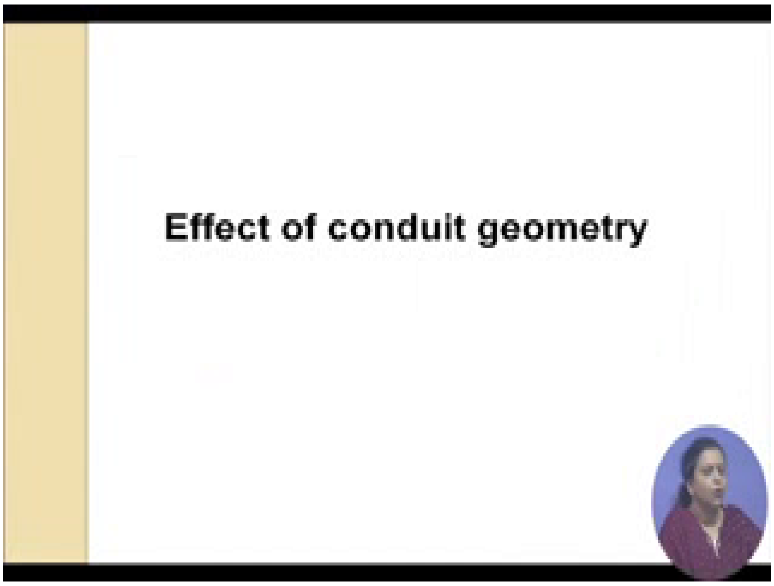

Well, what the next thing and regarding the enlarge range of slug flow with naturalization also I have discussed. Well the next thing which I would like to discuss today is the effect of conduit geometry.

Now, in this particular aspect as we all know that the majority of the studies they have been concentrated on circular tubes. Now when we are dealing with macro systems, what we find is? That instead of a circular tube if we shift to any other symmetric vertical geometry, say for example, an equilateral triangle or a rectangle and or a square we find that there is not a very significant influence of conduit geometry. For example, the only thing which happens is in a rectangle or a square or a triangle the corners are there and therefore it is the corner effect, there is some additional amount of fluid drainage in the corner effect or in the other words if you say there is some, this creates some amount of stagnant zones where, the liquid tends to get confined. Now due to this some local characteristics or may be slug flow is occurring in both the circular, but as well as a rectangle conduit, but may be the ranges are slightly different or may be the slug parameters may be slightly different, but over all we find that the morphology does not change much.

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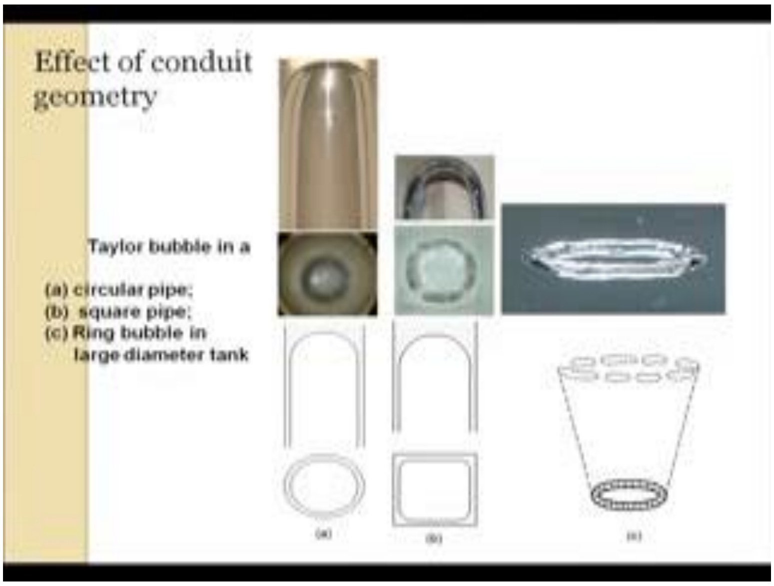

If we change the rather, if the geometric it symmetric and vertical no matter what the shape is, as is evident from this particular slide if you see that the Taylor Bubbles it is just the simple case of multi phase flow or two phase flow as I mentioned. A single bubble rising in a circular tube we find that the bubble geometry if you observe it is circular in both cases a square and circular tube it is symmetric, but in the circular tube conduit the bubble geometry is circular whereas, in this particular case it has got flat surfaces with rounded corners and as a result of which we find due to these particular edges, the bubble find a rather sorry the liquid film it finds some extra space to gain out and due to this extra space of draining out, due to the corner effect it can be grain faster as a result of which the bubble rises faster in a square conduit as compare to a circular conduit.

But other than that, there is no much great effect of conduit geometry in vertical symmetric cases. The only exception which I would just like to mention today will be evident if I just show you the video here; we find that in a circular tube.

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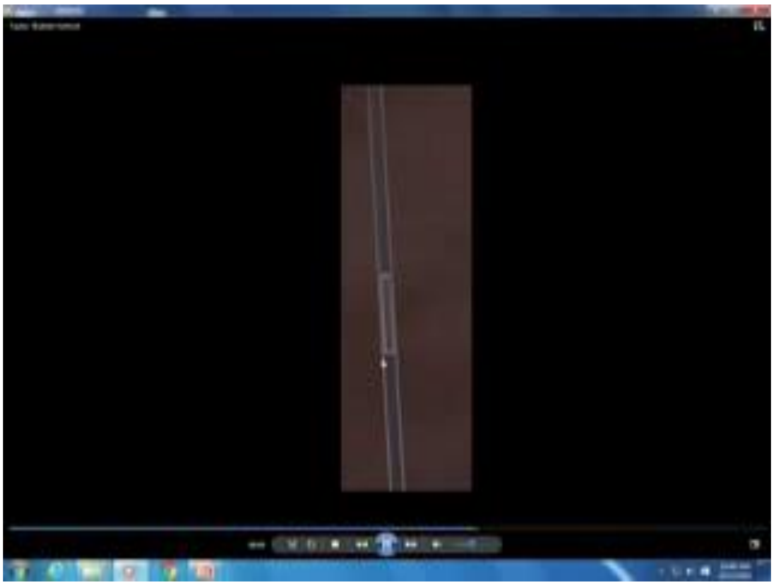

If you observe as I have already mentioned the bubble is perfectly symmetric there is nothing extra that I can show here, but since it is the circular tube. Therefore, the both the nose as well as the tail it is rounded. Now in this particular circular geometry if I just insert another rod and make the geometry annular, we find that the bubble shape changes drastically.

If we observe the bubble shape in this particular case is fine that. Firstly, the bubble does not rap the tube completely, as will be evident if you observe that the bubble partially encloses the tube and there is one particular portion where, the bubble there is no bubble and liquid flows as a continuous bridge in this particular portion. Therefore, we find that the nose as moves to one side and there are liquid films on the inside and outside a wall and in addition to these two locations of the liquid film, we also have a liquid bridge between the two edges of the bubble extending from the inner to the outer pipe, through which liquid flows and due to this additional passage of liquid flow, we find that the bubble rises faster in this particular case and. This was expected to be counter intuitive phenomena.

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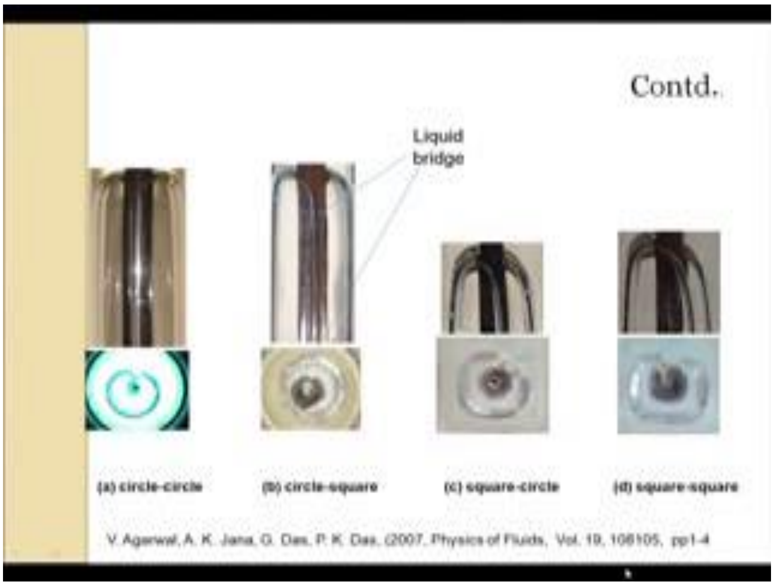

Because what we observed in this particular case was, that we are actually constricting the passage and due to this constriction, what happens is the bubble nose instead of be in the centre, it has shifted to 1 side. It becomes parabolic unlike the spherical nose for a circular tube and we find that the bubble actually it opens up. It is no longer symmetric, it no longer encircles the inner tube completely and as a result if we observe the Taylor Bubble in a circular tube, we find that while the bubble is rising any particular cross section can be divided into two religions; the bubble and this circular bubble and the annular liquid film while just on insertion of the rod what to we find, that the cross section through which a bubble is passing is has been divided into four religions. There is the bubble which is now kidney shaped, it is no longer axis symmetric bullet shape. There is an inner liquid film between the bubble and in the inner rod in here and there is an outer liquid film between the bubble and the outer rod and apart from that there is one particular position, the 1 particular portion where there is liquid bridge which is falling between the two edges of the bubble.

Now, we had investigated the Taylor Bubble dynamics in concentric geometry where, a circular rod inserted in a circular passage. A square rod inserted in a circular passage, a circular rod inserted in a square passage and square rod inserted in a square passage. We found that like un obstructed passages, we found that when the outer rod was circular no matter what is the shape of the inner rod, the bubble it had a circular cross section or rather semi circular or it had a shape of a crescent, but when the outer cross section was a square the squarish shape of the bubble with flat surfaces and rounded edges is evident and in all the annular geometries, irrespective of the shape of the inner and outer rod, we find that the four regions exist, in contrast to the two regions of the cross sectional view of the bubble in a circular pipe.

Now, this is something very interesting and this was very counter intuitive and more importantly what I would like to say? We had expected that when we obstruct the passage naturally the bubble it faces the obstruction and it will force to rise at a lower velocity, but on the contrary we found that the bubble actually rises faster in an annular passage as compare to a circular tube; number one. Number two the rise velocity increases not only with an increase in diameter of the outer tube, but also with an increase in diameter or dimensions of the inner tube which implies that the more constricted the passage becomes, the faster the bubble rises.

Now, all these we were talking for macro systems where, as we know gravity and inertia are dominant. As a result of which the dimensional is number which governs.

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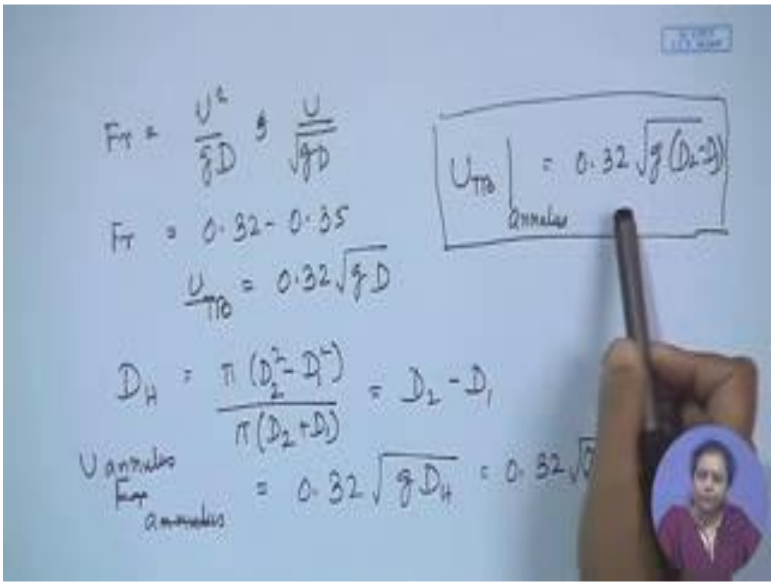

The 2 phase flow in macro system is the fraud number, which is the ratio of inertia to buoyant forces. It can also be written down as U by g D. Now in this particular case for what we find, that naturally when for inertia dominant systems when a bubble is rising then, for most of the cases the other forces are not very important. The viscous forces and the surface tension forces are not very important when the bubble and air bubble yet

Taylor Bubble rises through a liquid of low velocity and more or less small with surface tension. Therefore, under these conditions we find fraud number is a constant and the constant has been obtained by different researchers in the range of 0.32 to 0.35 which implies that U, rise velocity of the Taylor Bubble is equal to something 0.32 or 0.35 whatever it is root g D and therefore, as the diameter increases the rise velocity of the Taylor Bubble should increase. This definitely happens for the case of the circular tube.

Now, if we consider an annulus. From our information gathered from single phase flow naturally what we do? When we have to a extend the information obtained for circular pipes for any other geometry, we adopt the concept of hydraulic diameter which is nothing, but 4 times the hydraulic radius and which is the ratio as we all know of the cross sectional area divided by the wetted parameter.

Now, what is the hydraulic diameter for a concentric annulus? We know that the hydraulic diameter D H this is going to be equal to cross sectional area where, D 2 and D 1 are the inner and outer diameters of the annulus and the wetted parameter is this. So, the hydraulic diameter is D 2 minus D 1. So, what does it mean? This means that if we extend our knowledge of single phase fluid atomically means that the fraud number for an annulus should be something like root g D H which is nothing, but 0.32 root D 2 minus D 1 right?

Now, from all our experiments as well as from experiments which have been reputed in literature, we are found that just like circular tubes, the Taylor Bubble rises at a constant velocity for a concentric annulus as well. Therefore, the fraud number is constant for a concentric annulus and it also varies in the range of 0.32 to 0.35. Different researchers have reported values in this particular range. Naturally that implies that the rise velocity of a sorry this should has been U annulus I am sorry. This implies that U T B in an annulus it should be equal to if the rise velocity from our knowledge of single phase flow, the rise velocity should be expressed in terms of the inside and outside dimension of the annulus from this particular equation.

If we have to extend the knowledge rather the information or which is available for single phase flows to multi phase flow systems. Now from this particular expression what do we find? We find then the rise velocity should increase with increase in the outside diameter of the annulus, this definitely happens, but it should decrease with increase in the inside diameter of the annulus. Well this does not happen. From experiments we have seen that the rise velocity increases both with increase of the inside as well as with the outside diameter of the concentric annulus. And this suggests that even for us the simplest case of two phase flow where, the one particular phase is flowing through a stationery column of the other in such a situation also we find that the hydraulic diameter is not a proper characterizing parameter for a concentric annulus and therefore, fresh investigations are required in order to understand the rise of Taylor Bubbles in a concentric annulus.

Some researchers they have done lot of experiments regarding it and several expressions are also been suggested and then finally, it was find out that the nose of the Taylor Bubble it changes, it becomes sort of an elliptic where, the major axes oriented vertically and this particular shape the Taylor bubble adopts because this enables it to rise at the maximum possible velocity and from several mathematical analysis which can be seen by referring to this particular paper.

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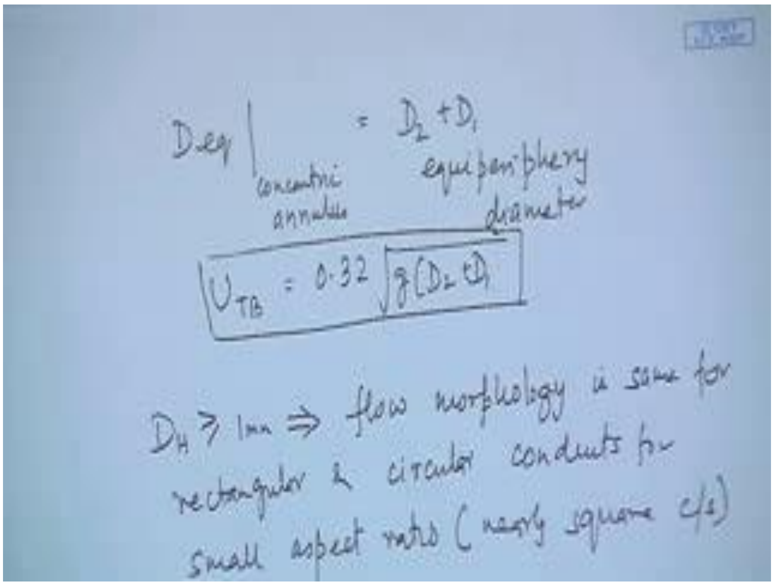

The people have found that the proper equivalent diameter for a concentric annulus is not the hydraulic diameter incase of Taylor Bubble rising, but it is actually they have called it as an equi periphery diameter and this explains the phenomena that we have to see, that the rise velocity of the Taylor Bubble it increases both with increase in the dimension of the inner as well as the outer tube. With this particular definition the rise velocity expression becomes as shown well.

This was something very unique that we have observed in macro systems and regarding micro system. Firstly, this could not be extrapolated because the first thing is a Taylor Bubble does not rise in a micro system because of diminution effect of buoyancy and increase in effect of surface tension. Therefore, some people have worked on concentric annulus or rather two phase flow to concentric annulus where, they are reputed slug flow it is expected that the Taylor Bubbles which have been encountered during two phase slug flow in a concentric annulus and also exhibited a similar phenomenon, but not much has been reported on it well.

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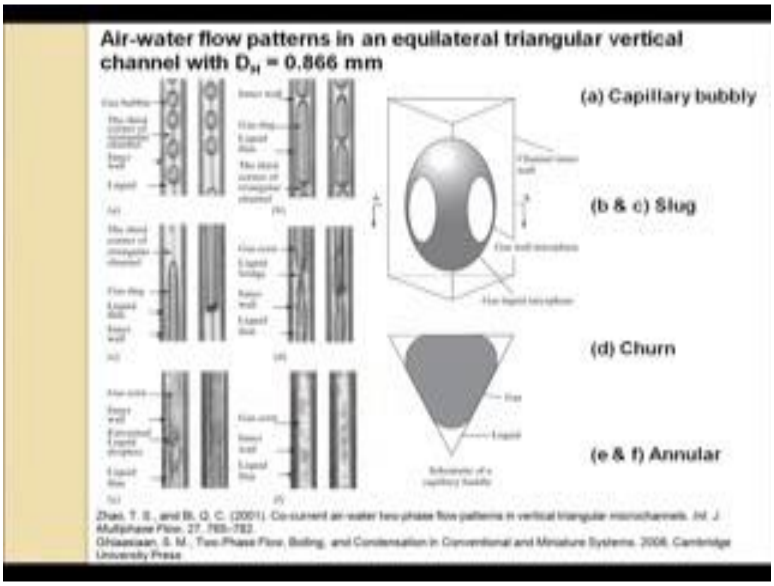

Next if we consider rectangular and equilateral triangular conduits. As I have already mentioned for your hydraulic diameter greater than equal to 1 milli meters more or less people have observed that the flow morphology is same for rectangular and circular conduits for small aspect ratio, which implies nearly square cross section right. So, this people have since more or less we have come across the same type of flow patterns. The only think which is unique in this particular case, is the corner effect which I have already mentioned.

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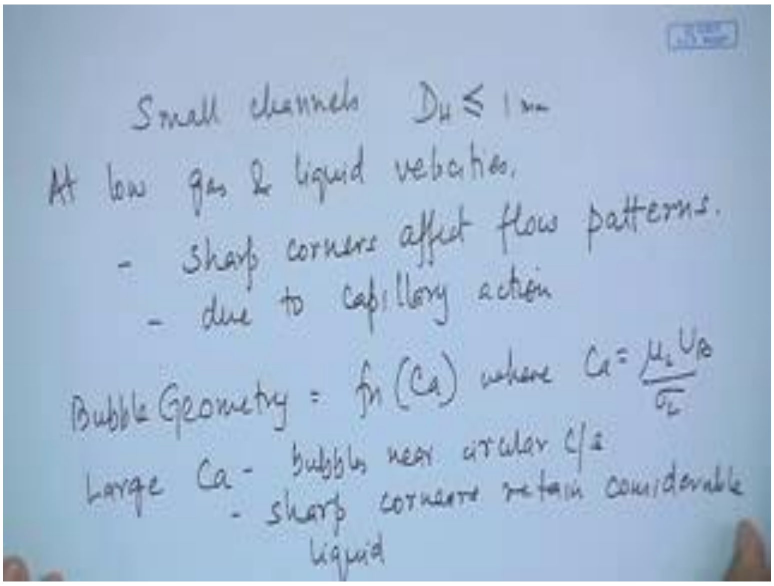

But in small channels what people have seen, in small channels with D H less than equal to 1 milli meters at low gas and liquid velocities. Under this condition what people have seen that movement we come to such small channels, wall effect becomes important and therefore, under this condition sharp corners they affect the flow patterns to a significant extent.

This has been seen, why? Due to the capillary action, the capillary action in macro systems it existed. Sharp corners also there and the capillary action was also there, but since the other forces were much important. The capillary action did not exact a very sharp influence on the flow parameters, but in this particular case we find that due to the presence of the sharp corners, what happens? There is a stagnant liquid which is entrapped in this sharp corners and therefore, we find that essentially due to capillary action a bubble claim flow can exist even with the stationery liquid film and. So, therefore, the dispersed flow pattern that used to be observed for circular tubes with disk shaped bubbles much smaller in dimension as compared to the dimension of the conduit they are replaced by a bubble train flow where, large bubbles are stacked one above the other which and they are connected at the edges and they flow to the center through a encircling liquid film and we find that the geometry on the bubbles, if you observe this particular shape it gives.

Therefore, one thing I would like to mentioned instead of bubble now we have a capillary bubble flow and if you observe the shape of the bubble you find that generally the geometry are the shape of the bubble geometry, it is a function of capillary number. Where, as I have already mentioned capillary number in this particular case is mu L U B by sigma L and if you observe what we find for large capillary number, bubbles they are nearly circular in shape because large capillary means lower effect of surface tension. Bubbles they are nearly circular in cross section.

But they have sharp corners, retain considerable liquid. This is the characteristic of flow patterns or bubble and slug flow patterns in rectangular channels with low aspect ratio, at low gas and sorry for with the hydraulic diameter less than 1 milli meters at low gas and liquid velocities. Firstly, there are sharp corners and they have much significant effect on flow patterns as compare to the larger systems or larger scales. Secondly, due to capillary action good amount of liquid gets retained in the sharp corners and the bubbles flow more or less to the center, if the bubble geometry being a function of capillary number. For large capillary numbers bubbles have nearly a circular cross section.

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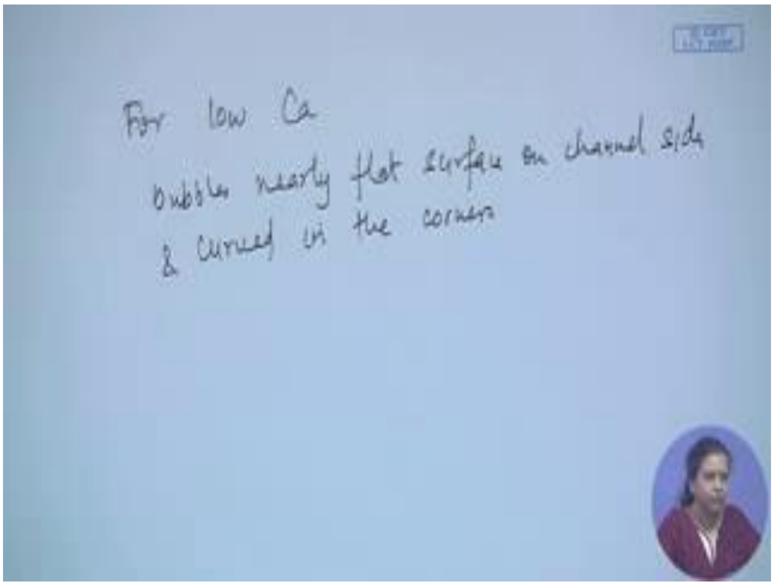

And for low capillary numbers we find that the bubbles are, they are no longer circular in this case they are nearly flat on the channel side.

Therefore, they nearly flat like the channels sides and they are curved in the corners. This is the characteristic which we have in this particular case, we find and this is very evident from here. A low aspect ratio we find that they become flat at the corners and this happens both for rectangles square and triangular bubbles and they have curved at the corners right. So, this is the weight any particular symmetric geometry with corners or edges inference the Taylor Bubbles or rather influence the flow patterns in macro systems.

Naturally since the flow pattern is predominantly slug, cap bubbly, bubble cane in whatever we you used to you wish to call. We find that the bubble shape is influenced in the way, we have discussed the bubble shape is the function of capillary number.

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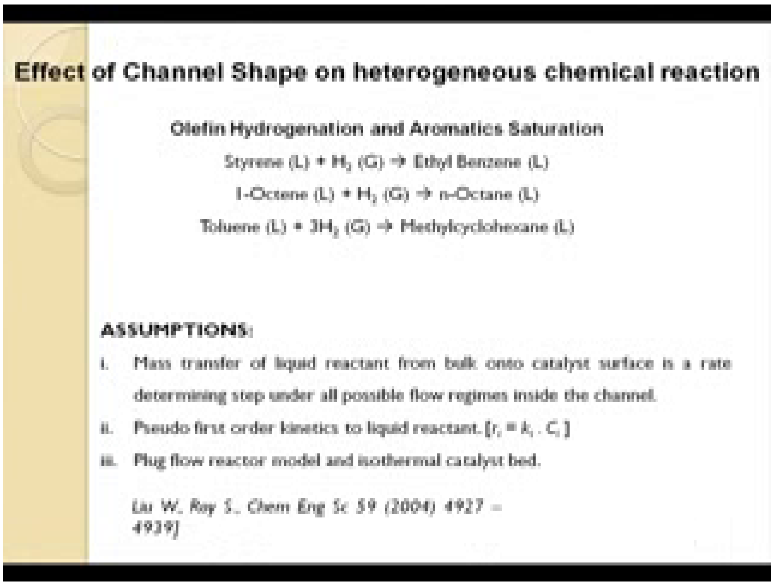

Now, there is some very interesting and the interesting application I should say of the conduit shape on heterogeneous chemical reactions of both fast and slow reactions and in micro systems or milli systems, this is particularly with reference to monolith reactors which are very popular in automatic as a reactor cases and in the next class, we will be discussing how the channel shape influences the heterogeneous chemical reactions and how this helps us in a proper design of micro reactors.

Thank you very much.