Adiabatic Two-Phase Flow and Flow Boiling in Microchannel
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Lecture – 14
Influence of Operating Parameter on Flow Patterns (Contd.)

Well, hello everybody. We continue without much waste of time, I would again welcome you, and we continue with our discussion on the effect of operating parameter.

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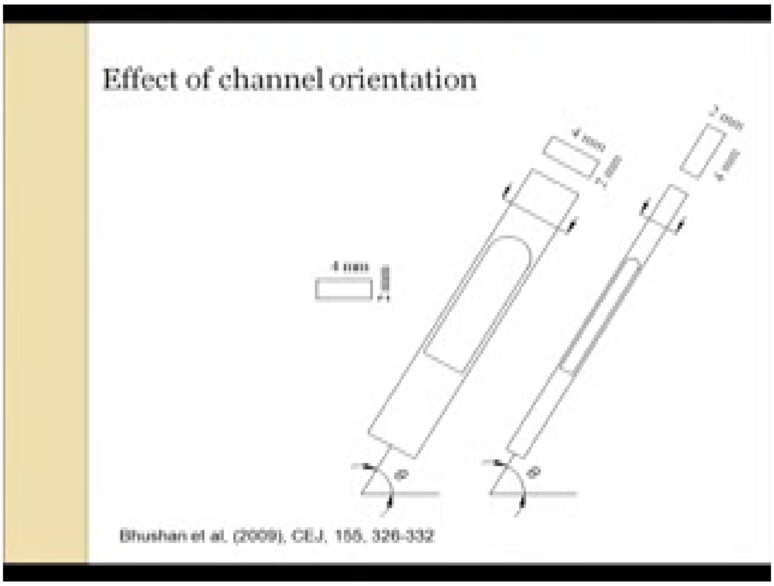

We were actually discussing the effect of channel inclination, we have already discussed, and I have told you that, well channel, the effect of channel inclination its, although counter intuitive, it is same for, your circular tubes, or for other concentric, for geometries, including a concentric anglers, a rectangular square etcetera. But I just wanted to mention one interesting thing, which again we are observed in our multi-face flow laboratory, regarding a rectangular conduit.

Now, just see, if you take up the rectangular conduit, the conduit, suppose it is horizontal, and which are start in inclining it, we in incline it either in this particular way, or we can make the conduit like this, and we can incline it in this particular way. Normally it should hardly matter, no matter whether we are inclining it, along and axis, which is passing through the narrow phase, or along an axis, which is passing through the wider phase, normally it should not matter a much. For larger channels, it did not matter, but when we perform the experiment in our 4 millimeter to 2 millimeter size conduits, and we were performing experiments, we found something very interesting. What we found is, we are trying to measure the rise velocity, what we found is that for this particular orientation, felt sorry, from for this particular orientation, when it was rising, we found that the, the nature of variation of the rise velocity width, and angle of inclination and was as expected.

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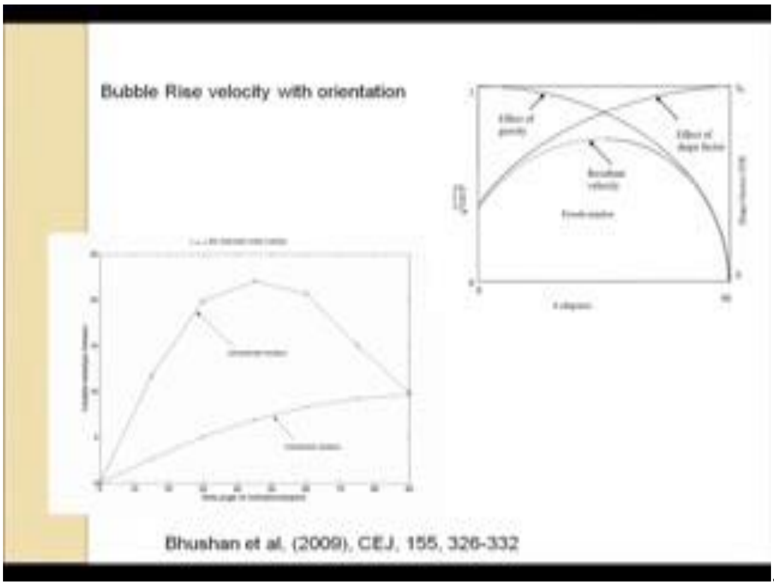

The inclination angle, it gradually, sorry, the rise velocity, it gradually began to rise from the horizontal orientation, it attained the maximum somewhere between 40 to 50 or something, and then it started decreasing again. Just like the typical curve, which we observe, for liquid tailor bubbles, in circular tubes, gas tailor bubble in circular tube, as well as your the even for, liquid drops, this liquid drops, I did not mention I will not going with the details of it, we do not have so much time.

We find that the liquid, liquid systems when a lighter liquid rises through a heavier liquid, its not as a liquid tailor bubble. Same way, if a heavier liquid is, is made to fall through a lighter liquid, it also assume the same tailor bubble sort of a axis symmetric bullet shape, and falls down, and we have named it as a tailor drop. There too, in tailor drops also, just to mention they also they exhibit the same type of the characteristics as liquid tailor bubbles, or react tailor bubbles, their velocity also increases from the horizontal orientation, attains a maximum around 40 to 55 within this particular angle of inclination, and then it decreases again. There also we find that the wake region is much less, but the bubbles are less stable, and the tend to break up faster than the liquid tailor bubbles.

Well to come back to a discussion. We find that for the, for the, the first orientation, which is the orientation shown here, we see that the bubble rise velocity, it exhibits the same type of curve as is expected, but if suppose the tailor bubble is held in this, this particular way, and it is made to rise in this particular fashion, we find for firstly, that the rise velocity is always less than the other orientation, number one. The number 2 we find that in this case, the velocity rises steadily, from the horizontal to the vertical orientation, and the rate of rise is faster initially, and then it gradually becomes much slower and; obviously, their this goes beyond saying that the rise velocities in both the orientation are the same for the perfectly vertical and be perfectly horizontal orientation, that is quiet expected.

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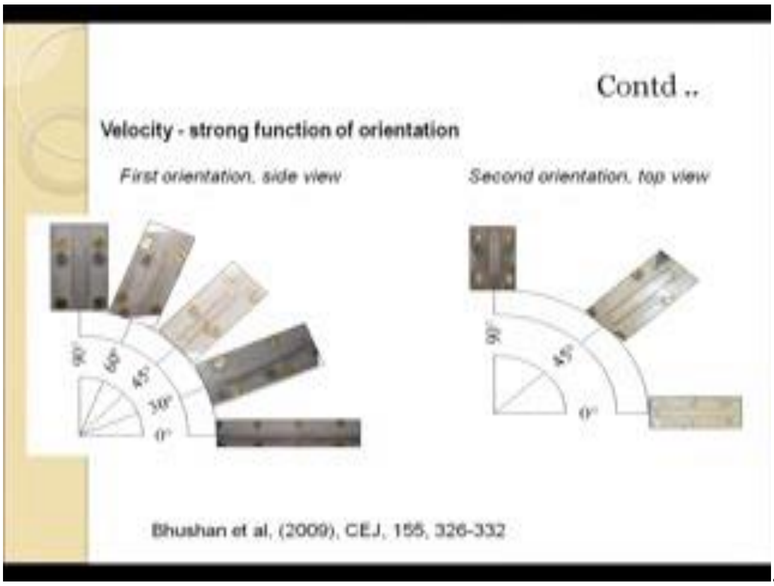

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Therefore, naturally we wanted to investigate the primary reason for it, and in order to understand the reason what we did, we tried to observe the shape of the bubble because, we knew one thing from all are experiences on tailor bubbles rising through liquid filled conduits, one thing we knew that the rise velocity, it is governed by the shape of the nose. Once the nose is formed we, we know that the nose is invariant of the, of no matter how the volume of the bubble, or how long the bubble is, the nose once formed, is a function of the channel dimension. In a particular conduit, if the geometry and dimension are unchanged, the rise velocity of a tailor bubble remains unchanged. This is something which, which should be remembering student of multiphase flow.

Therefore, we naturally it came to our mind, that definitely it is the shape of the nose which should be different in the 2 cases, and we found that ours supposition is correct, as we see from this particular slide.

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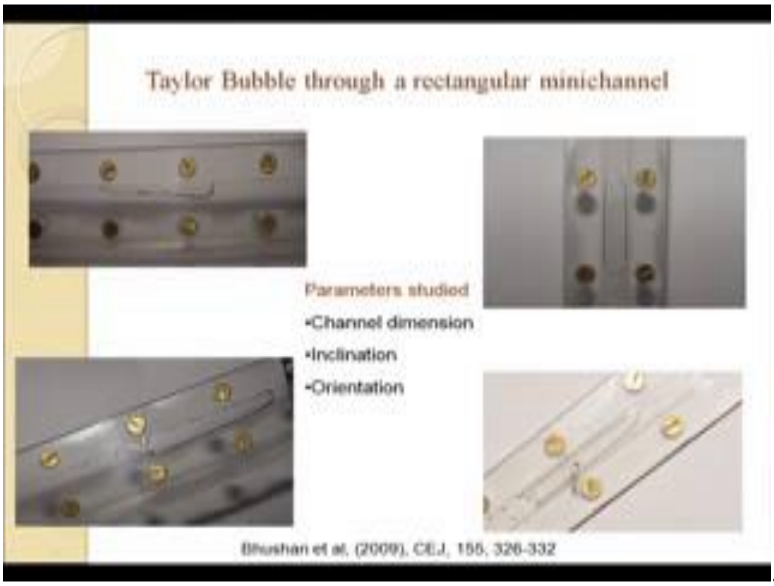

I think a better view will be this. Here if you see in the horizontal case, we find that the bubble it is, it is completely asymmetric and completely irregular in this particular case. Now as we start increasing the inclination what do we find? We find that the bubble it gradually starts becoming pointed, it becomes more pointed in this particular case. And gradually as we keep on increasing the inclination, what we find, that when we obtain the vertical orientation, again the bubble has attained the bullet shaped as access symmetric shape, with rounded nose and the flat body. So, therefore, we find that the change in shape, in this particular case, is as we had expected for, rather as we have found for, yet tailor bubbles or kerosene tailor bubble in the previous case, and therefore, since the change of shape was as anticipated, the rise velocity curve with inclination, was also as expected.

On the other hand, when we observed the bubble shape, in the second orientation, let me tell you, that you both the orientation the photograph had been taken from the broader phase, quiet naturally, the photograph had been taken from here. So, naturally for this particular orientation, the photograph was taken from the top, and for this particular, sorry, for this particular orientation the photograph was taken from the side, and for the other orientation the photograph is taken from the top. In this case we observed that, the bubble shape remained unchanged with orientation. The bubble it was access symmetrically placed in the annular liquid film, it had rounded nose and at a rounded tail, and this particular bubble shape was retained, while we were trying to change the inclination of the channel.

Naturally for this particular case as it expected, gravity was played the only role, and as a result in this particular case the, the, the bubble velocity changed according to gravity, and this is what is explained in this particular curve. Now since this is something very unique, only for a rectangular conduit, I thought that its worth some discussion, and we should be discussing it, and this particular slide it showed you the, the tailor bubble parameters, as its shifts from the horizontal to the vertical orientation, for the b type orientation. And this is was quiet expected you know, because we find that, that when the channel is kept in the particular way, and it, it the orientation changes like this, we find that there are spaces on the 2 side of the bubble where it can, the water can be flow can flow and when we make the channel inclined from the vertical, the bubble can move up, and can create at an additional channel in the bottom portion, through which the water can flow, but when we are moving it up in this particular orientation, we find that the bubble is almost compressed by the sides.

It is very less space actually move up and it, it actually as very less space for gravity to act on it, a similar situation which we encounter for a micro channels, where we had said, that this is the reason while bubble trend flow occurs, instead of the disperse flow baton, and the buoyancy effects are much less, this we had already said.

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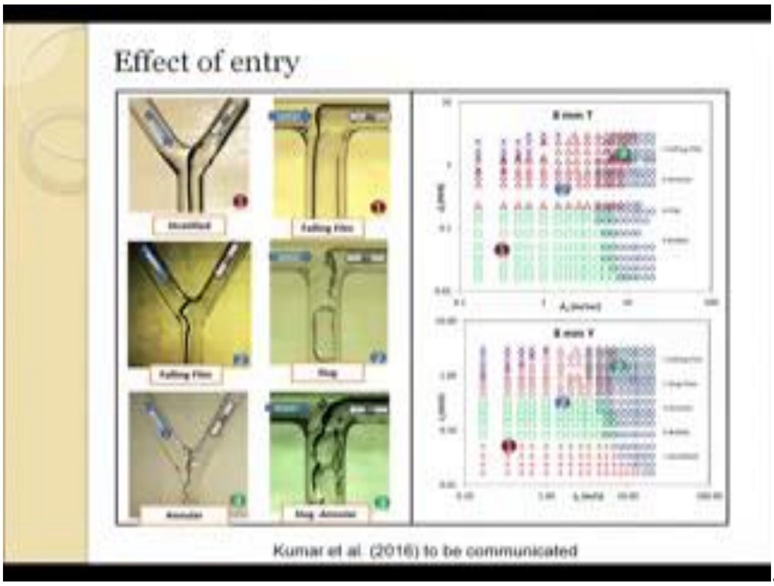

Well this is something see whatever we have been discussing for so long, well they were lot of things were for mini channels, but initially we discussed the effect of, some unique effect in macro systems, this is a very unique effect which I would like to tell.

Now, when we say that surface forces are important in micro channels, naturally the next question which comes; that means, wall wetability, wall characteristics, wall roughness, should be effecting the flow morphology, and along with that, we will be discussing this after a complete my discussion on this particular slides, along with that is not it not very obvious, that entry section will also the influencing flow parameter. Now not much study has been reported on this, some people definitely have done, they have used lot of different in less sections or injection nozzles, or mixer sections, as they are called may be one of them had a concentric or a co-axial type of mixer, one, most the people they use diametrically opposite, rather a t-type mixer is most common thing. Some people have used a y-type mixer also, but comparative study, every, most of the researchers working in micro and mini-channels, have also mention that, the fluid does not forget its history, and therefore, it is significantly influenced by the entry section.

Now, does this not occurs for a macro system? Possibly the macro system also quite influence by the entry section, but beyond the developing length, the entry section usually has not been observed to influence the flow morphology to a significant extent. But in this particular case, what we were interested in, we just try to find out that for minor variations in the entry section, really do we have any influence on the flow morphology? What we did? We performed some experiment, with air and water, in down flow for the entire range of mini-channels, extending from 2 millimeters to 12 millimeters, and we used different angles of the injection nozzle, we in the fluids (Refer Time: 13:43) air from diametric opposite points, across a t-junction, and then we subsequently performed experiments, by varying the angle between the 2 arms.

Now, in this particular case, I have just taken up one representative comparison, in order to highlight the effect of entry. Let me tell you this has been shown for a 8 millimeter case, we have obtained identical results starting from 4 millimeters to 12 millimeters, what do we observed? We observe a very interesting phenomena, for the case of the t-Junction, suppose both air and velocity are very low, then in that case what do we find? We find that or low velocities the water comes here, it is a glass tube. So, naturally water has a natural tendency to wet the pipe wall, it wets the pipe wall and flows as a concentric liquid fill, with smooth interface, usually we have designated this pattern as a falling fill flow, and the annular flow.

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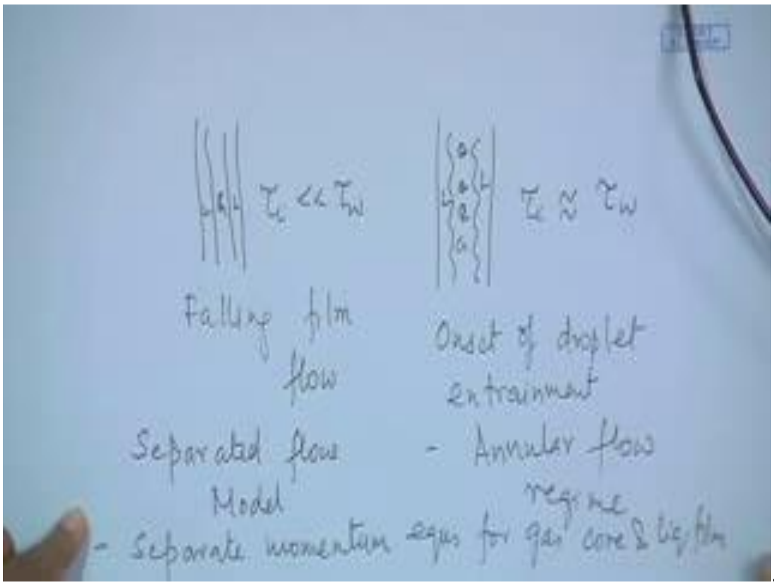

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Because for the down flow case ,what we have postulated is, that when the liquid and gas, they are flowing with the smooth interface, liquid here, liquid here, gas is here, we are going to call it as a falling film flow, and now as we replace the gas velocity, we find the surface become very wavy, and due to this waviness, liquid prompt less are entrapped they are enchained in the gas core, and this particular situation. were the onset of droplet entrainment occurs, we have named this as the Annular Flow Pattern.

So that our nomenclature, or rather several people have used this nomenclature, we have distinguish the 2 type of annular flows, primarily because, we found that in falling film and annular, it is marked by the onset of droplet entrainment, interfacial shade is going to be different. In this particular case we can neglect tau I, as compare to the shear stress, but in this the particular case, due to the increased waviness, tau I can be comparable with the wall shear stress, and there are additional shears at the liquid droplet portion.

Therefore, when we write down the momentum balance equation, which I had mentioned in my first or second class on the introduction of the multi-face flow, if you go to that equation you will find that, for falling film flow just a wall sheer stress is sufficient, but while we are trying to module the annular flow, both the shear stresses should be considered. And of course, in this particular case we can model it, in a form of a separated flow model, we will be very briefly touching a point these things in subsequent lectures, we can use a separated flow model, where the we will write separate momentum equations for the gas core, and the liquid film.

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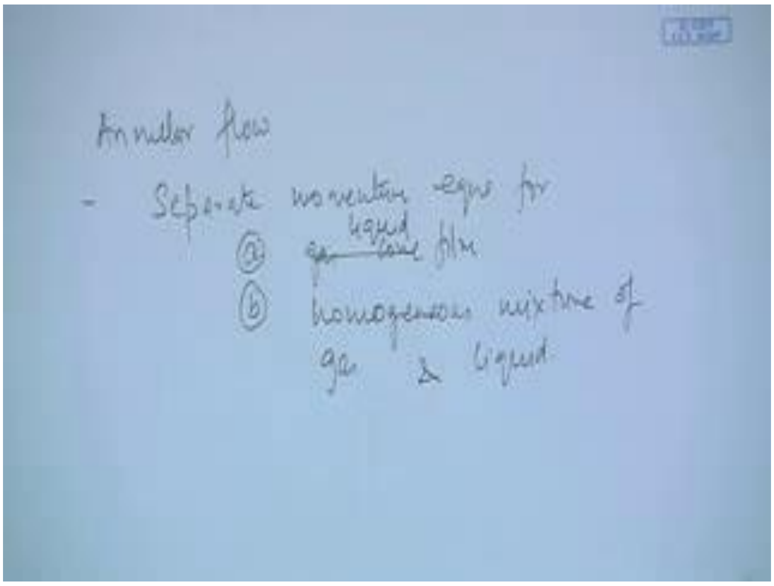

And this separate momentum equations, we will just put tau I much less than tau w, and we model the falling film flow. While for annular flow, we do the same thing, we can write separate momentum equations, for a, gas core, and b, it is it is not the, sorry, very sorry, for a, liquid film, and b, it is not the gas core, but rather homogeneous mixture of gas and liquid. If you compare in this particular case, I had told you that we are going to write separate momentum equation for the gas core and the liquid film, while in this particular case, we shall again do the same approach, but this case instead of a gas core, we have to consider homogeneous mixture. Now due to this reason, it is very evident that the same equations cannot be applied for low and high phase velocities, or in other words the onset of droplet entrainment needs to be given special attention, while predicting the pressure drop, and other hydrodynamic parameters of annular flow.

That is the reason why these 2 flow patterns have been differentiated, and they have been marked by different symbols, in the flow pattern map here. Well again I have digressed from what we are trying to discuss, but anyhow I thought its important to clarify this particular point because, so long we have just in dealing with bubbles slug churn and annular, suddenly here I introduce something like the falling film, and it might confuse the student that, if falling film is annular, then why use a different nomenclature. Now remember one thing, we demarcate flow pattern, just because we want to identify areas, where one particular set of momentum equations are applicable. Just like in single face flow, we demarcate laminar and turbulent, why?

In laminar flow, one type of equation is applicable, friction factor is equal to 16 by r e, for fanning section factor or turbulent flow, another type of momentum equation is applicable. In this case also, while we would try to keep the nomenclature to the minimum, we would like to differentiate those particular flow regimes, where we would want to have separate momentum equations, or in other words where the morphology influences the hydrodynamic soft flow.

Anyhow, now coming back, we find that for gas liquid down flow, the most natural flow pattern, which is the flow patterns which occurs for very low gas and liquid velocities, is the falling film flow. And as we gradually increase the velocity, if you observe this map you will find, that initially the flow pattern is falling free, as we increase the liquid velocity naturally what the liquid does?

It tends to break the, the gas la, and naturally it forms the slug flow pattern, again we keep on increasing the liquid velocity, the liquid inertia becomes more important, it tends to shear the pluck further into smaller bubbles, and we come across the bubbly flow pattern, but please remember, in this particular case for this millimeter size channels, we do not get a well dispersed bubbly flow patterned, for this particular case, the bubbles they are discrete cap shape ellipsoidal or disk shaped bubbles, with dimensions smaller than the conduit dimension, but not fully dispersed or emulsified.

Well, now, if we come back to our entry section, once we have understood gas liquid down flow through to millimeter size channels, we find that at low velocities in this particular case, we observe falling film flow, for quite a good range of velocities. Same experiments with the same diameter tube, we have performed for the same flow velocities, just we have changed the injection system.

Instead of introducing the 2 fluids from diametrically opposite points, what we try to do this time is, we, we try to insert them at an angle to each other, what do we find in this particular case? Just like this case the water is flowing through this arm and the air is flowing to this arm, but possibly the water, in order to wet this particular arm, and fall along the this particular channel wall, it needs to climb in the, in the, in the r, in the air arm, and, and since this climbing has to be against gravity, water, it prefer to fall down directly from here, and as a result what we find is, we obtain a unique flow pattern, which is not very common in the vertical conduits, and this flow pattern is known as the stratified flow pattern, as I shown in this particular map.

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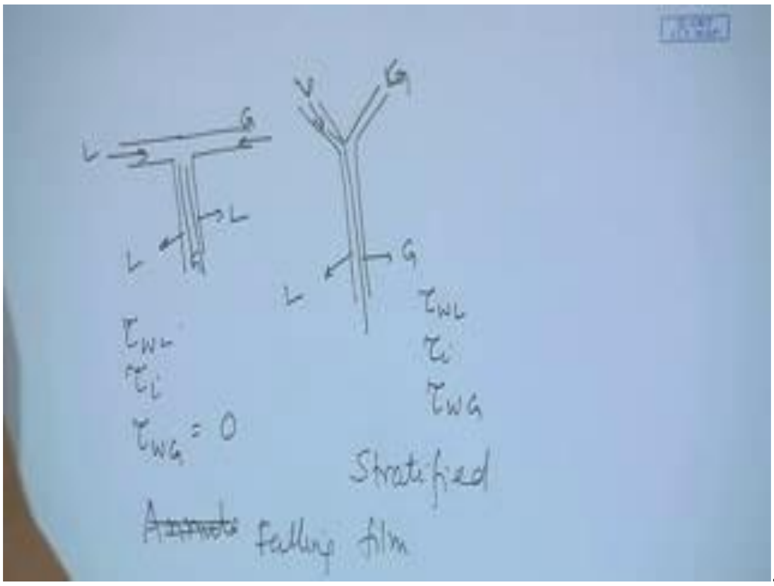

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In this stratified flow pattern, what do we get? In this particular case we have just like I have explained, this is liquid, this is liquid, this is gas, but in this particular case just to show you, what do we have through this, sorry, sorry this is liquid, this is gas, we find that the liquid is flowing along one side, the gas is flowing through the other side. So, in this case, this is the liquid portion, this is the gas portion. Both of them are flowing side by side or parallel to each other, in down flow, and both of them are in contact with the wall, as a result in this particular case, there was tau w l, there was tau I, which might be negligible, and tau w g was is equal to 0, this particular case, we have a tau w l, we have tau I, we have a tau w g as well ok.

And this particular, this is known as the stratified flow pattern. This is known as the annual, sorry, this is known as the falling film flow pattern right? Therefore, in this particular case, what we find is, that when the, we in claim the, the 2 arms of 2 entry arms at an angle, we find that we have come across a completely new flow pattern, which definitely is a separated flow pattern, but is different in distribution, compared to the falling film case, and in this particular case, both the gas and the liquid, they are coming contact with the wall, as a result of which the I got I written is, we come across 3 types of shear right? Therefore, this flow pattern map shows, that while falling film exists over a large range, what are T Junction, there is constable portion of this particular area is occupied by the stratified flow.

Now, we operate at a higher velocity, what happens? Moment we go to a higher velocity, there is a pinching action of a the water, as its evident here, and if we find that the gas cannot flow as a single core, on the contrary the liquid, it tends to pinch the air, and break it down into periodic slacks, and the slack flow pattern emerges. And this is evident from the flow pattern map if you observed, we have obtain slack flow pattern, in this particular case. On the other hand if you observed the y, we find that the deepening action of the water is not so very sufficient, and therefore, the water, because the water has to climb against gravity and then pierce the air, which is not possible, in this particular case it has just transitioned from the stratified to the falling film flow and so while it is slag, here it is falling film in this particular case.

At still higher velocities what do we find? We find in this particular case it is a slacked annular sort of a flow, there is a transition sort of a thing, because a bridging action of the water face still works, and it tends to break the long gas core periodically, or it reaches this the continuous gas core, whereas for the y junction we find, that the flow is more or less annular. Therefore, with this, it is quite evident that, entry section does have remarkable effect, particular again I should mention, that in the meso scale, and the effect in the much more pronounced for lower velocities, were initial forces are less dominant.

And in the process we are actually come across a completely different flow pattern, the stratified flow pattern, and here I would like to remind you, that when I had introduce multi face flow to you, I had very categorically mentioned that stratification occurs for horizontal and near horizontal conduits, that an expected phenomena, because gravity tends to aggregate the 2 faces, only for horizontal or near horizontal orientations, and at the effect of gravity diminishes as we go to the vertical conduit, and the flow pattern become much more axis symmetric. Very interestingly for gas liquid down flow in miniature systems, in, in mini channel specifically, we find that the, its not only the orientation which is so very interesting, but the effect of entry section was very interesting, and just by manipulating or by designing a proper entry, we could actually at a the stratified configuration which is typical of the horizontal orientation.

And this I think should be kept in mind, because this is not an very regular phenomenon, and this is something very unique that we have come across. Now, if you remember a few lectures back I have told you that, well we would concentrating on the meso scale, because in physics of meso scale is much more interesting, and it will be, it will impress the students, and to the course of the lectures you have already come to know, what are the specialties of meso scale, and what are the unique features of the operating parameters, that you could capture in this particular range well.

I end here today, and in the next class again, we continue on the effect of geometric and operating parameters, and we discussed the last topic, which I wish to cover in this particular series, it is the effect of wall wettability. Let us see what new things we have, we will be encountering in the next lecture, until then. Good-bye.