Multiphase Microfluidics
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Lecture – 01
Gas-Liquid Flow: Flow Regimes

So, in this lecture we will talk about flow regimes, what we were discussing in the previous lecture. But now we will come to the flow regimes in small diameter channels.

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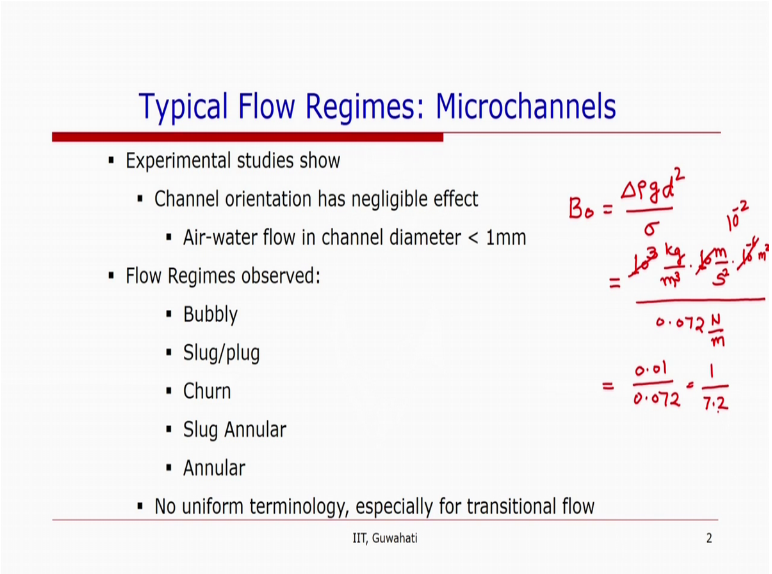

So, briefly we looked at the (Refer Time: 00:45) number or bond number criteria, that can be used to define that what defines or what is the critical bond number at which one can start looking at that ok these are the channels; where you can expect the micro size effects; starting to show up in. There were three different criteria that we discussed in the previous class.

So, the experimental studies all they have shown that in a micro channels because the gravity does not have much effect. So, for channel size less than 1 mm about less than 1 mm for air water flow. For different gas liquid systems, this number may change that about 1 mm or 2 mm, the channel orientation does not have any effect. So, if we look at the bond number so, which gives us an idea about the things, which is delta rho g d squared over sigma.

So, if we take the density of water to be 1000, and the density of air is almost negligible. So, we keep 10 to the power 3 kg per meter cube as delta rho. Let us take g for convenience 10 meter per second squared. And d if we take 1 mm so, that becomes 10 to the power minus 6-meter square, divided by sigma which is 0.072 Newton per meter. So, if we cancel this out we will get 10 raised to the power minus 2 here. So, that will be 0.01 divided by 0.072 or about 1 by 7.2.

So, the buoyancy force is about one seventh of the capillary forces of subsystems force for a channel of 1 mm. And as you reduce the size of the channel, this ratio is going to decrease further and further. So, with that in mind let us look at the flow regimes. The major flow regimes that have been observed in the micro channels are similar to what we have observed or what is observed in vertical flow in conventional channel. So, one have bubbly flow, slug flow, churn flow. annular flow and slug annular flow.

But if we look at the literature, which has been there for quite few decades, at least 2 decades there have been lot of ah publications on flow regimes in micro channels and few revues in the last decade. So, it seems that there is a lot of confusion in the nomenclature of the flow regimes. Specially the transition flow regime, everybody will agree that there is a bubbly flow regime, there is a slug flow regime, and there is a annular flow regime. But what happens in between these the transition flow regimes might be given different names. So, we will look at some of the representative literature and see.

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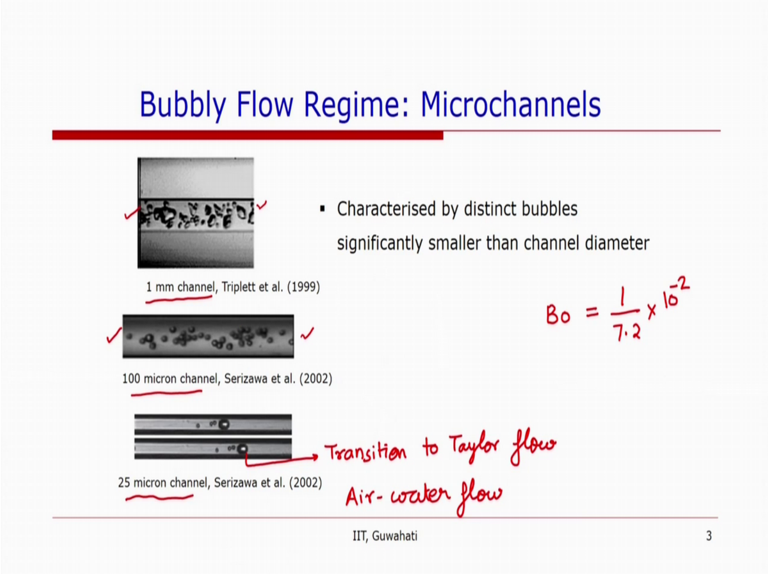

So, let us define the flow regimes one by one. So, the bubbly flow regime, I have put 3 pictures from 3 different publications or 2 are from the same publication actually. So, this is the bubbly flow in 1 mm channel, in 100-micron channel and 25-micron channel all for air water flow.

So, bubbly flow is characterized by distinct bubbles. So, one can see there are bubbles, and they are significantly smaller from the channel diameter at least in the first 2 images. In the second image where we see the bubbles are of small size, and then these bubbles are almost a spherical. Because at this 100 micron, the bond number will be 1 by 7.2 into 10 to the power minus 2.

So, the gravity will not be important in surface tension will be dominating, and you see on these moments to be spherical. Environment channel one see that there bubbles, but these bubbles might be not necessarily of a spherical shape. Some of them which are small they might be also spherical shape, but is for clear from the image. But larger bubble clearly are not of spherical shape that might be because of the higher velocity.

The third one, where we have a larger bubble which is almost of the size of the channel and the smaller bubbles. So, this we can treat as the boundary between the Taylor flow regime and bubbly flow regime. So, the bubbly flow regime can be the flow regime, where the bubble size grows that it is spherical, but starts occupying almost the entire channel so, this is where we can say the transition might happen. But the general picture of bubbly flow is something like this or this where the bubbles are smaller. and they are sufficiently smaller than the channel size. The shape might be spherical or non-spherical depending on the flow conditions ok.

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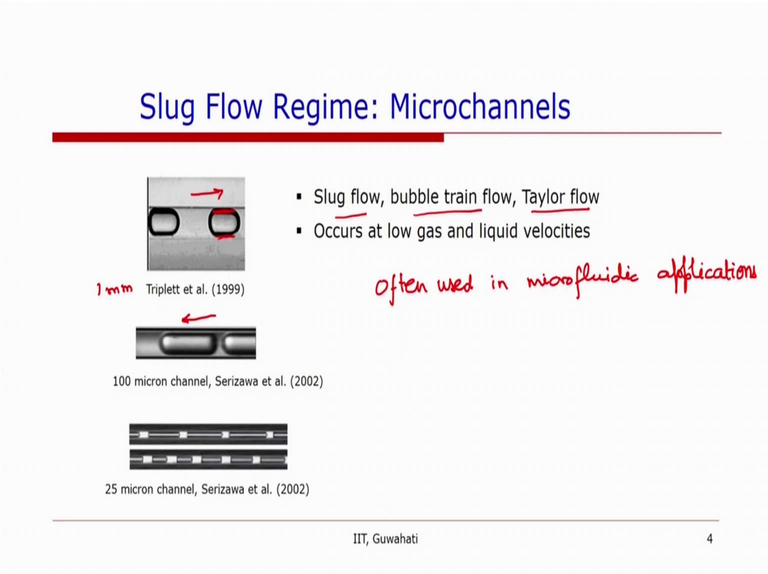

So, the next flow regime is slug flow regime that occurs at low gas and liquid velocities. The bubbly flow regime might occur, at higher liquid velocity and low gas velocities. So, the slug flow regime as you might see here they are characterized by the flow of bubbles of the size of the channel.

And these bubbles are separated by a thin film surrounding the channel wall, again this is in 1 mm channel from Triplett et al and this is from 100-micron channel and 25 micron. and the flow direction in this case is in this direction in here you have the flow in this probably happening in this direction and in this case again that is what very clear from here.

So, anyway so, this is 25-micron channel, and this is 100 micron channels the bubbles they are also known as Taylor bubble, bubble train flow, slug flow and this is a often used flow regime in microfluidic applications. , So, we will look at it in detail later.

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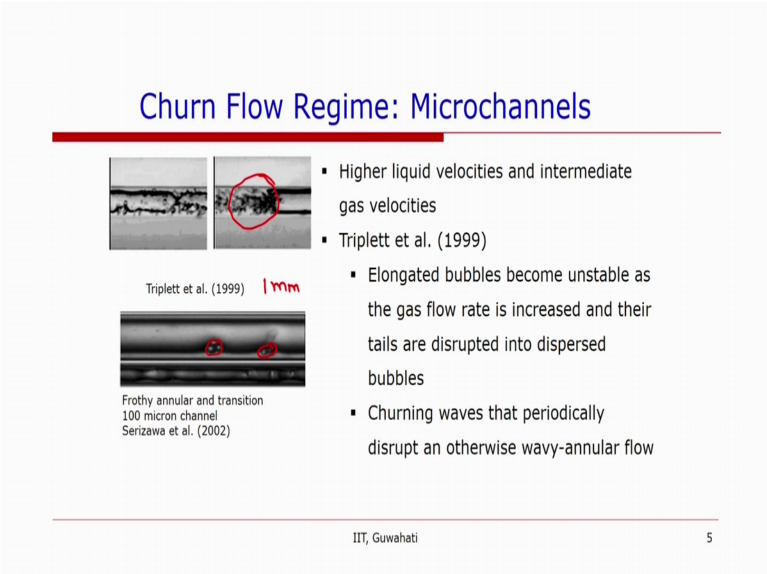

The next flow regime is what we call churn flow regime, and churn flow regime is a transition regime. It occurs at relatively higher liquid velocities, and intermediate gas velocity. So, these 2 pictures which are from Triplett et al in a 1 mm channel. They have defined the churn flow for two different processes. The first one you have elongated bubble so, something like this. And these bubbles start becoming unstable, because when the gas flow rate is increased and the tails of the bubbles are disrupted by the bubbles dispersed into ok it.

So, in one case we have the bubbles long Taylor bubbles, and then the gas flow becomes higher and the Taylor disrupted. The other cases we have churning waves that periodically disrupted otherwise wavy-annular flows. So, you have waves or annular flow where we have waves, and on this there are some more bubbles or droplets. So, the churning waves so, this is called churning wave.

Now, I have also kept in this category, what is called frothy annular and transition flow regime. So, this is a transition flow regime where we have wavy annular flow, and in between there are some bubbles there. Similarly, in frothy annular there is annular flow, but there are some bubbles in between what we see, and these 2 images are from Serizawa et al in a 100-micron channel. And no such thing was observed in 25-micron channel.

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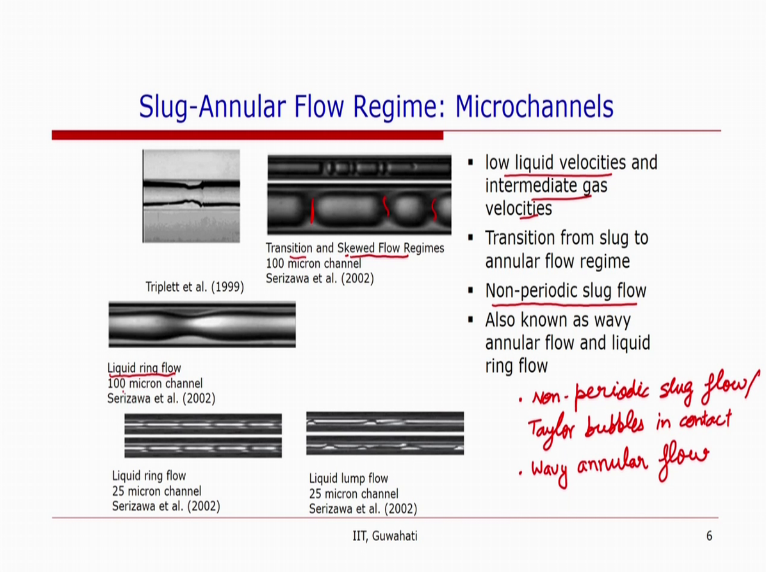

Further on slug annular flow so, I will also keep slug annular flow in the category of transition flow regimes between slug flow or Taylor flow and the annular flow regime. So, it can be characterized by 2 processes; it occurs at low liquid velocities, and intermediate gas velocities.

And one can have the slug flow is; because it is periodic slug flow is periodic, and when it starts becoming non-periodic. For example, you have lot of bubbles coming together there is almost no slug between them and this is; sometimes called as slug annular flow people have given a different name for example, Serizawa et al has called these flow regimes as transition flow regime or a skewed flow regime.

So, I would suggest the slug flow regime, a periodic or non-periodic, slug flow Taylor bubbles in contact. And the other one is just after that which is maybe annular flow. So, flow one have the interface between 2 bubbles and broken and there is a continuous code. But there are waves on it for example, this picture, and this is termed as liquid ring flow by Serizawa et al.

So, they have this liquid ring slow observed in a 100-micron channel as well as in a 25 mm, 25-micron size channel. They also have a liquid lump flow; which does not seem to be accessed metric and there are lump of liquid in between. So, I have also kept this in the slug annular flow regime , but it might also well be put in the category or churn flow regime.

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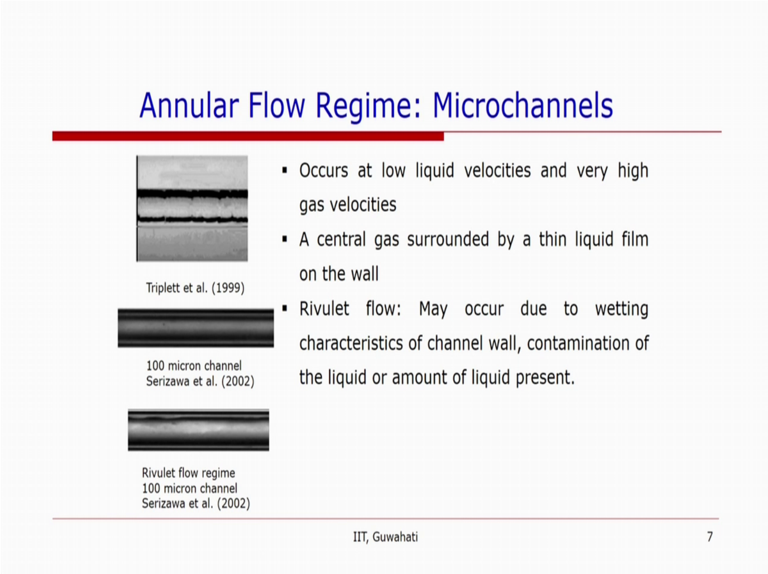

Then finally, we have annular flow regimes of and the gas velocity is increased further. When get the bubbles have merged the waves have subsided, and there is a continuous gas code, and there is a thin liquid film on the wall. So, this occurs at low liquid velocity and very high gas velocities.

So, one have a central gas codein when the liquid flow rate is relatively small and the gas velocity is high, and the channel is hydrophobic, then one can also have a rivulet flow. So, I have kept this in this category, and this these are the few images from Serizawa et al Triplett et al, and this is for rivulet flow regime any 100-micron channel by Serizawa et al.

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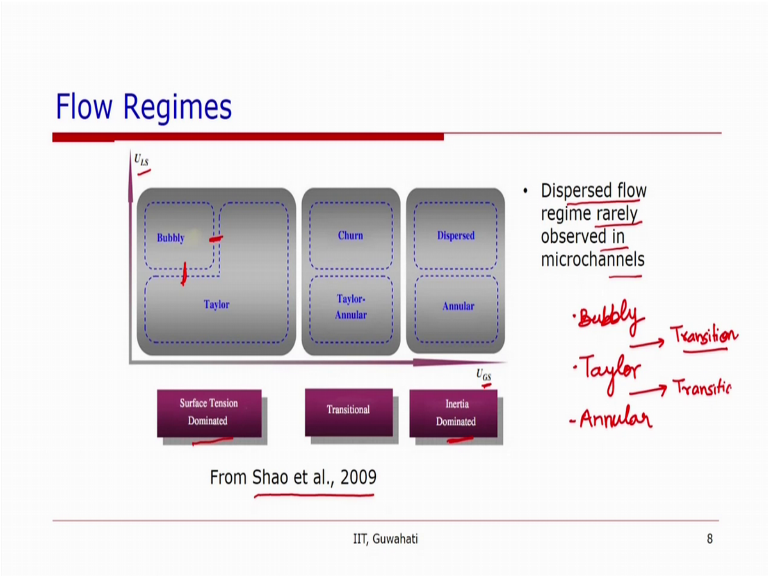

So, this picture gives an idea about the um flow regime distribution based on the liquid, and gas superficial velocities. And where what kind of force which are dominated so, Shao et al (Refer Time: 14:47) they have identified or specified 3 regimes. One at low gas velocities, where the surface tension is dominated and one get bubbles. And the other one where the inertia is dominated, and one gets annular flow regime. The dispersed flow regime even though they have put put the suggest at the dispersed flow regime has rarely been observed in micro channelsand in between these flow regimes, there are churn and Taylor annular flow regime.

So, basically what we can say that broadly speaking there are 3 well agreed flow regime that are observed in micro channels bubbly, Taylor and annular. And there are transition regime between bubbly and Taylor flow regime, so that transition will come by as we can see here by it can be because of increase in gas velocity, or it can be because of increase in the liquid velocity. And there is a transition between Taylor and annular flow regime, which is basically with increase in gas velocities.

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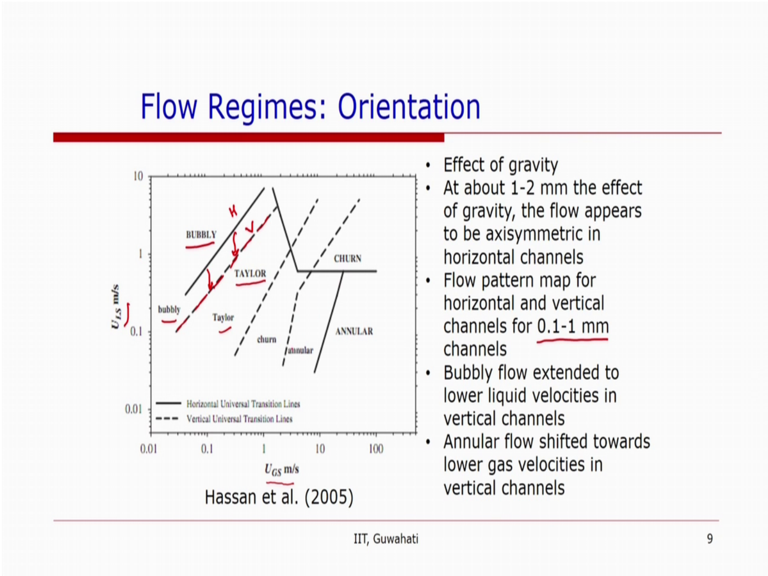

So now let us look at some effect of some of the parameters, and what are the studies that have been done in the literature, and what are the general conclusions that we can make about the effect of some of the flow conditions, or the geometric conditions on the flow regime.

So, the first one is up there orientation. So, basically orientation will affect the flow regime map if there is an effect of gravity. So, we said at the start of when we started discussing the flow regimes in micro channel. That day does not seem to be any effect of gravity.

And this study by Hassan et al, where they have plotted flow regime map, for channels size ranging from 0.1 to 1 mm and they have plotted the boundaries for horizontal which are given by capital, and boundaries for the vertical channel which are from the small letter.

Now, bubbly flow, if you see, the bubbly flow is extended to lower liquid velocities. You can see the liquid velocities this is for the horizontal channel and this is for the vertical channel. So, what we can see that the bubbly flow occurs at lower liquid velocities in vertical channel. similarly the annular flow it is shifted towards lower gas velocity in vertical channels.

So, for this transition, what they have suggested that it might be because when the bubble breakup happens, then in the vertical channel the bubble breakup process is also assisted by the gravity force along with inertia. So, in vertical flow the bubble breakup might happen earlier so, that is why, this is at lower liquid velocity.

Similarly, in the annular flow the annular flow regime the gas code it is assisted by the inertia because of the buoyancy force or the velocity; that is because of buoyancy, that will assist or that will increase the gas code velocity. So, the annular flow transition may come in early.

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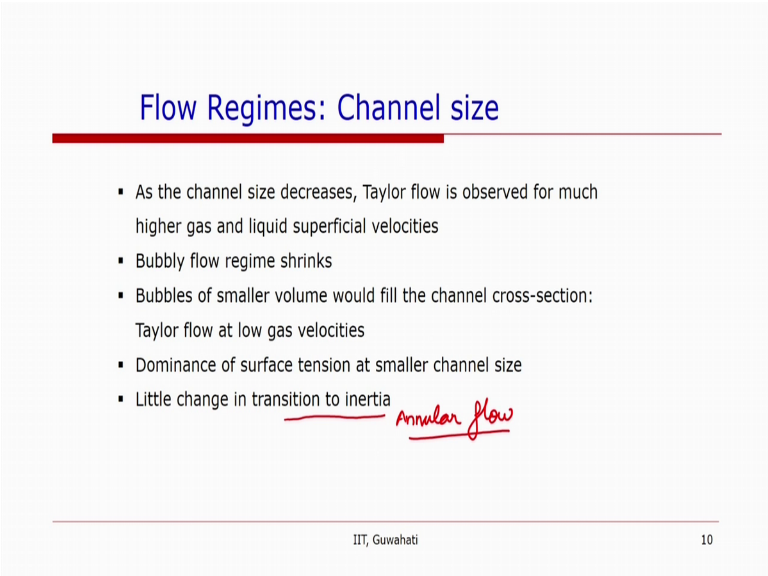

Now, another effect the effect of channel size. So, edge we have seen that the bond number it is value decreases as the channel size decrease. And there will be a significant difference between the bond number at 1 mm and bond number at 10 mm to be precise it will be about 10 to the power minus 4. So, the 4 order of magnitude difference at 2 different , 10-micron size, and 1 mm or 1000-micron size, there will be very large difference in the bond number.

So, as the channel size decreased Taylor flow is observed for much higher gas and liquid superficial velocities of the area of pi it by the Taylor flow is large. This one of the explanation for this might be that the bubbly flow regime shrinks. Because even if a smaller size bubble comes in the channel, it occupies the channel cross sectional area and then because the channel cross sectional area is small. So, it has to expand and become a Taylor bubble.

So, the transition to Taylor bubble comes in early as the channel 5 decreases. the bubbles of the smaller volume will , and at the smaller size the surface tension will be high; however, there is no change in transition to inertia also, there is no transition no change in transition to annular flow, Taylor flow what annular Taylor flow or slug annular flow, what annular flow there is not much change in the transition in that; now channel cross section.

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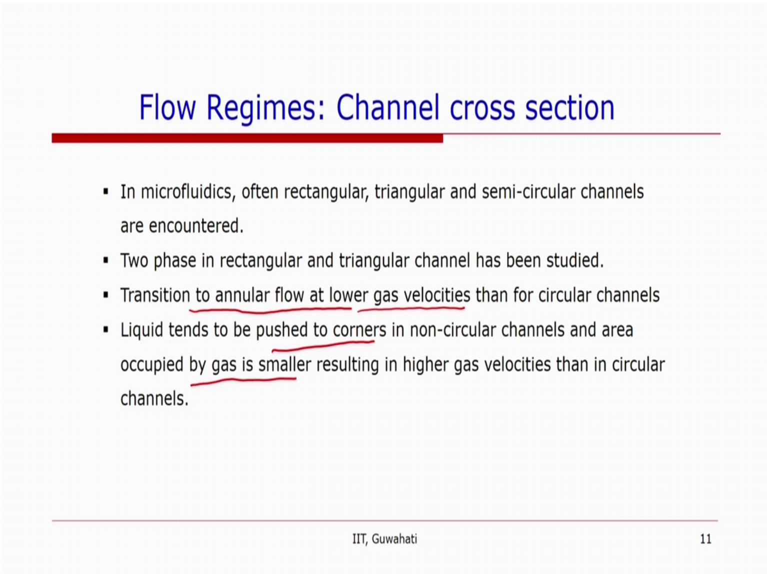

So, microfluidics, if you look at the number of applications that microfluidics has been used. The channel is not necessarily a circular channel or a cylindrical channel as a generally the case in the conventional channels. The channel is often a rectangular or semicircular or sometimes even triangular channel or a square size channel. So, in all these non-circular channels, they have sharp corners. And the liquid near the corners that stays there and the liquid goes there and stays there it remains a stinger.

So, the liquid tends to be pushed to corners, in these non-circular channels, and the area occupied by the gas. So now, the gas has less area available in the channel to occupy. So, the gas velocity because the gas; the area for which is available for the gas for example, in annular flow, the gas velocity becomes higher. So, this results in higher gas velocity in non-circular channels.

So, this results in that the transition to annular flow it occurs at lower gas velocity. There is not much change in the slug or slug annular or in the case of bubbly to slug transition. But what has been observed that the annular flow occurs early probably because the velocities for the same flow rate and the same channel size are larger the actual gas velocities are larger in the noncircular channels.

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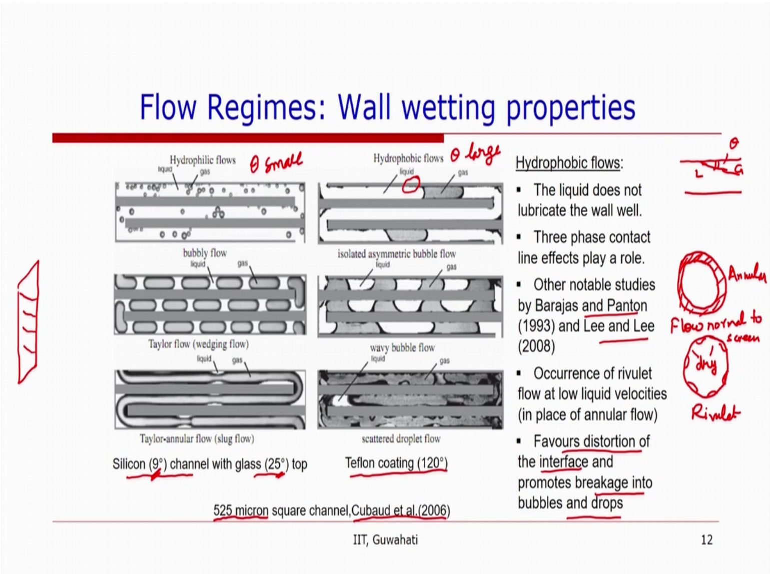

Now another point that is very important in micro channels that the properties of the channel walls. The channel walls it might be hydrophilic hydrophobic. So, hydrophilic means it likes the water and hydrophobic means it does not like the water. So, that means, there is in the hydrophilicity and hydrophobicity that comes into picture only when there is a 3-phase contact line. So, on one side you have liquid another side you have gas so, because and that that will depend on the contact angle.

So, generally when it is hydrophilic, then contact angle theta is small and for hydrophobic channels theta is large. Few studies have been done on the wall waiting or hydrophilicity and hydrophobicity or wall contact angle properties on the flow regimes. Notable among them is by Barajas and Panton, Lee and Lee at the one by cuboid.

So, in the hydrophobic channel as we can see that the liquid does not always lubricate the wall well. So, there is a 3-phase contact line here whereas, in hydrophilic channel we see there is bubbly flow, and the bubbles which are there they are smooth bubbles, and then one has the liquid Taylor annular flow and slug flow what they have observed. And this is done in a rectangular channel, which is 525-micron size. The channel is silicon channel with a glass top the silicon have a contact angle of 9 degree and the glass top have and then you know of contact angle of 25 degree.

The other one the other study for hydrophobic channels has been done in the same kind of same channel, but with the Teflon coating which has a contact angle of 120 degree and one can see the difference in the flow regimes that one get in the channels. So, one thing is, that once is when the channel is hydrophobic then one see a lot of 3 phase contact lines forming.

So, for example, one gets rivulet flow; rivulet flow means, that on the channel wall if we are looking at the cross section. Annular flow will have a continuous liquid film is represented by a has Daria here; this is annular flow normal to screen in this case rivulet flow, one can see that there are reverse small rivulets. But there is some dry area as well; so, this is a rivulet flow.

A very common example of rivulet flow, if you are sitting on a bus and it is raining and the bus is moving with a very high speed. You might see some of the liquid on the window screen, you might see that the liquid is going in the moving in this direction, right? So, it is not a continuous film, but they are small river kind of thing which are observed. So, that that is similar to rivulet flow.

So, in general the hydrophobic or large contact angles they favors the distortion of the gas liquid interface because the interface the liquid does not like to be near the wall and the interface so that there are all the chances of formation of a 3-phased contact line, you have gas liquid and solid touching each other. And this also promotes breakage of liquids and gas into bubbles and droplets.

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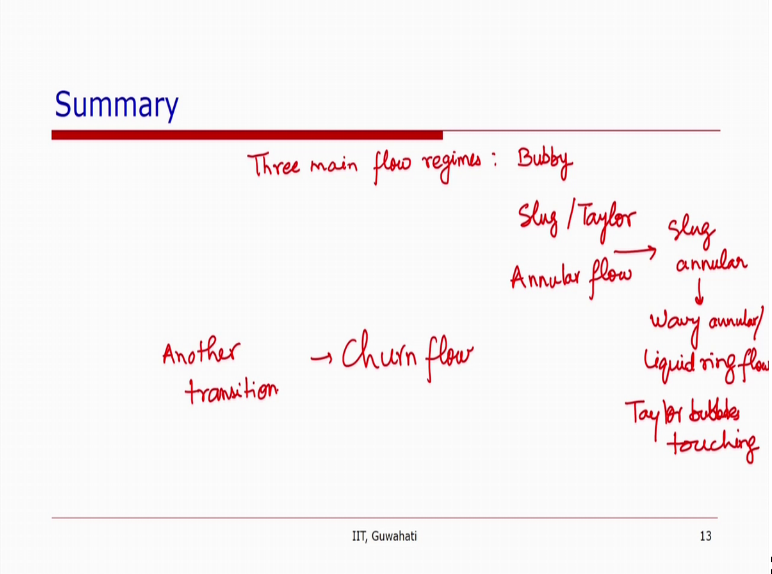

So, in summary what we have looked at is the flow regimes in micro channels, and we have 3 main flow regimes; what we call bubbly, slug or Taylor and annular flow regime. We also have a transition flow regime between slug and annular flow which we call slug annular, it can have wavy annular or it is also known as liquid ring flow. Taylor bubbles touching. Apart from that we also have churn flow; which is basically when you have higher liquid velocity in the regime where you have intermediate gas velocities, and higher liquid velocities, then one can have churn flow regimes. and this is again another transition flow regime.

And we have also looked at the effect of some of the parameters; such as the channel cross section, channel, hydrophobicity and hydrophilicity, the orientation of the channel. So, we will stop here and in the next class this is bubbly and in the next lecture, we will look at another flow regime map which has been come from the microgravity flow regime map, and how it can be adopted or how it has been adopted for the micro channels. And then we will look at the different flow regimes ok.

Thank you.