Adiabatic Two-Phase Flow and Flow Boiling in Microchannel
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Lecture No - 04
Two Phase Flow through Micro Channels (Contd.)

Well, welcome again to the 4th Lecture of this particular section on Two-Phase Flow and Flow Boiling in microchannels. We continue with the discussions on the different flow patterns. Now what did we observe? We observed that in this particular case your body forces are negligible compared to self extension forces. For that case what happens is the first thing is stratification is suppressed. As we have already discussed. The next thing is there are less effect of channel orientation, and the influence of channel orientation it decreases with pipe diameter.

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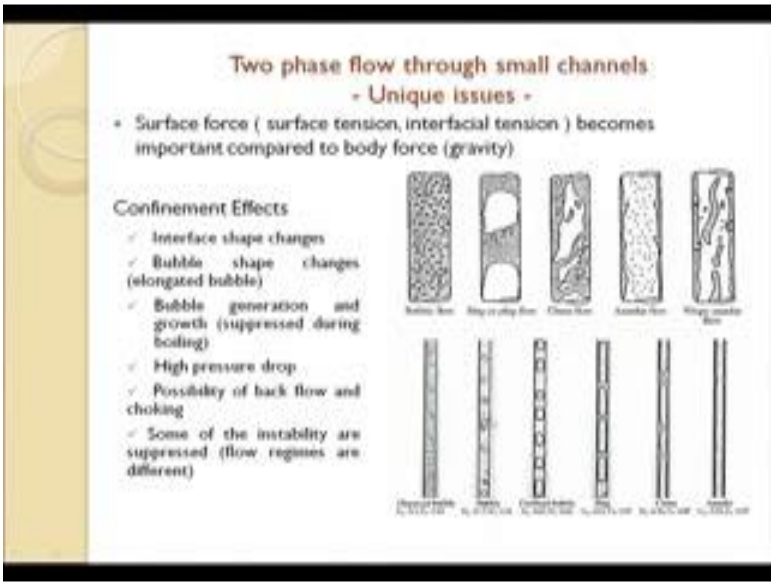

This was evident when we compared the flow patterns in the vertical microchannels with the flow pattern in the horizontal milli channels.

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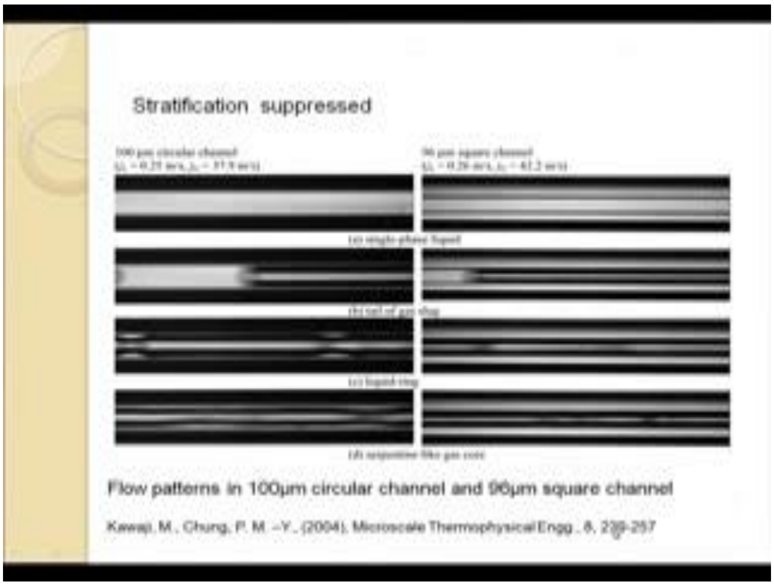

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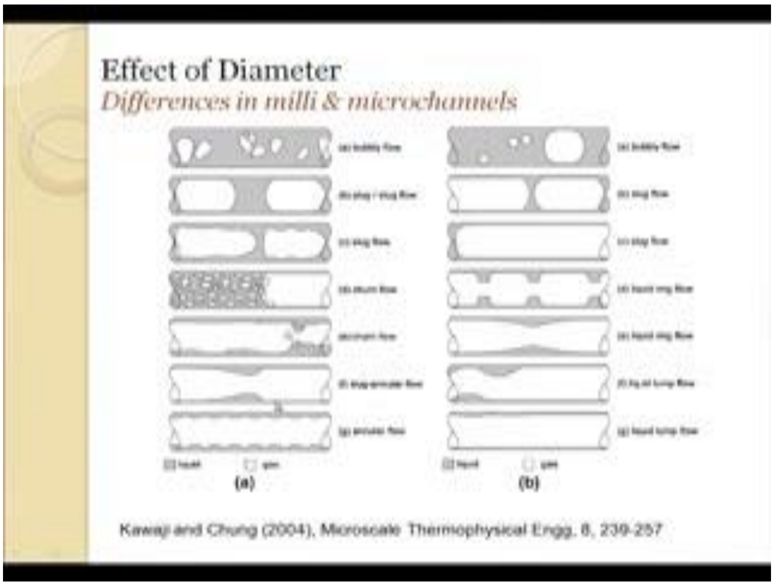

We found the more or less same flow patterns are there. We have dispersed bubble for a very small range; we have annular again for a very small range. The primary reason for this is; firstly, as I have already told you that.

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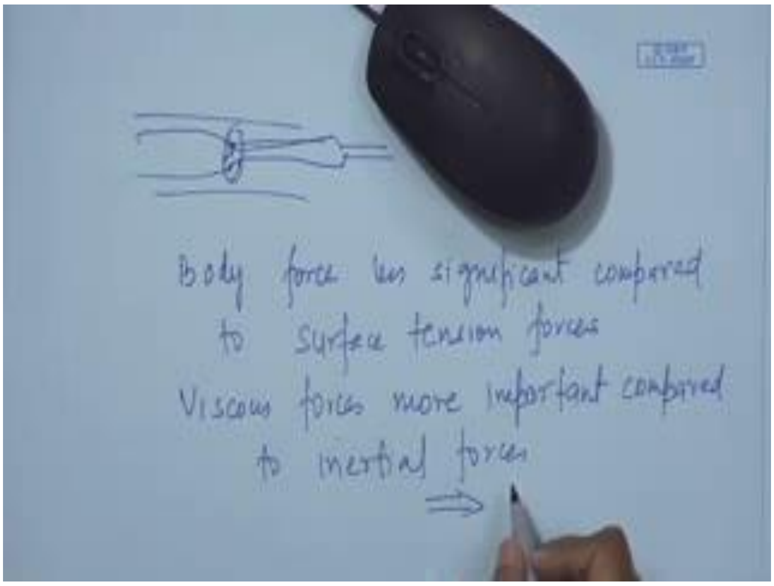

Body force less significant compared to surface tension forces. Due to this what happens? The effect of inclination is less as symmetric distribution is less. The other thing is, we find that viscous forces more important compared to inertial forces. What does this imply you tell me, when I say viscous forces is more important compared to inertial forces. It automatically implies that we are dealing with low Renaults number flow region. Therefore, in this case we encounter Renault's numbers which are in lamina flow region.

Naturally in this particular case, what we come across since they are primarily in the lamina flow region, the sheer affect is very less as a result of which this bubbles once formed they have very less tendency to qualis or break down etcetera. Therefore, bubbly flow and annular flow they are much more suppressed, because all sorts of interfacial waviness, the sheering, the churning, these things are not there. Number 1 bubbly flow which is very common here is not there. Churned flow the way it is found in macro channels with large erratic churns of gases oscillating in a random fashion it is not periodic; mind it, they are just oscillating in the random fashion up and down if you recollect the video of churn flow which I have shown in the last class. That type of churn flow is not present for your micro systems.

On the contrary we find that the Taylor bubbles start getting larger and larger they almost appear to be staged one above the other and depending on conditions. Say for example, the gas velocity, the liquid velocity, the tube dimension, in fact the tube your geometry or of the wall conditions depending on everything the transition from slab to annular can occur by several ways. One can be at very low liquid velocity, the Taylor bubbles the just act 1 above the another, and gradually they qualis with one another and they form a continuous gas core.

Now, in this particular while they are getting staged they are very thin liquid slugs which are intercepting the continuity of the gas core. And this step of flow pattern we find people call them as bubble train flow. Now whenever you are going through the literature on microchannels the first problem you will face is that for the same distribution people have used different, different names. Now the first thing you have to understand is that basically all the names they suggest the same distribution. Just because the people were not very much conversant with the different types of distribution, so with small differences may be a name was assigned to describe its character.

For example, we have confined bubble flow and this is particularly more important with respect to boiling. I will not be describing it or I will not be discussing it in details in this particular class. But there is something known as the confined bubble flow where the bubble after being formed at the nucleation side, they start growing and the moment they start growing they encounter the other wall. So, they cannot grow or cannot detach from this particular wall and rise just in a macro channel system, so they get almost stuck up between the 2 walls and they elongate in the flow direction and then they start flowing. This or they pushed up by the incoming liquid, this is known as Confined Bubble Flow.

Then we have something known as the isolated bubble flow, where we have isolated bubbles the way it is shown. Remember one thing as I have told you the tendency of qualisons and break up is very less here. Once formed they more or less retain their identity. This is known as the Confined Bubble Flow or the Isolated Bubble Flow. Then when the bubble starts becoming larger they again start qualising with one another and we have a qualising bubble regime, but all these are different versions of the slab flow pattern.

The other thing is which I missed on the way that while the slug is getting transition to the annular flow pattern this occurs one by the short liquid necking as I have said. Sometimes what happens, we find that the Taylor bubbles become quite large and the liquid velocity is also possibly appreciable. Therefore, there is gas shredding from the tail of the Taylor bubbles just like the formation of aerated liquid slugs in macro channels and due to this particular gas shredding they form an erratic sort of a composition and there is a lot of waviness in the interface. Therefore, this is also termed as the joint flowing.

What we would prefer is this entire paradigm of flow distribution which mark the transition from the slug to the annular flow pattern can be clubbed as the slug annular transition. For our purpose, we have the intermittent flow pattern or the slug flow pattern, we have the slug annular transition; we have the annular flow pattern. Even in annular flow pattern we find that the serpentine like core flow has been reported by a large number of researchers and that as we have seen as the primary reason for this is the increase in viscous forces. The more increasing in importance of viscous forces suppresses the formation of bubbly and the churn flow pattern

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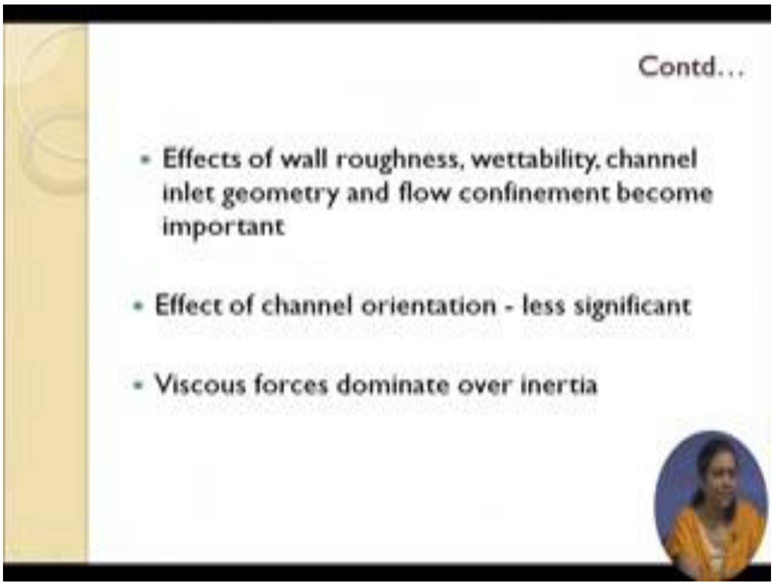

Well, along with if we find the flow [FL] there is one more thing that while stratification gets suppressed and surface forces start becoming important. Naturally, the conditions of the wall become very important in this case. And we find that the effects of the roughness of the wall, the wettability of the wall whether the wall is hydrophobic or hydrophilic. The inlet geometry such things become very important under these cases. They were not so very important in macro channels. Naturally these things require an additional discussion and we will be having this discussion in the course of the lecture 6.

Then as I have already told you viscous forces dominate over inertia, in other words we are operating at a low Renault's numbers range.

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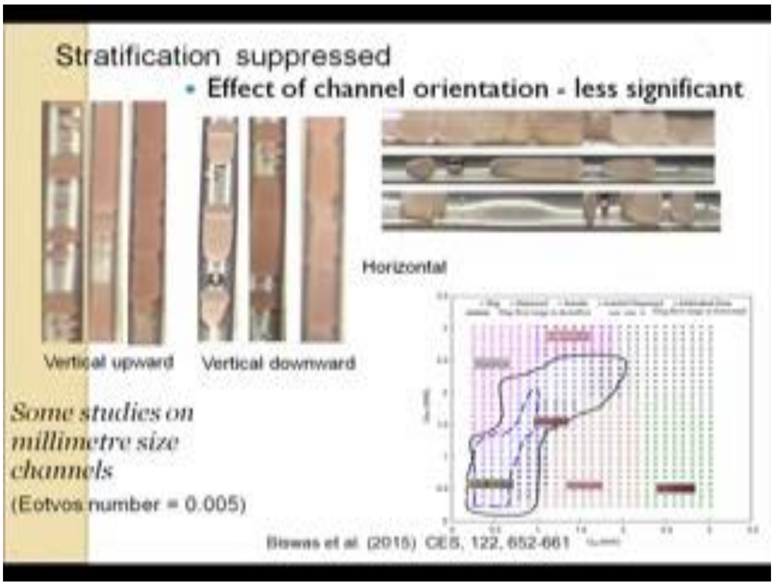

And the most important thing that affect of channel orientation is less significant. Now, these we have already seen for air water flows in mini channels, microchannels it is even less. Here there is one particular slide from experiment stand in the multi phase flow laboratory of the chemical engineering department. Here also we find that for vertical upward, vertical downward, horizontal flow. We find that more or less they are marked by slugs the slugs become larger and then we have annular in all the three cases.

This shows the insignificant affect of orientation even in millimeter sized conduces both for gas liquid as well as liquid systems. On the contrary I would like to show you the remarkable affect of orientation. This I had mentioned, but did not exhibit this yesterday. I would just like to show you the effect of orientation in macro systems.

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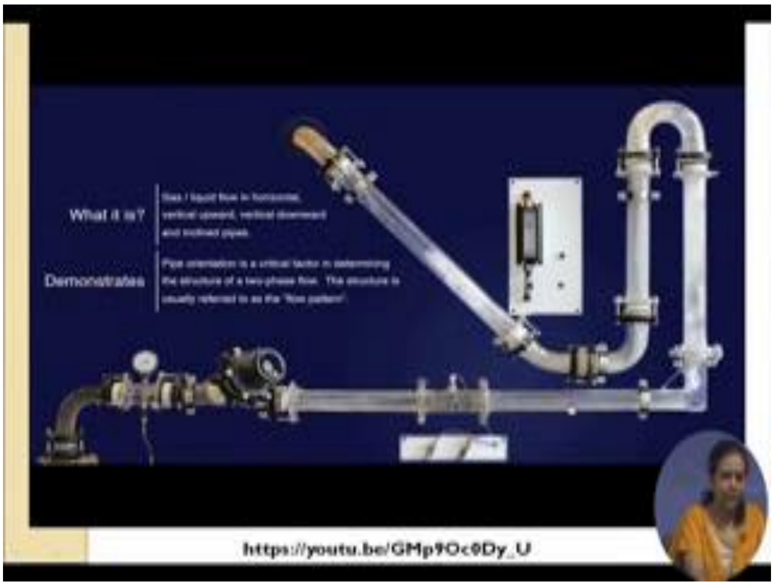

In this particular case see this is the very good video which I have got from YouTube just to show the effect of orientation. You find two-phase flow, air water flow occurring in a horizontal tube in a vertical up flow, vertical down flow, and then in an inclined tube.

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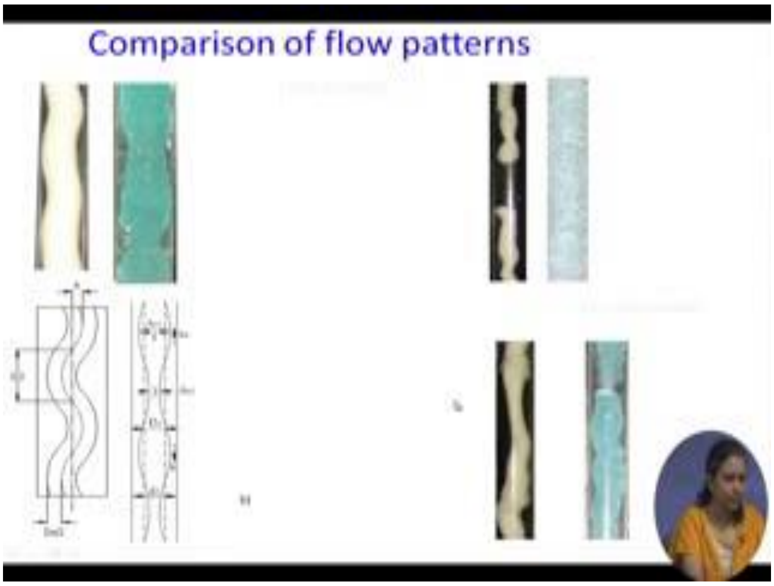

You can very well understand stratification here the formation of slugs. In this particular case remember one thing this will be referring later on this type of bends and keys they induce slug flow. We find that the flow gets decelerated during up flow by gravity, they get accelerated by gravity in down flow, and this is quite evident if you observe the distributions. And there are some sort of secondary flows in this particular tube.

Therefore, here you find the distinct effect of orientation on flow patterns in macro system. (Refer Time: 11:09) I show you the flow patterns or the effects of the orientation in the case of microchannels. Therefore, this is one particular thing which should be keeping in mind when we go.

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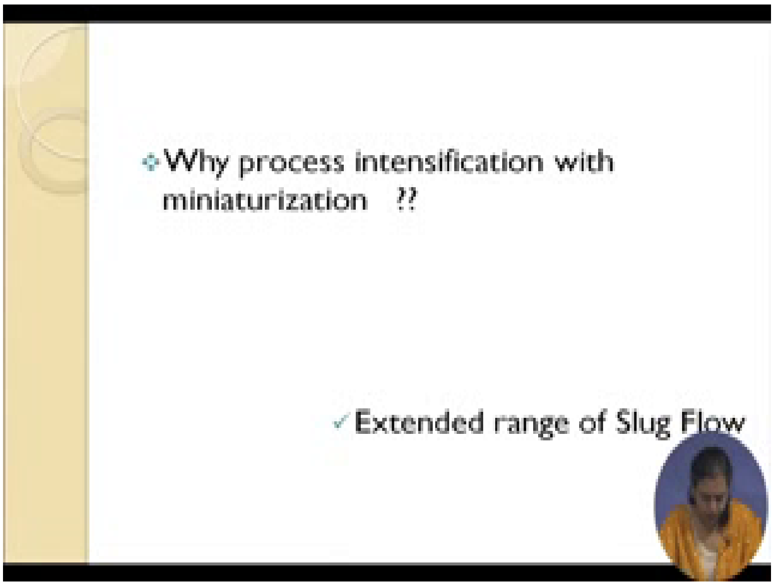

In general we find where the body forces becoming more significant. [FL] one more thing that suppression of annular flow this I forgot to mention that whenever there is some amount of waviness in the liquid film the waviness is sufficient to breach the Taylor bubbles. This is also another cause why we have enhanced range of slug flow in this particular case.

Now we find that no matter how much we discuss and whatever we say the net effect on the flow patterns be it liquid liquid, be it gas liquid in miniaturized systems is an extended range of slug flow. And this is a very, very fortunate situation I should say. The slug flow range it occurs over a wide range of any particular condition where we had bubbly flow in macro systems, we had slug flow because the bubbles get larger and they are they are of comparable dimension where the pipe conduce. Where we had churned flow we have long log plugs in this particular case, where we had annular flow also in this particular case we find that since the waviness is quite sufficient so therefore the 2 waves they get ridged and they form plug flow.

And here I would like to tell you that this is the primary reason why we have process intensification in miniaturized systems; it is primarily because of the extended range of slug flow. Why is it so special?

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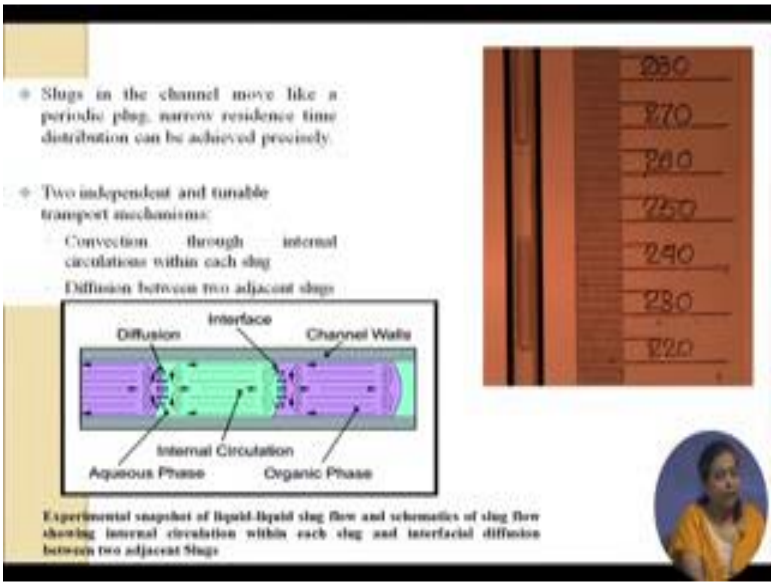

Let us now see how slug flow occurs? We had already spent quite some time doing the introductory section also for this particular case. What we find? We find that elongated liquid plugs or gas plugs were flowing and they are separated by a channel wall by a liquid film. And also between 2 plugs there is a plug of another liquid or if it is a gas plug there is a liquid slug in between. Now in this particular case if you find the entire plug surface is available for mass transfer.

While if you observe the annular flow you just find that the only the interface between the gas and the liquid or between 2 liquids is available for mass transfer. This case even the edges are also available. Moreover you find since there is a continuous concentration gradient here. So therefore, some sort of conviction currents is set in between the fluid at the periphery and through the center.

Therefore, regular convectional control currents are set in. And due to this particular internal circulation within the slug we find always fresh surfaces are being exposed for mass transfer to the other liquid. Same thing happens here also; here also we find some sort of re circulation takes place in the slugs of both the phases. As a result of which we find that here also there is continuous replenishment of fresh surfaces and this explain the enhanced transport property under the slug flow pattern. And this explains the reason for process intensification in miniaturized systems.

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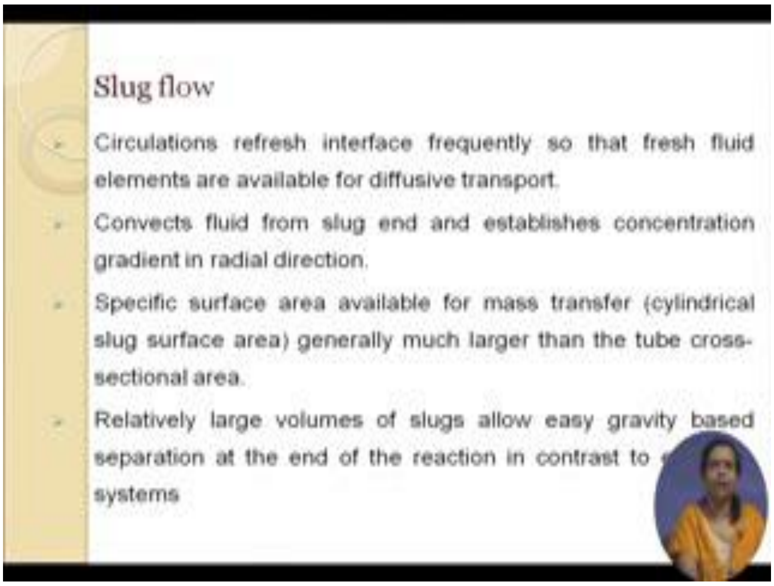

You can always argue that inter facial area is more for the bubbly patterns; therefore they should be enhanced transport in the bubbly flow pattern. It is very true the inter facial area is more, but if you observe you find that mass transfer or heat transfer it is depend upon the coefficient.

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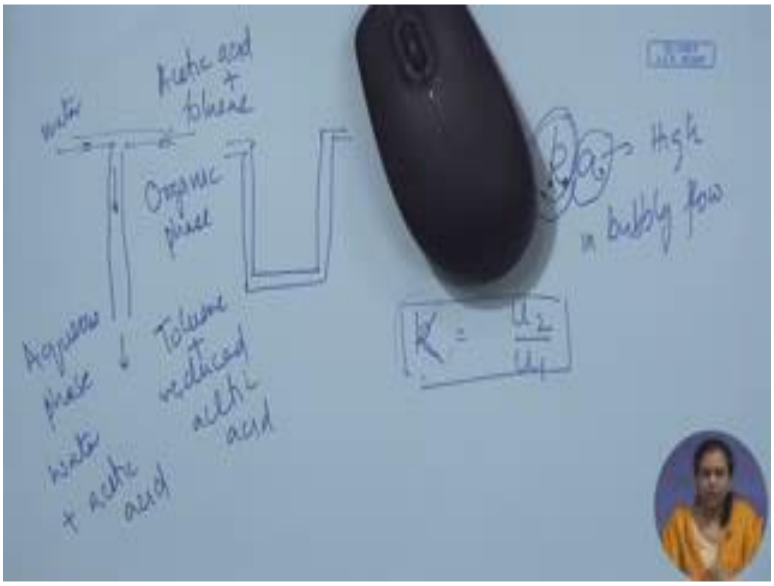

Say for mass transfer the overall metric mass transfer coefficient which is nothing, but k into a, that is important. Now definitely a is high in bubbly flow, I agree with you. But because of the small relative velocity between the 2 fluids there is a very less slip effect. As a result of which the slip effect it induces some amount of churning mixing. I will not use the word turbulence, because usually we operate such low Renaults number that what turbulence will not very correct here but it induces so much of mixing and agitation that that, that is absent for bubbly flow pattern. Do you understand? Since the slip; what is the slip? It is the ratio of 2 velocities. I do not remember whether I had explained in the last class or not. The slip ratio is given as both are K.

Make it capital K it is given as the ratio of the incentive velocities of the two-phases. Now higher the slip is more is the churning and more will be your mass transfer coefficient. Now in bubbly flow what we have, we have a higher a, but a lower k. And in annular flow the a is also less the k is also less, but in this particular case due to the churning I was showing you the k is also high and the a is also high because of the presence of edges as well as the surfaces.

With everything we have fined that it gives us an enhanced k the overall volumetric mass transfer coefficient and this brings about process intensification. And again there is another advantage of slug flow not related directly to process intensification is in this particular case if you observe it is sort of a separated flow pattern also, the gas slugs, the liquid slugs, etcetera, and etcetera. Therefore it is very easy to separate the two-phases also after they have flowed through this pipe through any particular system. And this is particularly very important for your micro systems because it is very difficult to separate micro emulsions, micro dispersions so on and so forth.

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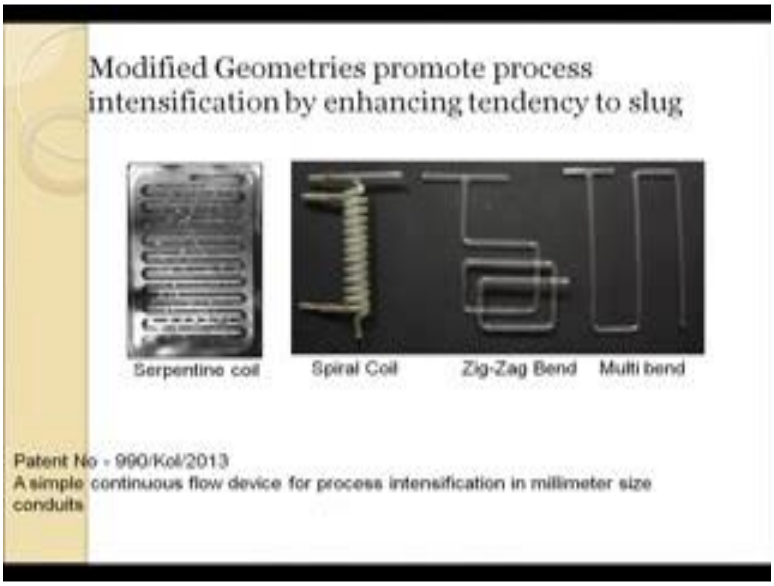

Now, before I proceed further I would be quite interested to show you. See I have explained you that because of the extended range of the slug flow we get process intensification. But I would just like to show you one particular example where in the multi phase flow laboratory of the chemical engineering department of IIT, Kharagpur we have actually performed or rather we have actually obtained enhanced slag flow and we have obtained mass transfer in the slug flow pattern. Now how did we do it? We were working with mille channels, and we found out that in mille channels also suppose we have large number of bends then slug flow range gets enhanced.

What we did? We took three different mille channel geometry. 1 was a straight tube with the t entry where we were working with water and towline. Therefore, water was coming through one particular arm of the t towline to the other arm and they were flowing downwards. The other things which we did were that we took we induced one particular bend and the same geometry, the same length we just made it to encounter simply one particular bend. And then what we did we multiplied the number of bends.

Therefore, three conduce that we are working; 1 was this particular downward geometry, one was one single bend, the other was we used a multi bend. Now in these three situations what we found was that we were working with 2 millimeter diameter tube. Definitely we were having slug flow for quite a range in this particular down flow geometry. The slug flow range is increased here and it was more in this particular case.

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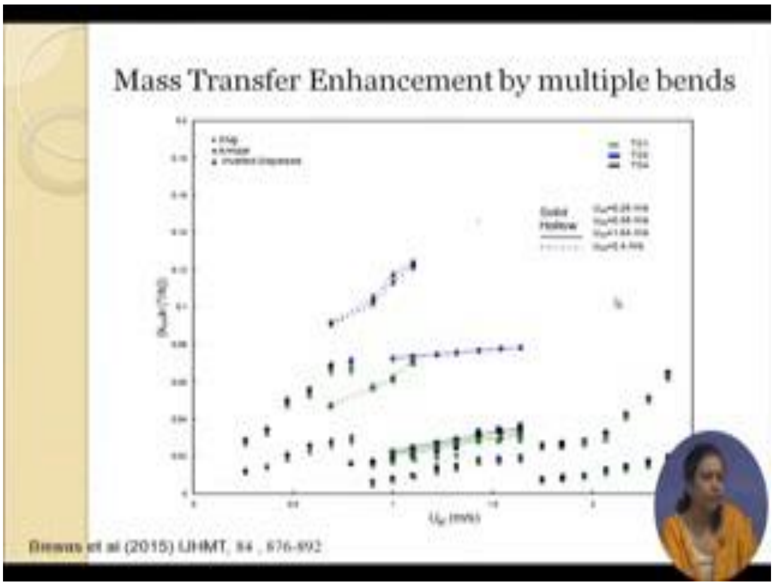

We were trying to measure the overall mass transfer coefficient when water and towline was flowing and acetic acid was defusing from the towline phase to the water phase.

Actually acetic acid plus tolling was entering as the organic phase and the water was entering. And during the course of this flow acetic acid was defusing the organic phase to the aqueous phase. At the outlet we had got towline either free of acetic acid or with reduced acetic acid, and we had brought an aqueous phase comprising of water and acetic acid. And we measured that during the flow just to find out the amount of acetic acid which has defused we measured the amount of mass transfer which is occurred and we tried to find out the mass transfer coefficient.

Now, here we have tried to plot it for several constant water velocities while kolin velocity was increasing. For that we find that, we can observe that these data are for the slug flow patterns. Slug flow mass transfer coefficients are much higher as compared to the annular flow pattern, this was number 1. And then also within the slug flow we found if I do not know for that you can understand this t s is the multipent device. Always in the multipent device the mass transfer co efficient was higher, even when we had slug flow in all the three geometries. Then we encountered a situation when there was slug flow in the single bend and multi bend geometry and there was in the straight pipe.

You can just imagine the extent of enhancement of 2 to 2.5 times enhancement of mass transfer co efficiently observed when the flow pattern in the bend devices were slug fine in the straight tube it was annular. So, from here immediately we can know that how much enhancement the slug flow pattern can provide over the other flow patterns; namely the annular and the dispersed flow patterns.

This was 1 way to show that slug flow enhances mass transfer or heat transfer. And then the other thing is when we are working with micro and mille channels there is a range of slug flow takes enhanced. In that way it is quite evident that this is the reason why miniaturization is the password now and why we effect process intensification using miniaturized channels.

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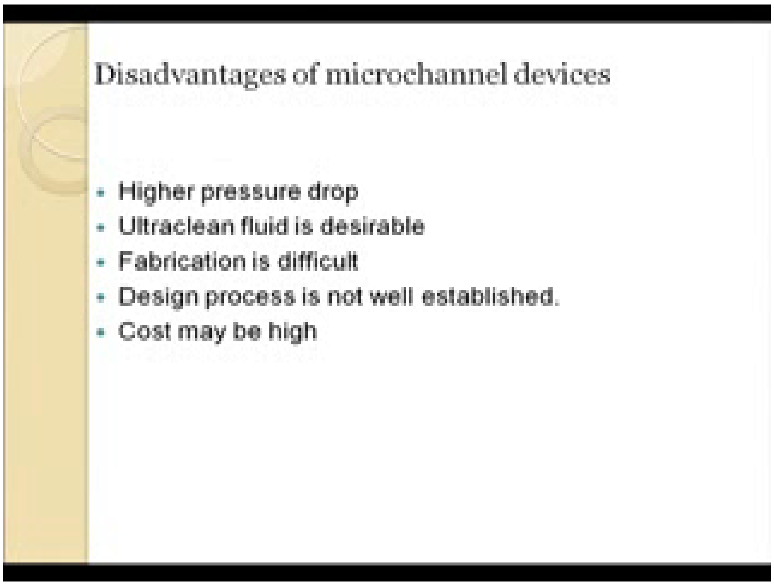

But 1 thing you have to remember that everything cannot be rosy about any particular device then, research would have ended that cannot not happen. So, there are several disadvantages of these microchannel devices as well. What are the disadvantages? First thing is you have to use ultra clean fluid there is an every tendency of the channel getting choked. Fabrication is different from common sense we can say. Designed process is not very well established that also goes without saying. They are very expensive definitely. The other thing is the pressure drop is very high.

Therefore, we have to take these into considerations while we are working with micro channel devices.

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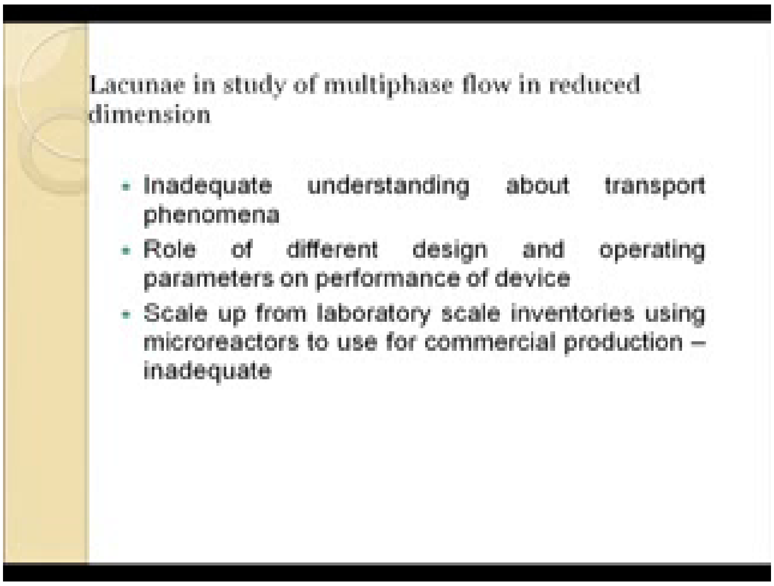

And the problem of working with microchannel device is or rather the lacunae or need for studying microchannel device is primarily because that, till now we have understood that the macro and the microchannels voice devices they are having quite different flow pattern and therefore the information which we have for microchannel devices cannot be extended in a straight forward manner to the microchannel system. And we do not have inadequate understanding about the transport phenomena in reduced dimensions. Till now we need further investigation to understand the role of different design and operating parameters on the performance of the design of the device and scale up is also very important.

Now, 1 very important thing I had forgotten to tell you. I had discussed when we are discussing multi phase microchannel flow I had told you that well we have an extended range of slug flow and all those things. There is another very important thing to remember. I have told you that the pressure drop is very high filed flow occurs in microchannels. When pressure droplet is very high naturally, if it is a gas liquid flow what happens, the gas comprehensibility come into picture and comprehensible flow characteristics set in. And as a result we find this almost everybody has reported that if you observe the flow during the microchannel you find that a large number of flow patterns occur while the flow is going on.

While in microchannel systems after a developing lane to be found at the same flow pattern used to occur and maybe it was slug it was churn accordingly we used to knew the flow pattern for any particular given condition. But in this case if you observe, I think this particular slide will be better for you to appreciate this things that I am trying to impose upon you. If you observe this whole thing it was taken at one particular instant of rather for one particular location for different instant of time. At one particular time what did people see? They saw single phase liquid flow, then they saw the tail of the gas slugs, then there was something like liquid ring flow and then it became serpentine like core. Now this is a very frequent occurrence in this microchannel flow. We have the simultaneous occurrence of a large number of flow patterns in the flow pattern at the same instant of time. Now when this occurs what is the problem, then how do you define what is the exact flow pattern which exists under known conditions.

What people have done for that is they have taken up the probability of finding any particular flow pattern in a condude at any instant of time. And they have found out the flow pattern which has the greatest probability of occurring under a given set of low conditions. And then that particular flow pattern assigned under that particular condition for construction the flow pattern maps.

Now regarding flow patterns maps I should thing I will be elaborating it a little more. We do it in the next lecture while we continue discussing the two-phase flow through micro gents.

Thank you very much.