Multiphase Flow
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Module No. # 01
Lecture No. # 04
Flow Pattern Maps Fascinating Taylor Bubbles

Well good morning to all of you once more. So, we were continuing with our discussions on the existence (( )) I believe to confuse all of you that there were so, many different types of flow patterns, so, many different systems we had considered the different tube diameters and all those things, but anyhow at the end what I have tried to do is.

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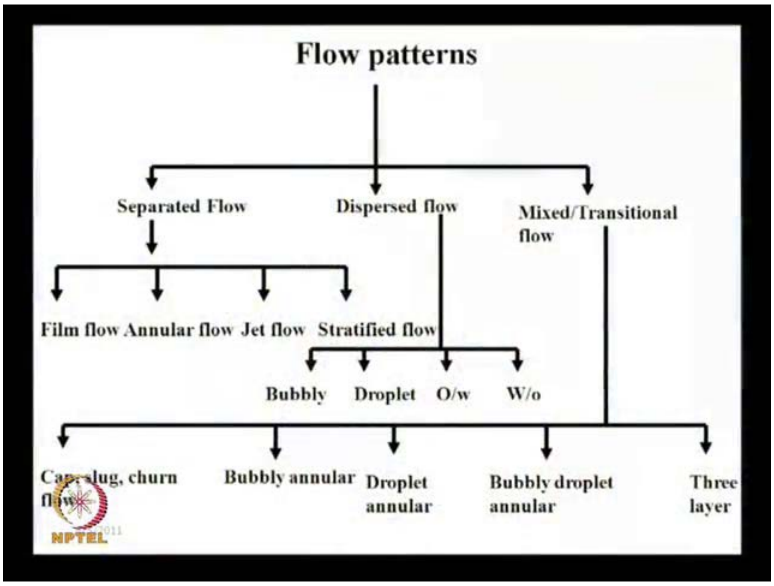

I tried to summarize the whole thing by this one particular table which I had showed you where in very concisely. I have shown you that actually the flow patterns can be separated flow or dispersed flow with a transition between the two.

When we have separated flow it is very easy to model them we can just consider them as two separate fluids. When it is completely mixed flow or it is completely dispersed flow or homogeneous flow again it is very easy we can consider it as a single fluid with suitable average properties. Is it not? The entire thing is mixed. So therefore, the properties are uniformed throughout in it is cross section along, it is along the cross section, along the length fluid properties are uniformed throughout. So, therefore, we can consider it as a pseudo fluid. Agreed?

But the main problem is the transition zone, same thing occurs for single phase flow as well the transition zone, but the unfortunate situation here is for most of the circumstances we operating the transitional regime. Unless we go for very high velocities or very low velocities we are mostly operating in the transitional flow patterns and we find that the range of flow patterns which are covered by the transitional circumstances.

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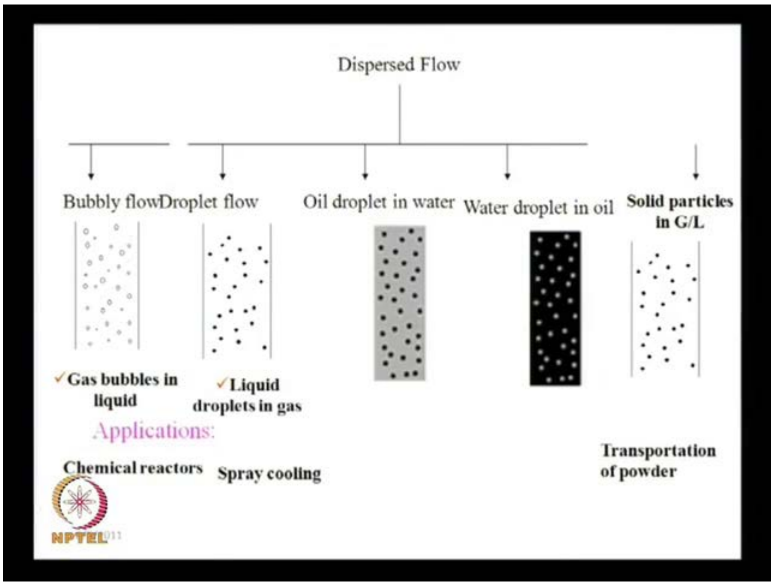

So, after the flow patterns the next thing here we have got something about the where the disperse flow occurs and the more or less. The industrial applications of this.

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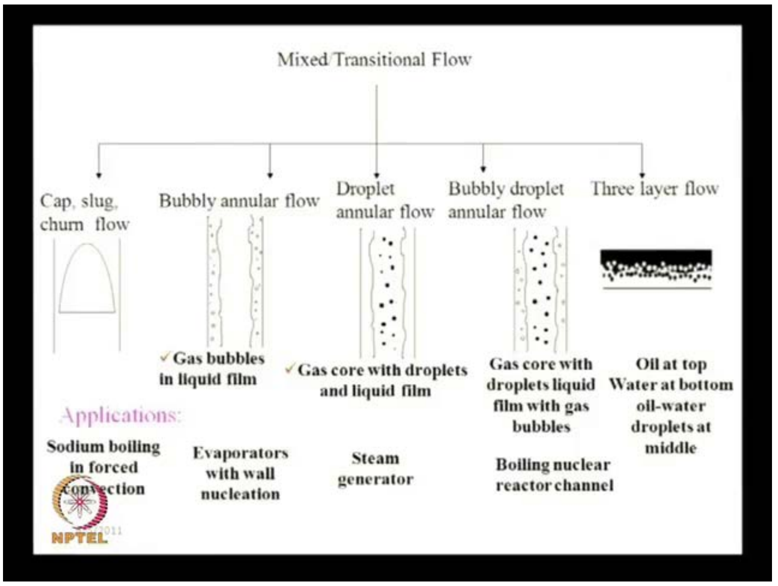

The industrial applications of this type of type of flows etcetera.

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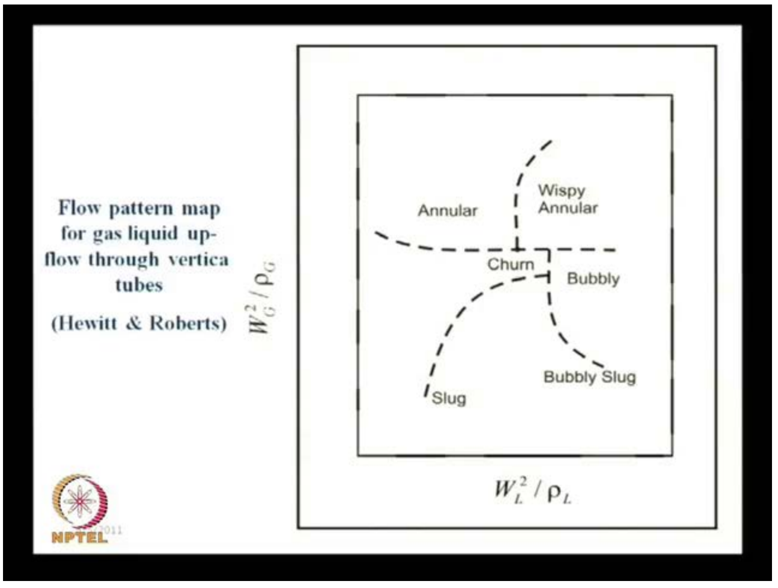

Now, the other important thing is we know what are the different flow patterns which are occurring, but under a particular circumstance say for 1 particular liquid velocity, 1 particular gas velocity, 1 particular pipe diameter, 1 particular pipe inclination. Which is the flow pattern? Which is going to exist? See unless we have any idea regarding this you cannot operate, you cannot predict the pressure drop, you cannot predict the heat transfer or the mass transfer characteristics. If a reaction is going on you cannot find out the rate of the reaction, the kinetics of the reaction, unless you know the distribution.

So, while it is very important to know the type of distribution it is also very important to know which distribution will exist under different circumstances. Now, for that particular case you can have different type of approaches, but the see whatever we do we always like to have some graphical representation or some picturisation. So that it is easier for us to grasp it. So, the most conventional way of representing the range of flow patterns under wide variety of operating conditions is by a graphical approach, where all the range of existence are represented on a two dimensional graph paper.

For that what we need? We need the two access of the graph, unless the access are properly defined we cannot define the range of existence of the flow pattern. Now, what type of access we would like to take? Generally normal under normal circumstances we would believe that some non dimensional sort of access is going to be better. And for single phase flow what we have the moody's plot, f verses r e, but in single phase flow r e is the single most non dimensional group as far as incompressible flows are concerned. But in this case one particular dimensionless group which is a ratio of 2 important forces that is not going to be sufficient in our case.

Because in this particular case inertia is important buoyancy is important, your surface forces at times they become very important property different types of properties are important, viscous forces are important. So therefore, a number of dimensionless groups governed the situation, we have Reynolds number definitely which is very important, but again if you try to define the Reynolds number.

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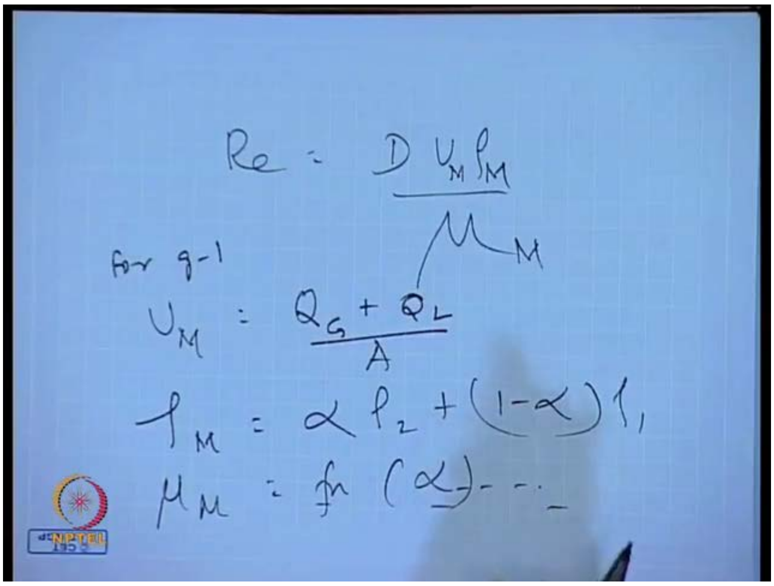

So, what do we get R e equals to D U rho by mu, single phase flow in this particular case diameter diameter U it becomes say the U mixture velocity. What is the U mixture velocity in this particular case? It is the inlet velocity of inlet combined velocity. In other words if we denote the volumetric flow rate as Q then it is for gas liquid cases if we take, then it is going to be Q G plus Q L by A. Agreed? What is this rho? In this particular case it has to be rho m, again for finding out rho M what we require? The void fraction as I have already told you, mu it becomes mu M again for mu M some it should be some sort of a function of alpha plus a large number of other things as well.

So, therefore, we find that finding out Reynolds number was very easy in single phase flows not only that we can find out Reynolds number just from simple measurable properties. You take a fluid measure the velocity in which it is flowing know it is density, know it is viscosity, their properties characteristic of that particular fluid and you can find out the Reynolds number. In this case it is not so, straightforward why because the insitu composition comes into b. And apart from this other forces are also very important.

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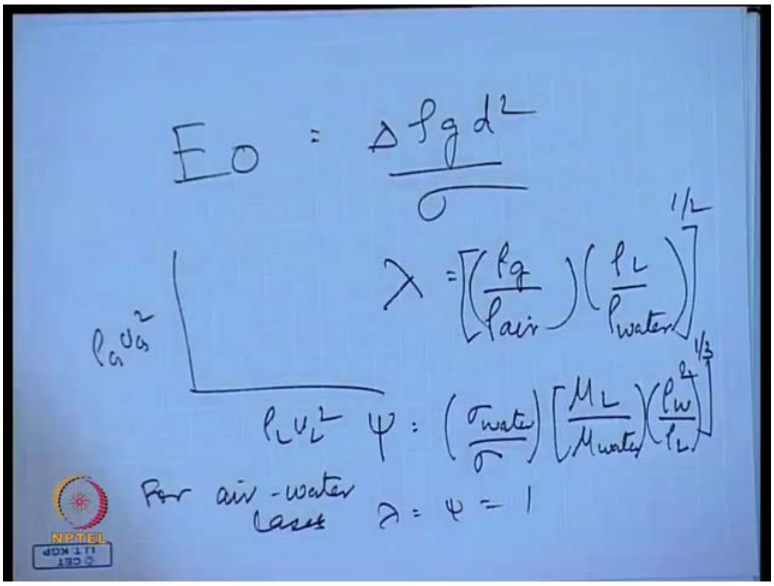

For example, say the eotvos number if you take, this is another very important group I do not know whether you have heard about it. This is the ratio between the buoyancy force and the surface tension forces, for gas liquid cases it is the surface tension of the liquid for liquid liquid cases it is usually sigma the interfacial tension between the two liquids, this force becomes very important. Now, the thing is we can identify, but there are more than 2 dimensionless groups which govern the range or rather which govern the existence of flow patterns.

So, if we use a 2 dimensional plot it becomes slightly difficult. The other important thing is when the flow pattern it is transitioned from one particular pattern to other. Suppose we are going from the bubbly to the slug flow pattern 1 set of equations 1 set of mechanism governs this. From slug to churn or churn to annular another mechanism governs this. So, that means, different forces are important under different circumstances. So, the force balance which will be applicable for bubbly slug might not be applicable for slug churn or churn annular flow cases.

So, therefore if we select just two dimensionless group they might not be appropriate for the entire range of flow conditions or flow velocities that we are encountering. Usually what we find is? For the bubbly flow cases or the transition from the bubbly to the slug. What happens the bubbles? As I have told you they increase both in frequency as well as in size and then finally, they coalesce to from the Taylor bubbles and this gives rise to the slug flow pattern. That I have already mentioned. So, in this particular case bubble coalescence is much more important. For bubble coalescence what we have to know?

A critical bubble packing more or less a critical void fraction is necessary where the bubble coalescence become so, rapid that Taylor bubbles begin to form. Is not it? So, in this particular case a critical bubble packing is very important. At the same time if you notice slug to churn transition lot of confusions are there regarding, what is the exact mechanism of transition. But if you just see apparently what you find Taylor bubbles? They become larger and larger. Once they become larger what happens? They become unstable and then they breakdown and total a chaotic motion starts, does it not represent the flooding situation which you have read in your undergraduate classes. Is not it?

So, very frequently the slug churn flow pattern transition that is governed by the flooding equations and at the same time churn annular it is governed by flow reversal. So, we find that usually the normally accepted mechanisms they are different for bubbly slug churn and churn annular transitions if we are considering just air water cases. Since air water cases are much more developed we will be referring mainly to those cases and we will be touching upon liquid-liquid, gas solid and such other cases as the situation is going to demand.

So, we find that identifying a pair of dimensionless groups is not very easy therefore, the main problem of representing the range of existence of flow patterns on a 2 dimensional plot is just identifying the access and we find a large number of attempts have been made in this particular regard.

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Flow pattern maps for vertical up flow of air-water based on generalized co-ordinates

Author	Fluids	Pipe Diameter	Coordinate Parameters
Kosterin (1949)	Air-Water	1 in.	β, j
Kazlav (1954)	Air-Water	1 in.	$(\beta, j^2/gD)^{1/2}$
Galcgar ct al. (1954)	Air-Water,-Kerosene	0.5 & 2 in.	G_g, G_l
Ueda (1958)	Air-Water	2 in.	W_g, W_l
Hewitt & Roberts (1969)	Air-Water	1.25 in.	$\rho_l j_l^2, \rho_g j_g^2$
Nishigawa et al. (1969)	Air-Water	1 in.	j_l, j_g
Govier & Aziz (1972)	Air-Water	Data from others	Y_{j_l}, X_{j_g}
Oshinowa & Charles (1974)	Natural Gas-Oil		$(\beta/1-\beta)^{1/2}, Fr_{tp}/\Delta E$
Spedding & Nguyen (1980)	Air-Water	4.55 mm	$j/(gD)^{1/2}, j_l/j_g$
...n & Kang (1981)	Freon-II3 Vapor-Liquid	1 in.	$j_g/\phi_1, j_l/\phi_2$

And if I show you I have got a table which will show you the range of access which people have suggested you are not suppose to remember them it is just to give you an idea about the different access. Which people have tried why people have there are much more this is not an exhaustive list it is just in 1981. We find that the range of access which people have tried it is just because they have got so much confusion and they were not satisfied with the selection of any pair of coordinates. And we find that the most commonly occurring maps they are the oldest map for horizontal flow is due to baker and for vertical flow it is due to Hewitt and Roberts.

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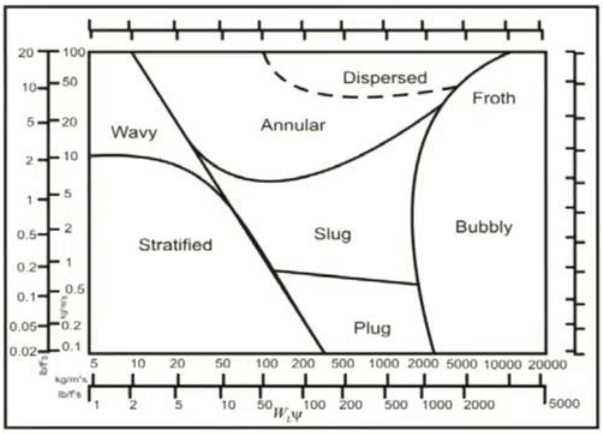

Flow pattern map for concurrent gas liquid flow through horizontal tubes (Baker)

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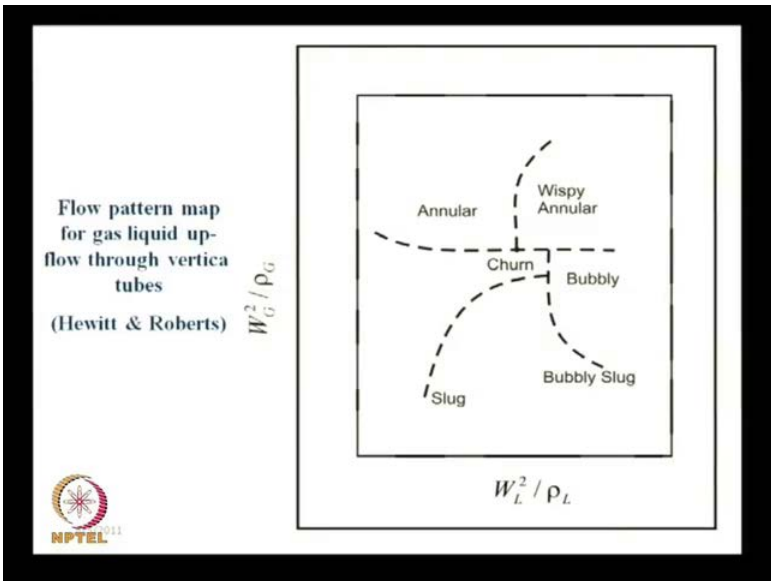

Now, this vertical flow map if we find we find that in this particular case, they have used the superficial momentum flux of the gas as the y axis superficial momentum flux of the liquid as the x axis. It is basically rho L U L squared this is if you transform it becomes W L square by L.

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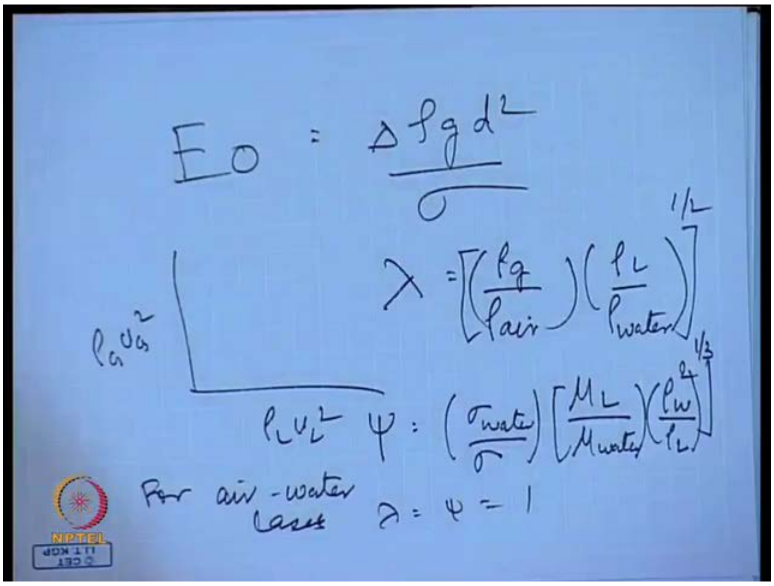

So, it is primarily here you have rho G U G square and here you have rho L U L square. And there you can very well understand that often your gas momentum flux is high liquid momentum flux is low you have annular. When your liquid momentum flux is high gas momentum is low you have bubbly and in that way the entire region has been divided into different regions. Where different flow patterns exist under different region in the different regions. Remember one thing here the transition they have been shown by single lines, but remember one thing at one particular condition immediately the bubbly flow transforms to the slug flow pattern that cannot happen. There has to be a range of condition where bubbly flow gradually transforms into the slug flow pattern.

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So therefore, usually although in flow patterns we have a tendency of showing them as single curves, but usually they occur over a range of condition they are not definite curves and that is why these curves are shown as dotted lines.

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Similarly, we find for the horizontal flow cases the baker the map which it has been given it is W G by lambda W l psi etcetera. Where these lambda psi they are just ratios of property.

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This lambda it is given as rho g by rho air you will get in any standard text books this is not very important. Rho liquid by rho water this is whole to the power half and this psi this is equal to sigma water by sigma of the liquid that you are using mu liquid by mu water rho water by rho liquid whole square whole to the power one-third. So therefore, these are the dimensionless rather these are the two property groups which have been defined such that the liquid properties defined with respect to water. The air properties sorry the gas properties defined with respect to air and you will find that for air water cases both lambda and psi they reduced to 1.

Therefore, under such circumstances it is basically a mass flow rate of gas verses the mass flow rate of the liquid, which is shown by the bakers plot. And if you observe here again you find that low gas and liquid flow rates stratified flow as the gas flow rate, is increased naturally the waviness increases. Then we find that when it is high liquid more or less low gas it is bubbly high liquid, high gas frothy and this is high gas more or less moderate to low liquid get annular. So, in this particular way the entire graph or the entire space this 2 dimensional space is has been divided into different regions showing the existence of the different flow pattern.

Now, since there was so much confusion regarding what should be the appropriate or the suitable coordinates to be used in the flow pattern maps. In most conventional way of doing it for gas liquid and liquid liquid cases is simply to use the superficial velocity of the 2 phases. Superficial velocity means we will be dealing with all the nomenclatures in details after we finish off in the flow pattern chapter.

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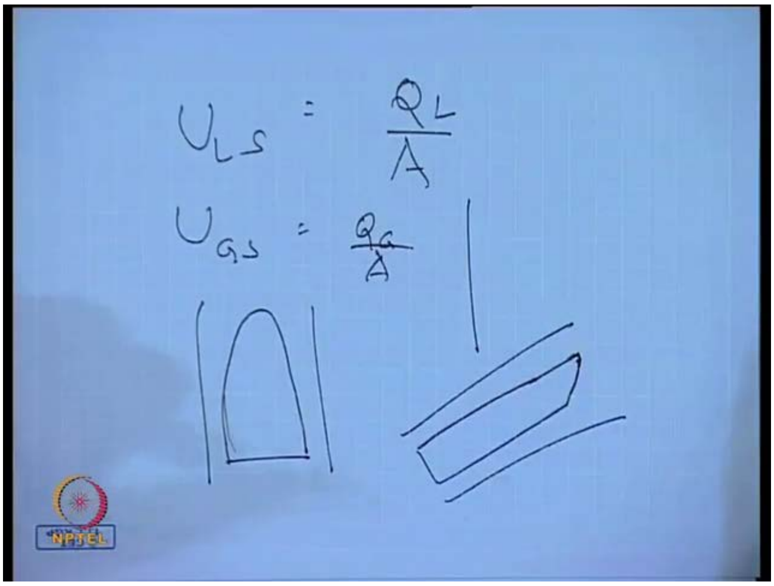

There we will be doing it in much more details it is basically the liquid flow rate by the area and gas flow rate by the area. So, these are the superficial velocities and this is the most conventional way of doing it.

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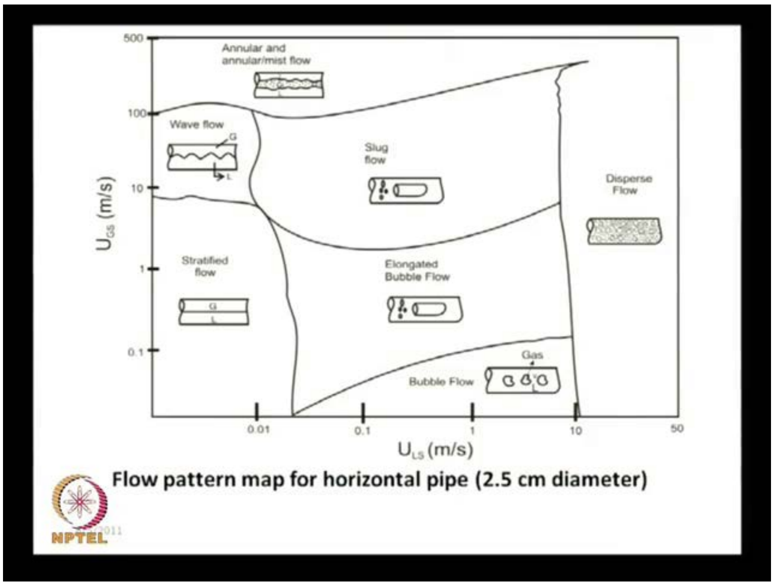

Usually as I have told you for gas liquid cases liquid liquid cases Reynolds number and Eotvos number there is another known as Morton number which is the property group. So, these are important for gas solid cases we find that the Reynolds number and Archimedes number I believe you know about these numbers these are much more important. Usually the maps were gas solid cases you will find there in terms of c d verses r e or may be Archimedes number verses r e and so, on and so, forth these things. I believe you have done a little in your fluid flow classes in under graduate classes. Is not it? Some portion probably.

So, anyhow the normal way of dealing with them the most conventional way at present is just to represent them as your gas velocity verses liquid velocity or vice versa liquid velocity verses gas velocity. Different researchers have used it in different particular ways and this is for a horizontal pipe it is self explanatory stratified flow at low phase velocities, annular flow high gas low liquid, bubbly flow high liquid low gas. And definitely the transitional flows they are all in between dispersed flow again it is a well dispersed just a second version of bubbly flow again it is for high liquid and low gas. Or may be low to moderate gases or something.

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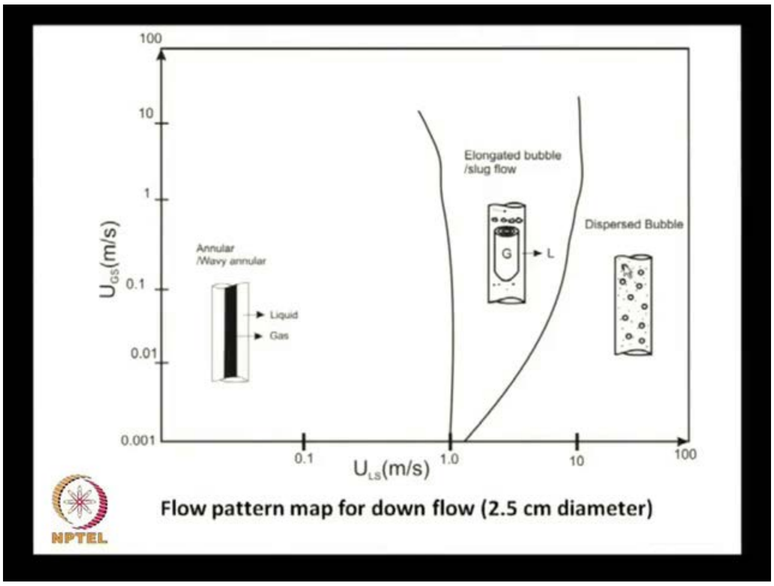

Same way we people who have represented the vertical cases vertical flow also where we have seen in all text books you will be getting those particular graphs. In those particular graphs we find that there is again bubbly flow, low gas high liquid, annular high gas low liquid and may be slug and churn at under intermediate conditions. And this is one for down flow case down flow naturally, the annular flow pattern is the most common because the wetted wall columns as you all know wetted films they are the most common occurrence for the down flow.

So, therefore, we find that in down flow cases the large portion of the map is occupied by the annular flow pattern. You get slug flow and bubbly flow over comparatively much more extreme conditions a large liquid low gas and so, on. And the variety of flow patterns are much less in down flow as compare to horizontal or the vertical up flow cases. So, these were the different ways by which flow patterns can be represented there can be much more ways, but remember one thing just learning flow patterns is not sufficient. You have to identify the flow patterns which operate under different condition, and you also have to know the range of existence of the different patterns.

The graphical way is definitely one, there are other ways also one particular way is to actually model the transitions and develop mathematical equations to predict the transitions. People have done that lot of mathematical equations are there and as I have already mentioned bubbly slug transition the modeling is done on the basis of bubble coalescence slug churn usually people use the flooding phenomena. Of course, other mechanisms are also have also been proposed by different researcher usually churn annular it is related with the flow reversal phenomena.

So, in this particular we what people have tried to do people have? I have tried to observe what is happening during the transition? What causes bubbly flow to transform into the slug flow? What causes slug flow to transform into the churn flow? What people have found out? Increase in frequency number of bubbles brings a body transition from bubbly to slug flow. While on the other hand it is not the increase in the frequency of Taylor bubbles, but the size of Taylor bubbles which causes transition from slug to churn flow. So, people have observed them very closely very minutely we have tried to understand the physics of transition and then they have developed mathematical equations to describe the physics.

Such models are known as phenomenological models which have been developed based on the phenomena, which is actually occurring. So, there are graphical representations, there are phenomenological models when people have proposed equations from phenomenological models for they have done. They have plotted the equations on the experimental flow pattern maps they have validated their equations and then they have tried to find out whether the equations are appropriate. Unless the equations are validated with experiments they have no use. Is not it? You can suggest whatever you like, but unless they agree with your experiments they do not show the actual physics of the flow situation.

So, the next approach to model transitions is by phenomenological models. Very recently several soft computing techniques have come up artificial neural network, the genetic algorithm such type of things have also come up to model the flow pattern transitions. They are particularly useful why because the physics is not very well known we really do not know exactly what causes the different transitions. So, therefore, this black box modeling concepts sometimes it when they are done properly with a large number of data then they give us quite accurate results. And more importantly when you use these particular techniques we can actually identify the ranges where the transitions occur.

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Definitely transitions they do not occur under fixed curves conditions. There is a range where under which annular flow gradually gives way to slug flow and slug flow gradually gives way to bubbly flow. So, in order to predict these particular ranges experimental flow pattern maps are fine, but for mathematical equations you cannot get a range you can just get a curve. So, this artificial your sorry the soft computing techniques can be useful computational fluid dynamics is also being used for this particular purposes. But anyhow this is quite a big challenge and more or less work is still on going on for whenever we encounter newer fluid types, newer geometries which are coming up with the increasing applications.

We find that the way of representing the range of existence of flow patterns is quite a challenge. So, this completes our discussion on flow pattern maps.

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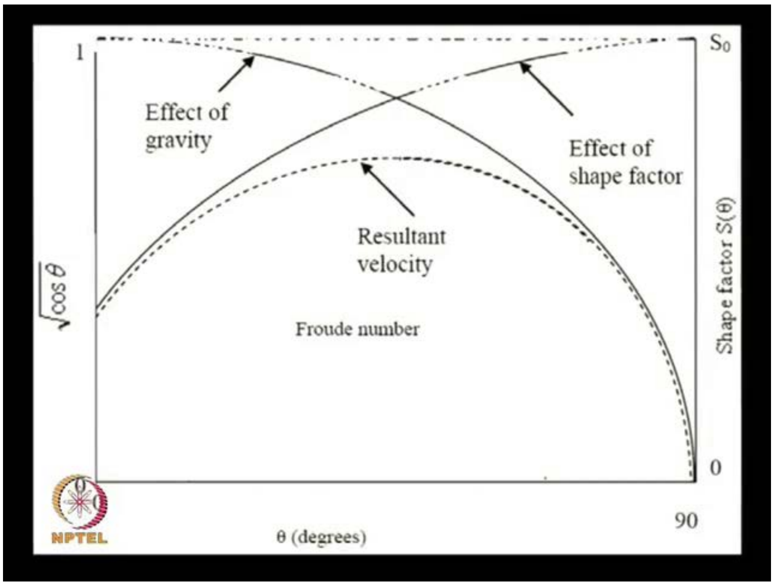

And after this as I had already told you. What we would be like to do is? As I had already mentioned that since we know flow patterns they are so, very complicated both the phases moving situation becomes much more complicated. So, I had just tried to show you the different situations when only one phase is moving through the other. Say the gas phase is moving through the liquid, this particular case will you call it a 2 phase flow situation. Packed bed case you did not call it to 2 phase flow situation, you remember it in this particular case remember one thing even here gas is moving through the liquid phase, but the inter phase is influenced by the motion. So, this is a 2 phase flow situation agree with me.

So, therefore, this is the simplest type of 2 phase flow situation that you can imagine of. Now, we find that whenever one particular volume of gas that is introduced in a stationary column of the liquid.

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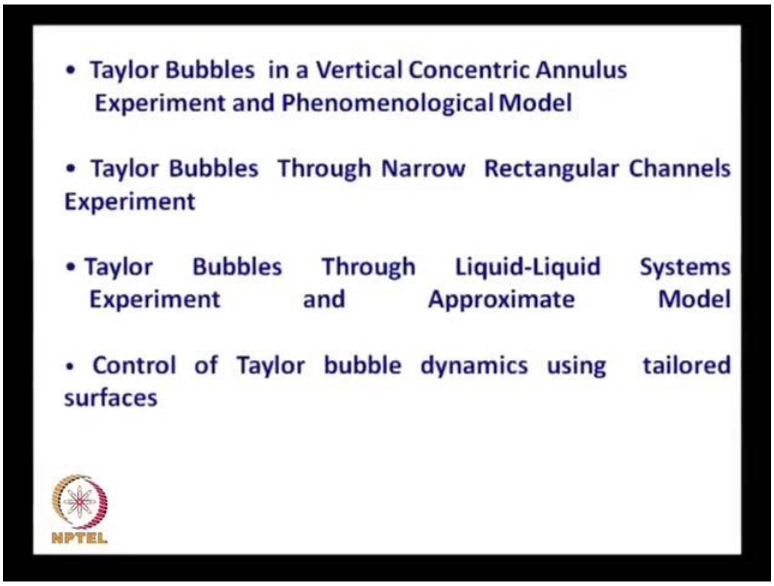

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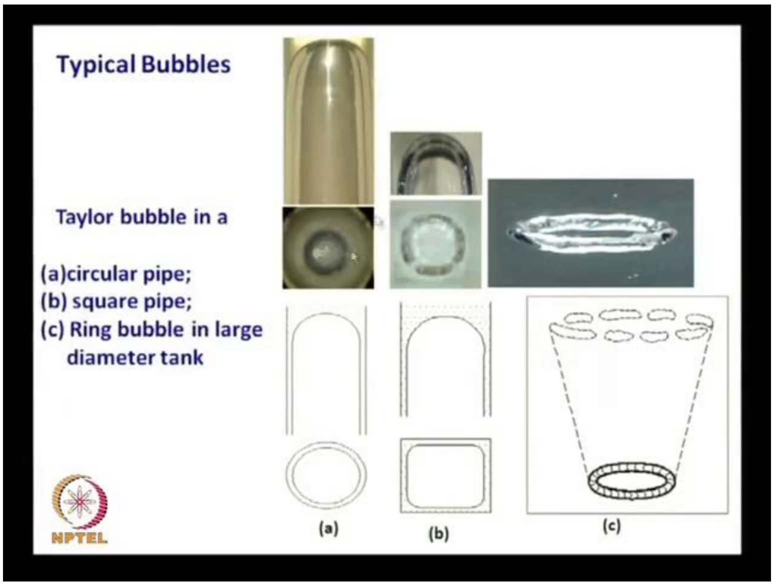

Usually we find that it rises up as a single elongated bullet shape Taylor bubble which we have already studied in slug flow. Now, interestingly we find that when such a type of air volume is introduced inside say an infinite medium that is a very large tank. Then in that case we form it does not form Taylor bubbles it forms ring bubbles something of this sort. These ring bubbles they gradually expand outwardly they become thinner and then finally, at a point while it rising it breaks up into a number of satellite bubbles. What we find? That, more or less they do not deviate from the access of symmetry, same air volume.

If it is introduced into a column or in this particular infinite medium if a column is introduced and the this particular bubble is confined in a by the walls of the column immediately, we find the shape it transforms and it becomes something like an axisymmetric bullet shape which is known as a Taylor bubble. Now, we find we have studied Taylor bubbles over a wide range of circumstances we have studied Taylor bubbles in vertically concentric annulus. We have studied Taylor bubbles in narrow rectangular channels in liquid liquid systems and in very narrow in milli channels under different wall conditions.

And I will just gave you a very brief idea of what are the different observations we have found, how even their motion or the rise of this Taylor bubbles is influenced by fluid type and conduit characteristics. So, this was what we found out and we I have already described the Taylor bubble to you it comprises of a bullet shape terrace with a hemispherical nose and a cylindrical tail as I have told you. Now, this shows the Taylor bubble in a circular pipe as well as in a rectangular channel, in a circular pipe if you observe the Taylor bubble it has a circular cross section.

In a rectangular channel or a square channel we find that it has got rounded edges, but a squarish type of a shape. And interestingly you find we find that when a bubble rises in a circular tube same volume rising through a rectangular or a square channel of more or less. The same type of dimension may be same characteristics we find that the Taylor bubble in the square channel rises faster as compare to a circular tube. Why does it happen? How does the Taylor bubble rise? It rises by the downward displacement of water. Is not it? When it starts to raise then the water flows as a thin liquid film, thin annular film and due to this fall in water the bubble starts rising.

Now, in a rectangular channel what we find there is additional liquid drainage by the corners. So therefore, liquid flows faster down and therefore, the bubble propagates faster in a rectangular or square channel this we have observed.

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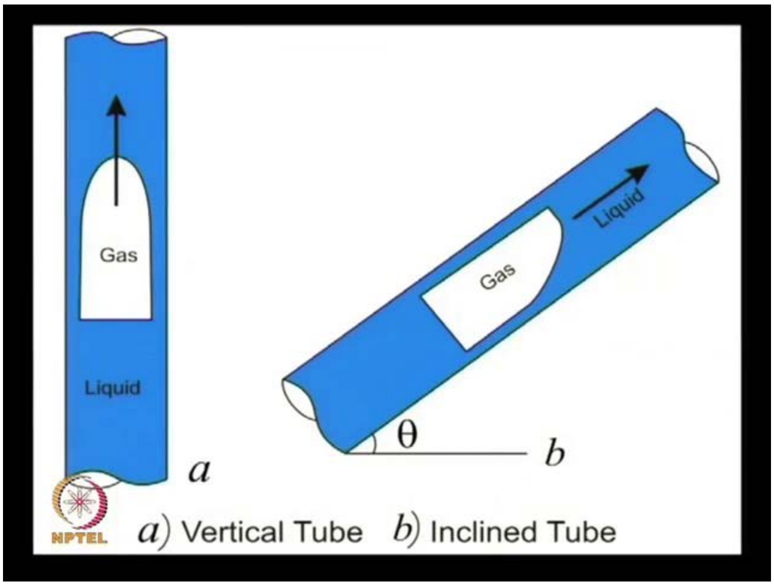

Now, after this next what we have tried to see is just if we simply the same channel if we inverted rather we incline it. Moment we incline it we find that this sort of a nice hemispherical shape this becomes a semi cylindrical sort of a thing and the nose becomes much more pointed. The it is more or less this the upper portion is flat the lower portion is sort of a hemispherical sort of a cylindrical sort of a thing and the nose becomes much more pointed.

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It is not very clear from this particular figure, but actually if we observe it we will find that for as incline case the nose becomes it is sort of something of this sort the nose becomes much more pointed. Now whenever the nose becomes much more pointed the rise velocity begins to increase and therefore, in a inclined tube the bubble travels faster than travels in a vertical tube. Is it clear to all of you? But I will ask you one thing so, that means, you mean to say that as we keep on inclining it the nose becomes more and more pointed. And therefore, more you incline the more the rise velocity should increase and then finally, when you make it horizontal the rise velocity should become the fastest does it can it ever happen.

So, the point is what happens is actually the thing is when you incline it the nose becomes more and more pointed, but at the same time the gravitational component decreases. So therefore, initially what happens the rise velocity begins to rise, due to the nose effect it continues more or less till an inclination angle say between 40 to 50 degrees people has have said 45 degrees. But usually what in our experiments we have found out is they more or less around 40 to 50 degrees like that the rise velocity is the maximum. After that more than the nose pointing phenomena the gravity becomes important, and then as you keep on inclining it towards the horizontal again the nose starts becoming rounded and rounded.

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So, therefore, it can be observed that we find what happens the noise pointing the effect of shape factor that keeps on incline increasing as we go from 90 to zero. Gravity keeps on increasing sorry this is the shape factor thing this changes in this particular fashion and the gravity changes in this particular fashion. There is an opposing effect due to which the resultant velocity profile is as shown it is maximum around a range of 40 to 50 degrees, it is lower for vertical and for more horizontal cases. So, this is the way in which inclination affects it.

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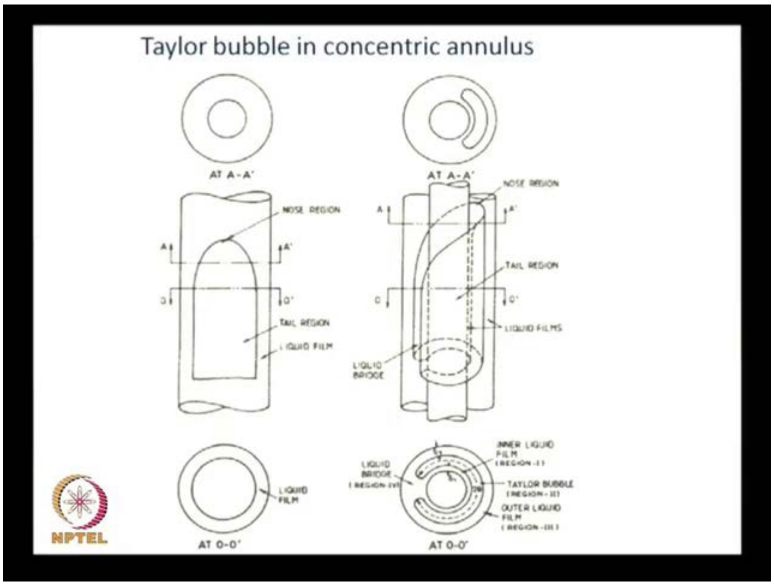

Now, the next thing which we wanted to study. What is the next thing, which we wanted to study? First we have studied a circular tube then we have made it a rectangular channel. The other thing in that circular tube if we just insert a rod, we make it a concentric annulus right, but anyhow whatever we make it when it is a concentric annulus it is also a symmetrical geometry. Is not it? Symmetrical vertical geometry. We have studied 2 others symmetrical vertical geometries a rectangular channel a square channel and a circular tube in all the cases the bubble was axisymmetric remember.

So, it was very well expected since this is also a symmetrical vertical geometry the bubble will be axisymmetric in this case as well, but very interestingly we found that in this particular case the bubble was distinctly asymmetric. Why it became distinctly asymmetric? Because we found that in this particular case the bubble which was rising when we insert a rod the bubble tends to wrap the rod. Is not it? But it does not wrap the rod fully it wraps the rod only partially and therefore, it gives a kidney bean shaped of an appearance which is evident here. Had it wrapped the rod completely then you would have got a axisymmetric a nice rotationally symmetric bubble that never happens.

What happens if wraps it only partially? So, as a result what happens? As a result we find that in this particular case cross section of the bubble has 2 regions, a Taylor bubble region and a liquid fluid region. Right for a circular tube, you agree with me? In this particular case the cross section has 4 regions we have a bubble, we have a inner liquid film, we have a outer liquid film and we have a liquid which between the 2 edges of the bubble extending from the inner world to the outer wall. So, just imagine in the circular pipe if we simply insert a rod how much complicated the situation become even for the simplest case of 2 phase flow.

So, this is very evident the bubble becomes distinctly asymmetric and more importantly it not only becomes asymmetric, but the nose becomes much more pointed as well. And when the nose becomes much more pointed we find that the bubble rises faster in this particular case. But the same diameter the outer diameter the bubble rises at a faster velocity in the case of a concentric annulus as compare to the circular tube. A very surprising results because we find that the passage becomes constricted, but that induces faster rising velocity.

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The other thing of course, this we have shown for different types of bubble in circular outer rod, circular inner rod, circular outer rod square, inner rod and so, on and so, forth. We have shown it for different circumstances and we find that for all the cases the bubble is asymmetric when the outer rod is square. Then definitely it has a squarish sort of a circumstance, but when the outer rod is circle it has got a circular cross section.

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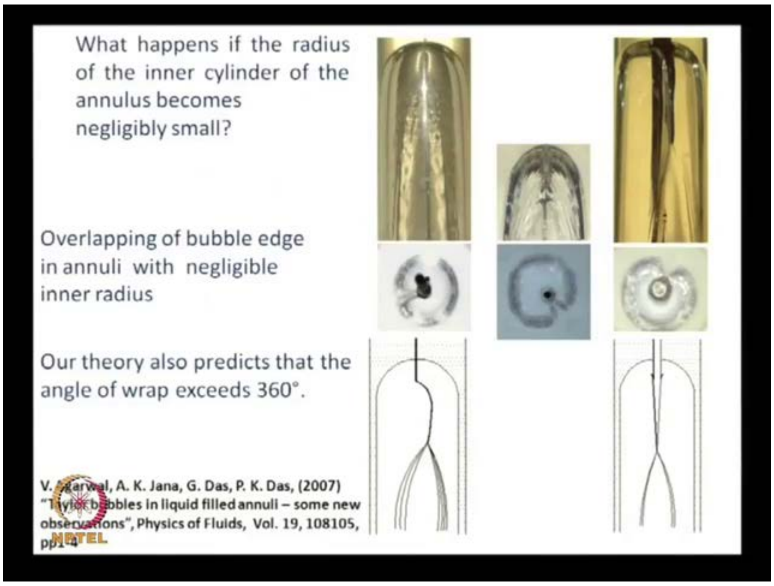

After studying this, the next thing which we wanted to study was. That for a circular rod the bubble was nicely symmetric for an annular it annulus it was distinctly asymmetric, the annular ring it opened up and there was a liquid bridge. Now suppose the inner rod it we keep on making it narrower and narrower till it becomes a very thin wire. Are you able to picturise the particular situation sure all of you? So, in this particular case, What happens? As we make the inner rod more and more small, we find that they keep on coming the 2 edges keep on coming closer and closer to one another.

So, we expected that when we make it a very thin rod then in that case the 2 edges should coincide and we should get a very nice rotationally symmetric bubble, which we observe for the case of a circular tube. But unfortunately we find that nothing of that sort happen and the bubble became a completely different shape in this particular case as we see from these figures.

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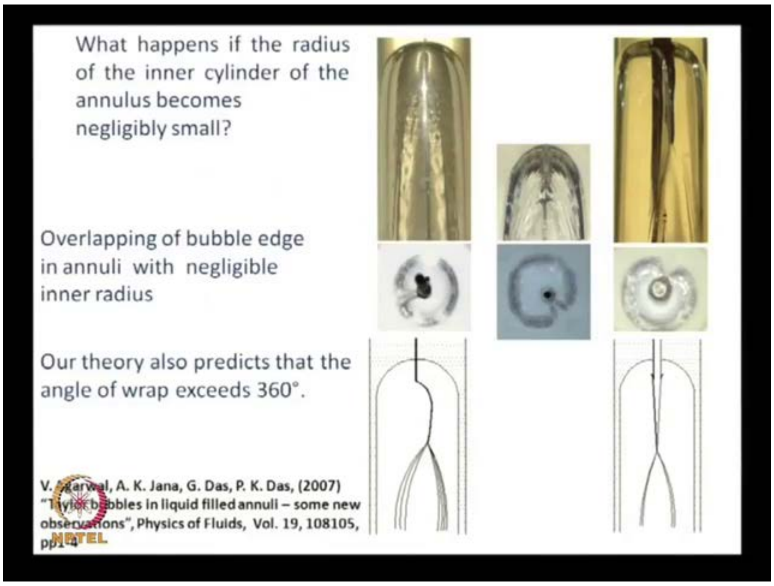

What happened in this particular case actually there was a cleavage at the tip. From the cleavage a line emerged and then after sometime the line bifurcated and water started flowing as streamlines in this bifurcated portion. It was a completely different shape as compared to the shape which we had observed for circular cases as well as normal concentrate annulus it was a completely different type of shape. So, we found that there was no smooth transition of the bubble from a circular pipe to a concentric annulus. All of them were discrete jumps because the physics governing them were distinctly different for all the cases. You just observe the previous shape this particular shape and you observe this particular shape it is completely different.

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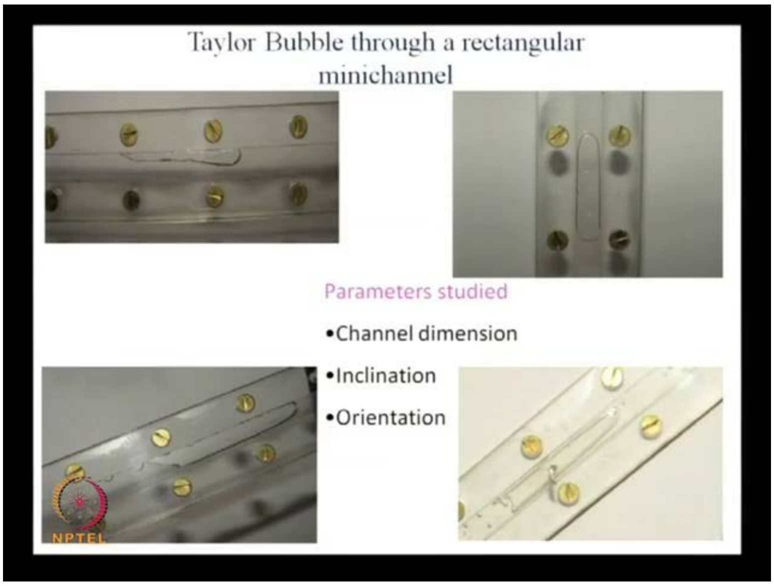

After this what we wanted to do is we wanted to study that well we have studied in circular tubes, we have studied in square channels, we have studied in concentric annulus now let us study for rectangular channel. What we wanted to study? Is, see rectangular channels we can keep it in this particular way and the bubble can rise through this. Now, when we incline the rectangular channel say from the horizontal to the vertical we can incline it in 2 ways. 1 is we can incline it in this way and we can increase it the other is we can make the channel like this and we can incline it. Did you get? So, this is the effect of orientation as well.

So, we can either keep the narrow phase perpendicular to the vertical access or we can keep the broad phase perpendicular to the vertical access. So, it can be inclined in 2 different ways and we wanted to find out that apart from channel dimension channel inclination does this orientation affect the rise of bubbles. This was the other thing that we wanted to find out now this effect of orientation could not be studied for any other symmetric geometries other than a rectangular channel.

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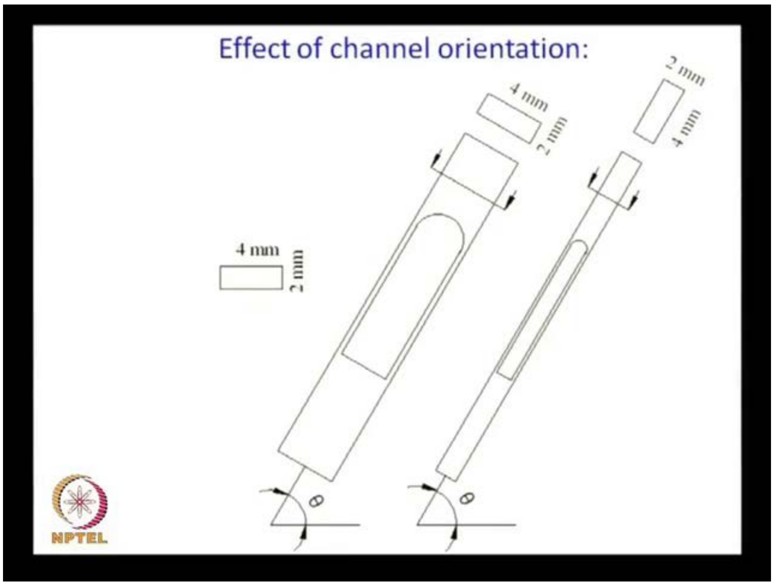

So therefore, we tried to study and we observed a very interesting phenomenon, these were the 2 situations the effect of 2 orientations that I was talking to you. We observed a very interesting situation in this particular case.

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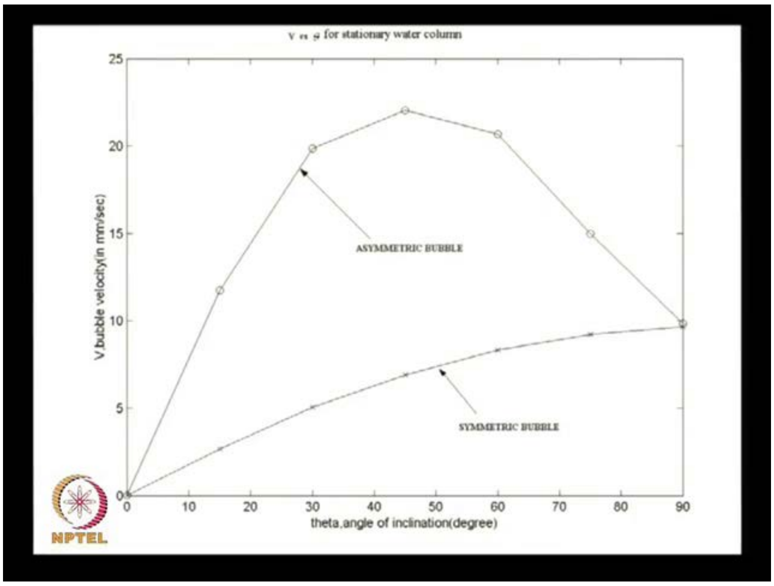

We found out that normally what we find that the rise velocity it gradually increases and then it decreases. Is not it? We have I have already discussed it for a circular pipe. We found out that when the bubble was in this particular orientations and the broad phase is perpendicular to the vertical access under this circumstance. Whatever we had seen earlier the same thing happen, the rise velocity went on increasing with inclination it reached the maximum and then it decreased. But when we are doing it in this particular fashion in the other orientation when the narrow phase was perpendicular to the vertical access under that circumstance, we found that we obtain results which we did not expect.

What we found rise velocity went on increasing and it was maximum at the 90 degrees means in the vertical orientation it is maximum. There is no such maximum minima case as we had observed for the previous situation. So, we find that whatever new geometry we invade some new physics comes into being that is what actually I want to emphasize upon you means this is the uniqueness I should say of 2 phased flows. So, then naturally when this happened we tried to find out what can be the possible reason for this in order to find out the reason we started taking photographs of the bubbles and then we reported the photographs for number of inclinations.

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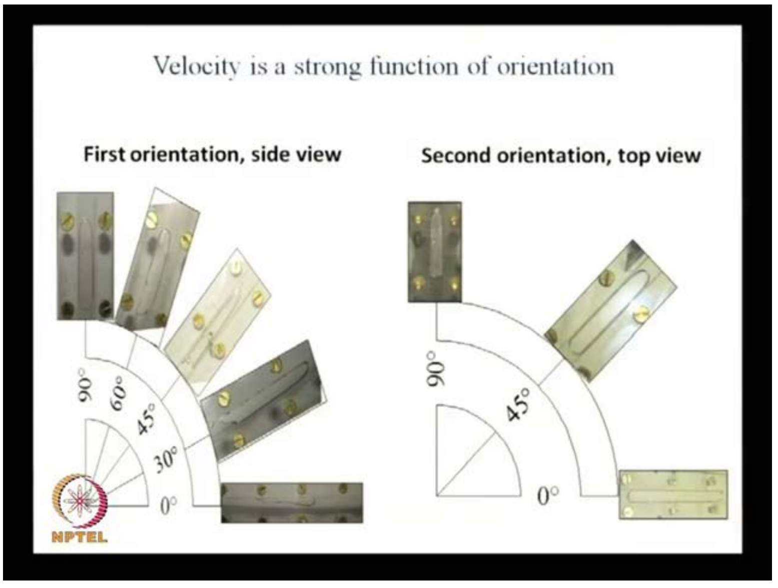

We found out that for the first case where the broad phase is (( )) rather it is perpendicular to the vertical plane under this particular circumstance we found that. If you observe I do not know how clear it is the nose gets more and more pointed, and here it is completely rounded gradually it starts getting pointed and the bubble is confined towards the upper portion. And finally, when we come to the horizontal there is no Taylor bubble sort of a thing, it is just an irregular mass of air which is rising or rather which is climbing along the upper wall. On the contrary when we deal with the second orientation, where the narrow phase is parallel to the bubble, we find that there is very less space for the water film to flow down.

And here we find that the bubble shape does not change with orientation, if you observe the bubble it is it always has a rounded shape in all particular orientation. So, the shape factor does not come into picture under these particular circumstances, the shape factor which was very important here. And due to this shape factor what we got we obtained a increase and then a decrease in rise velocity, in this particular case we found that the shape factor does not come. And therefore, it is only the gravity which governs the rise velocity and therefore, we found that the rise velocity keeps on increasing with gravity finally, in the vertical orientation it is the maximum. This was one other thing we found out.

Now, after this the next thing which we wanted to study was fine with air water cases several studies have been done true, we have taken different geometries and we have found out how it affects. Now, suppose we insert a lighter liquid into a heavier liquid and then normal circumstance what happens due to surface tension the liquid breaks down into drops and number of drops rise. But if we take a more or less narrow pipe in less than half inches we found that in that particular case also the lighter liquid rises up.

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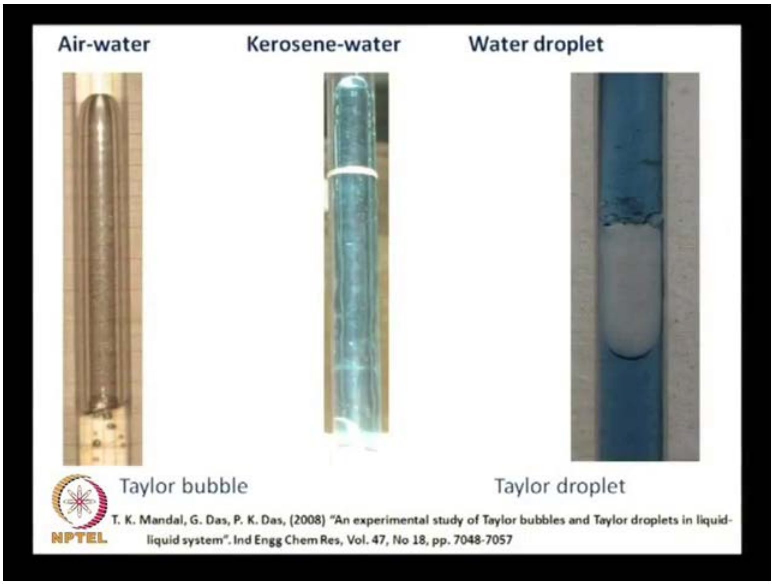

as a Taylor bubble in the heavier liquid as we have shown in this particular case it is a kerosene bubble rising in water.

Now, there is something very interesting about this liquid liquid case. We found out that when a lighter liquid is injected in a heavier liquid it rises up just like a Taylor bubble, on the contrary if a heavier liquid is injected into a lighter liquid from the top say water injected into kerosene. We find it falls downward also as a just assuming a shape of the Taylor bubble same shape it begins to fall down. And see this particular situation could not have been observed for gas liquid cases. Is not it? So, therefore we found that when we shift to liquid-liquid cases for gas liquid we have Taylor bubble for liquid liquid we have a Taylor bubble as well as a Taylor droplet as well.

So, we have both of this is the specialty of liquid liquid cases. And we found certain very interesting results also I should say in first result is we found that a Taylor droplet it is much more stable as compare to a Taylor bubble. The surface of the Taylor bubble is much more wavy, but if you can observe this you can find out that the surface of a Taylor droplet is much more smooth. But the Taylor bubble is less stable at when we keep on decreasing that rather keep on increasing the diameter a Taylor droplet breaks off faster than a Taylor bubble number one. Number two for the same pipe dimension a Taylor droplet travels faster as compare to a Taylor bubble these are some of the unique features that we observed for liquid liquid systems.

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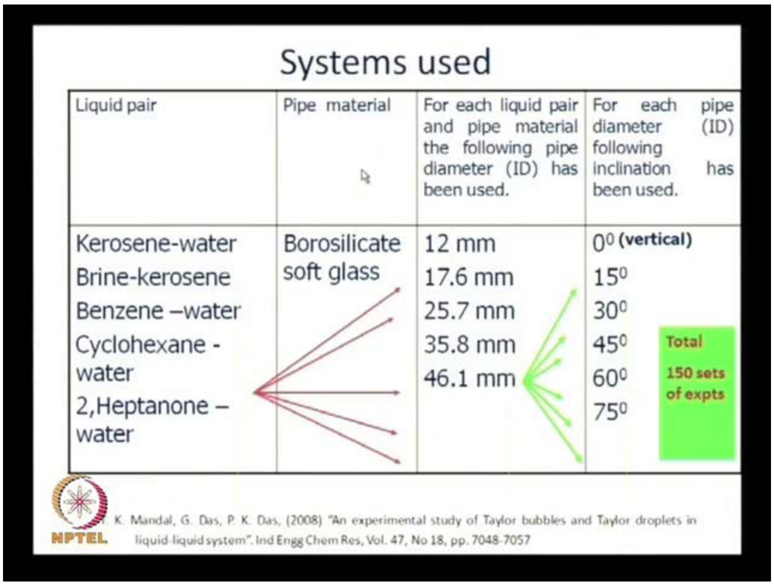

So, different features we studied with a large number of liquid liquid systems which

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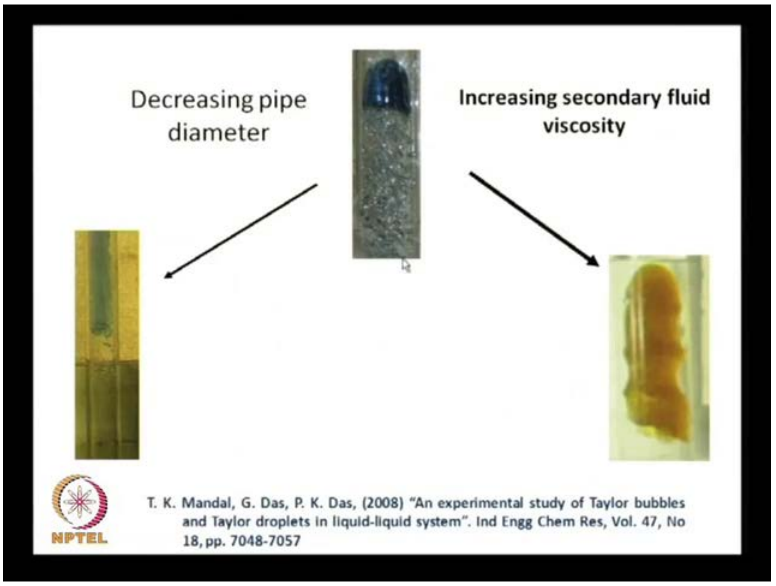

I have shown here and we found out several interesting features which I should say the most interesting features are as we have I have already mentioned. We find that the shape of the nose is more or less the same, but the Taylor bubble is less stable for liquid liquid cases. And we find that a Taylor drop is much more smooth, but it is range of stability is much less in this particular case, and the velocity if rise it is higher for a Taylor droplet. Interestingly for Taylor droplets and Taylor bubbles when we find we find that with decreasing diameter the stability increases, also with increasing viscosity if we find we find the stability decreases.

This was for kerosene water this is for lube oil water you can always you can see that in this case the shape is much more deformed as compare to this case. Of course, in here we found out that there is a large amount of vague region and the bubble is much less stable here, as compare to decreasing the diameter. So, in this particular case we found that in contrast to air water systems in this particular system, we found that the liquid properties. The property of the liquid forming the bubble or the droplet that is also very important. If we have higher interfacial tension bubbles are more stable, if we have higher viscosity bubbles are less stable, if we have larger pipe diameters bubbles are less stable. So, these are the things that we have observed in addition in liquid liquid systems.

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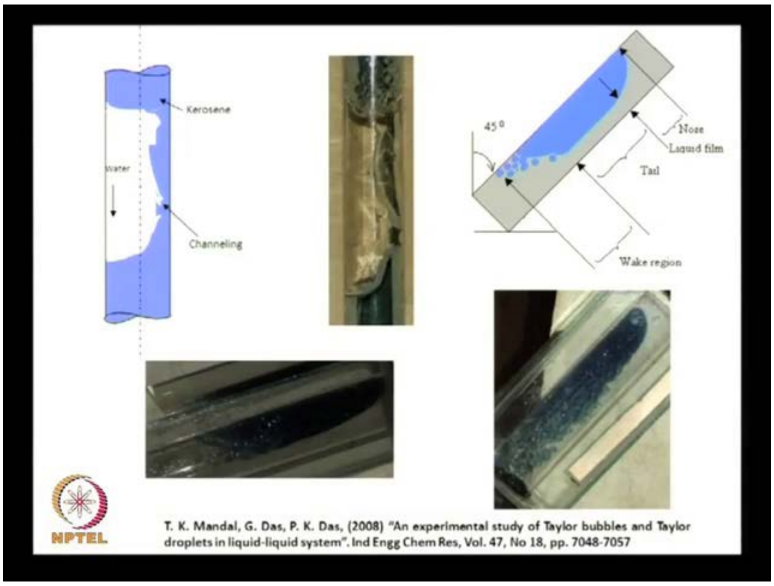

And another very interesting thing that we have observed for I think I have the slide for it, another very interesting thing that we have observed for liquid droplets. What is that? When water is see when that a kerosene Taylor bubble is rising through water what do we find that it is more or less axisymmetric, but when a water droplet is falling through kerosene we find what it does. It actually sticks to one particular portion and it climbs down along a one particular wall whereas, kerosene flows downward along the other wall. Or in other words we find there is a tendency of channeling in this particular case.

Why does it occur, can you tell me? Why does this channeling occur, when water droplet falls to kerosene? But it does not occur when kerosene bubble rises through water. Any idea? We have performed experiments in glass pipes of half inch diameter or less than half inch diameter. Any idea why this is occurring? The thing is remember one thing glass is hydrophilic so, naturally there is a natural tendency for water to stick to the glass surface. Is not it? So what, water tries to do is it tries to stick to that to 1 side of the glass and to spread on this particular surface. And therefore, since it does it pushes the kerosene on the other side which gives rise to this particular channeling effect which is so, very evident from this particular photograph as well.

This channeling effect is not observed for Taylor bubbles under any condition in vertical tubes. So, this is another very important thing, whatever new you do you find out so, this particular channeling you find for Taylor bubbles in inclined tubes. Whenever you incline it what happens the lighter phase tends to rise up and therefore, there is a channeling sort of a effect, but for vertical cases you will never find it. But when it is water droplet falling through kerosene or through any other liquid for the matter we find such a particular circumstance. Here in these 2 photographs if you have observed, you find the channeling in vertical tube for water droplet and then this case the more or less a similar sort of a effect for rising Taylor bubble when the tube is inclined. All these I have been done for circular tubes.

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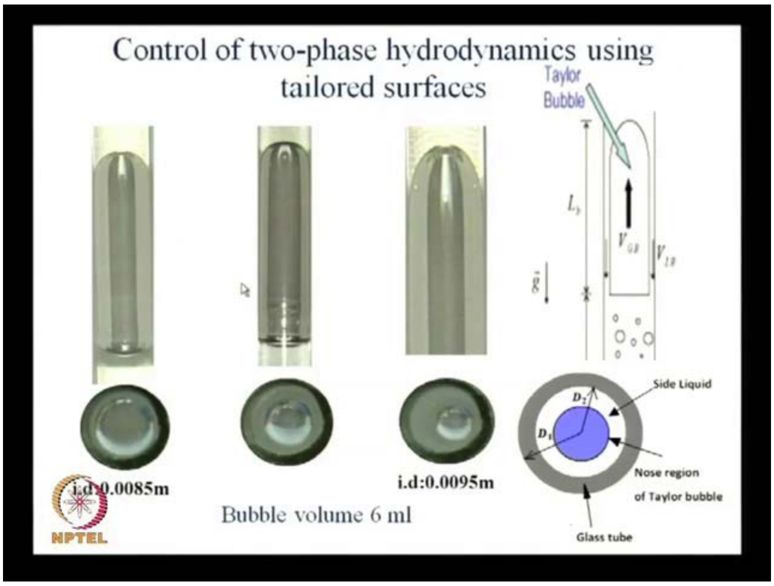

Finally I would like to conclude by telling that after all these things the last thing that we had done was we had tried to study the rise of Taylor bubbles in milli channels. May be we are we had varied the range from say 10 millimeters to about 2 millimeters this particular range we tried to study. Why because in this particular range we knew that the capillary forces, the surface tension forces or the wettability effects they become much more pronounced. Normally, this rise of Taylor bubble it is a inertia dominated situation it rises by gravity. Is not it? Just a lighter phase rises through a heavier phase, but in this particular case we find that the capillary forces start becoming important they start dominating over gravity.

So, we found out that let us study in this particular range and find out whether we find any new characteristics of the Taylor bubble in this particular range. And we also wanted to study that if capillary effects are important then definitely the wall wettability will be important, the contact angle will be important. If we perform experiments in hydrophilic tubes and hydrophobic tubes we might get different results so, that is what we wanted to study. We found out that, the bubble does not rise beyond the critical diameter more or less we found the diameter to be four millimeters and people past studies has also reported an identical diameter.

So, we found out that more or less in this particular case the bubble rises only after it exceeds or that the tube exceeds are the minimum critical diameter, but once it begins to raise it just takes up the same shape that we had observed for a bubble in larger tubes.

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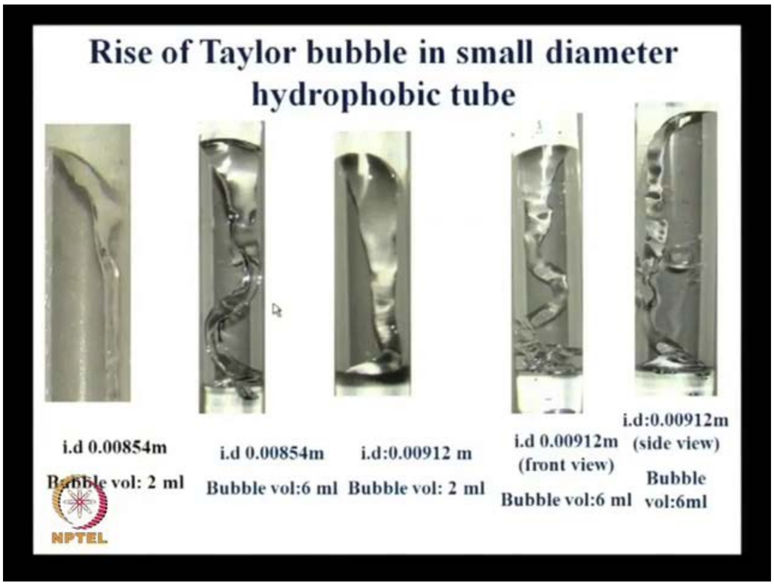

Interestingly, when we perform the same experiment with the same pipe diameter in a hydrophobic tube we found a completely different shape. Why? Because in the hydrophobic tube water was not able to wet the tube wall so, it could not form or the film which it forms in this particular case. So, if it does not form the film how will it flow down? What does it do? It forms a rivulet sort of a thing which has a meandering motion and the water flows as a rivulet while the bubble with the pointed sort of a nose rises up. The shape becomes completely asymmetric and very different in the case of a hydrophobic tube and very interestingly the rise velocity becomes faster for the hydrophobic tube as compare to the hydrophilic tube.

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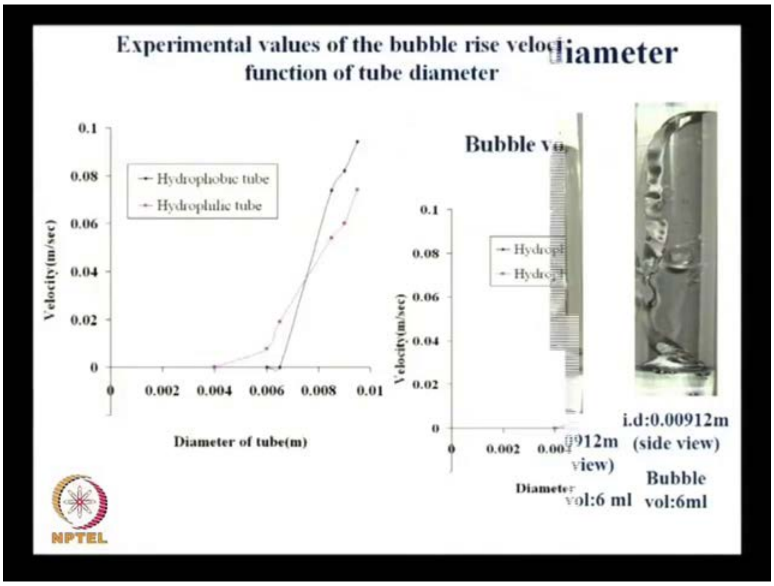

So, these were the different cases which we have studied and well this was all that I had to say to tell you just to show you that even for the simplest case of two phase flow. How the flow situation is influenced by externals parameters like tube characteristic and fluid characteristics? And how they change under different conditions and some unique characteristic of Taylor bubbles? Which are not observed under normal circumstances. So, this completes our chapter our discussion on flow patterns it was I think quite sufficient for all of you.

So, in the next class we will be starting some amount of modeling, but before discussing the models what I would like to do is I would like to give you a list of nomenclatures. Which will be using why? Number of nomenclatures you know from single phase flow, but we will be coming across a number of new nomenclatures as well. So, we will be spending some time on the different nomenclatures that we will be encountering we will be using those nomenclatures only in our classes of multiphase flow. Just to avoid any sort of confusion, if you wish to use any other nomenclature I have no problems, but then you have to define them and you have to use them.

So, we will be standardizing the nomenclatures which we will be using and after that we will be going for simple analytical model to deal with separated flows, mixed flows and or rather dispersed flows and transitional flows. Thank you very much for the time.