**Adiabatic Two-Phase Flow and Flow Boiling in Microchannel**
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**Lecture – 15**
**Influence of Operating Parameter on Flow Patterns (Contd.)**

Hello everybody and welcome again, I think this is a last lecture of the third week is not it. Therefore, it is my last lecture on the influence of operating parameters and what did we discuss; we 1st discussed the influence of phase superficial velocities which I have discussed a number of terms earlier also. Next was the effect of diameter, which again were was discussed earlier and after that, I came to the effect of conduit geometry which we found that apart from the interesting phenomena which are observed in macro channels; there are some other phenomena in micro channels.

Then after geometry we came to inclination and we discussed the general trends of inclination and also some special trends for rectangular conduits, which were observed in the multi phase flow laboratory of the chemical engineering department of IIT Karagpur.

Then again we discussed some unique effects of entry system, this I would say is very relevant to the current topic of our discussion because lot of researchers have said that, entry section plays quite a significant role in the distribution of the 2 phases in a micro channel, but not much has been investigated in this regard. Now we come to the last topic it is the effect of wall wet ability which would also give us an idea regarding the effect of contamination of the wall or what might happen if the wall if the wall is not properly cleaned and so naturally if you take a tube we expect some flow patterns, we find something very different; just because the wall is contaminated; it can also happen that when we start the experiments with a new micro channel we get some flow patterns as time progresses some amount of fouling or some amount of contamination occurs and we get different flow patterns, this can also happen.

Therefore, I thought that this particular topic should also be touched up on. Now mostly when we are performing experiments in micro channels we usually very rarely we perform experiments on single tube micro channel, they are either wound together in the form of helical coil or a serpentine of whatever it is.

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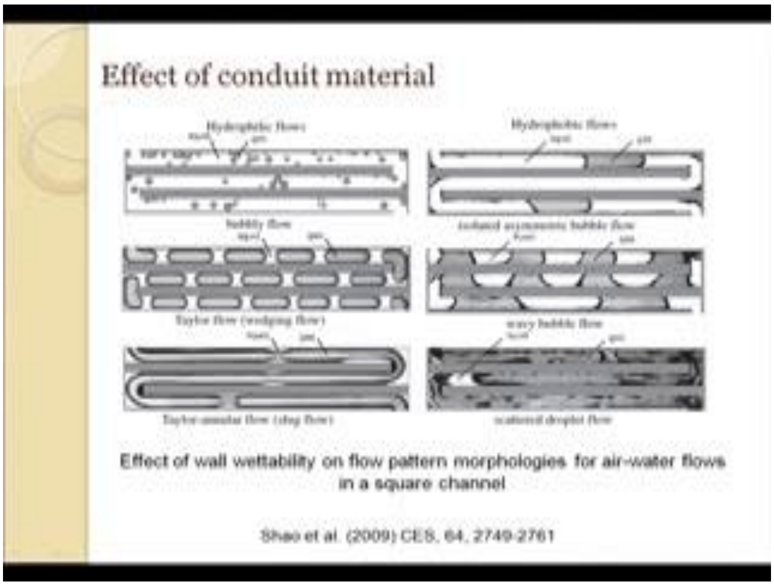


Therefore, these particular results they were reported by shoo et al in helical tube, it is almost like the shell side fluid. Now if you observe in a hydrophilic flow, these things more or less from our intuition we can see, naturally what happens, tube rather the liquid has a greater tendency to wet the tube wall. Naturally since the liquid can wet the tube wall in this particular case we see that, dispersed flow pattern or deformation of bubbles much smaller than the conduit dimensions are found; under this same flow conditions we find that in this particular case. The water does not wet want to wet the tube wall.

Because the tube wall has become hydrophobic; Naturally for as a result what happens, we finds so naturally in order to maximize the contact with the wall; the small gas bubbles they tend to quails and they form elongated Taylor bubbles and these Taylor bubbles naturally they force the liquid to form in a flux between the 2 bubbles.

And therefore, we found find that instead of bubbly flow; we now encounter isolated asymmetric bubble flow. It is sought of the confined bubble flow whatever way you want to say you can say it, but basically just to minimize the contact of liquid with the wall instead of bubble flow; now we encounter an asymmetric bubble sort of flow where it exhibits the periodic character of the slack flow pattern.

We keep on increasing the gas velocity, keeping the water velocity constant; this is a typical way of performing experiments in multiphase flows; just to understand the effect of the effect of the 2 phase velocities separately, quite expected as we increase the gas velocity we would we would come across the typical Taylor flow or slug flow, whatever you call.

This case also we come across something of this sought, but if you observe very closely we find that, although in both the cases the pattern is characterized by a periodic flow phenomenon, but the shape of the bubbles are completely different; while it was rounded on both sides in this case the curvature is in the opposite direction, fought the tail and the nose in the hydrophobic tube case. Thus identical thing can be observed for the asymmetric bubble flow also, because in this particular case in order to minimize the contact of the liquid with the wall, the morphology has to assume this particular shape.

Again we keep on increasing the gas flow, naturally the gas coats they start to qualising with one another and they try to form a continuous core of gas, pushing the liquid towards the wall, to form an annular film and naturally at the transition region what do we have. We have necking of the gas core by liquid flux, where the liquid flux they can form a ring shape structure or a liquid lump as we have already started. On the other hand in this particular case what do we have, we find that with increasing gas velocity; the gas almost form some sort of an irregular pattern, where liquid droplets tend to get concentrated.

Now, this particular flow pattern we have not encountered till now, in our previous experiments. In glass channels which were hydrophilic in nature. This sought of a scattered droplet flow in whatever name you want to call it where the liquid it tends to get dispersed at droplets and gas forms an irregular core, quite sort of an cavity phenomena, but not the join low pattern; in this particular case although this is some sort of instability, but this has this has no parallel to instabilities in macro flows right

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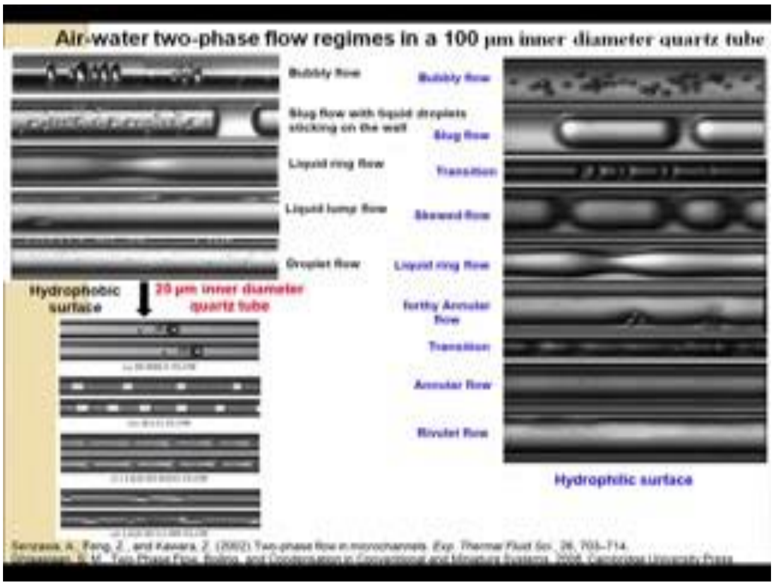


This sought of a flow pattern is not observed for your hydrophilic tubes. Therefore, in this particular case, we find the pronounced effect of conduit material same thing can has been observed or reported by other researches as well.

Here if you observe what to find, you find that when we have a hydrophobic surface we have already discussed with this particular part. The gas bubbles which are formed, they are quite disc shaped; the quite large and are comparable to the dimension of the conduit. Whereas uniformly dispersed bubbles dispersed in the continuous liquid, which also wets through the pipe wall can be observed here. Although in both cases we call both the distributions as bubbly, but the difference in the bubble characteristics are immediately evident.

Next after that quite naturally we are come to know from this our 3 week long lecture, that more or less after this as we increase that gas velocity we get slug flow film; this slugs we are very acquainted I have shown this to a number of times.; Just let us see what is the corresponding flow pattern in the hydrophobic tube. In this particular case we find that, by Taylor bubbles are flowing there is a liquid film, annular liquid film it is there in this case also here also, but this annular liquid film it tends to get rather it gets disrupted and forms some dry zones between the gas slug and the wall and on these dry zones some liquid droplets tends to stay.

Therefore, you can very understand how erratic this looks, that instead of a continuous liquid film between the Taylor bubble and the wall; we find some occasional dry zones with liquid droplets taking to them and the liquid droplets with the sticking are also spherical in shape in order to minimize the contact with the wall and after that we find that at low velocity this liquid droplets are sticking at high velocity they are carried away along with the water.

Now, if we if further increase gas velocity we find that, the liquid slug flow it is replaced by the liquid ring flow as expected, the liquid ring flows as more or less the same type of appearance because there is a no way since the gas has to form the core. So, naturally the liquid has to remain as rings; the rings are much more unstable in this particular case as compare to the hydrophobic case and we find that what the hydrophobic case, the liquid ring flow it gradually develops in to the liquid lump flow and then the droplet flow right.

Whereas, in the hydrophobic case we find that more or less the droplet flow is not very evident if you can seen all this cases, we definitely have a liquid ring flow, then if you wish we have an annular flow the transition from slug to annular can take a number of part as I already described earlier, may be the liquid slugs or the liquid bridges will become very small giving rise to the liquid ring flow and then at some point may be there will be liquid droplets which will be entrained in the gas core etcetera, but more or less from dispersed we have slug and from slug we get annular flow and for still higher velocities we find that, the gas core it flows as a serpentine form or it flows as a rivulet and this particular phenomena is not observed for macro systems.

Whereas for hydrophobic tubes as expected; since the liquid has a very less tendency to wet the pipe wall so, after liquid lamp flow it is very difficult for the small amount of liquid to maintain a continuous liquid film at the wall.

Therefore, we develop something of the droplet flow; you might recall that at the beginning of the lecture I have told you that, for adiabatic gas liquid cases we do not usually get a droplet flow. Therefore, whatever I had said, I am deputing it when we have dissented down the scales and we have entered into the domain of micro channels from the macro systems.

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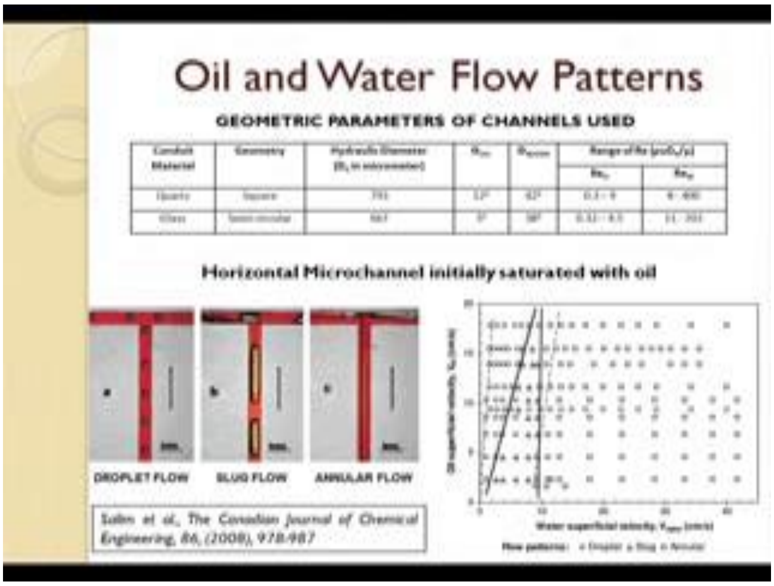


Now, for the reduction of tube diameter we find that the flow patterned does not change much; we have the bubbly we have the slag etcetera. We find that the tube material has a more pronounced effect as compare to the diameter for micro systems.

Well this was all for gas liquid flow patterns, the 1 thing I do not thing I have got a very good picture of this, but it demand some sought of a discussion at very unique flow pattern, I do not have a very good picture of it. It is the rivulet and multi rivulet flow, I have shown it for hydrophilic pipes, but this particular flow pattern I would like to give some time because this flow pattern it is also another unique flow pattern for your hydrophobic channels as well.

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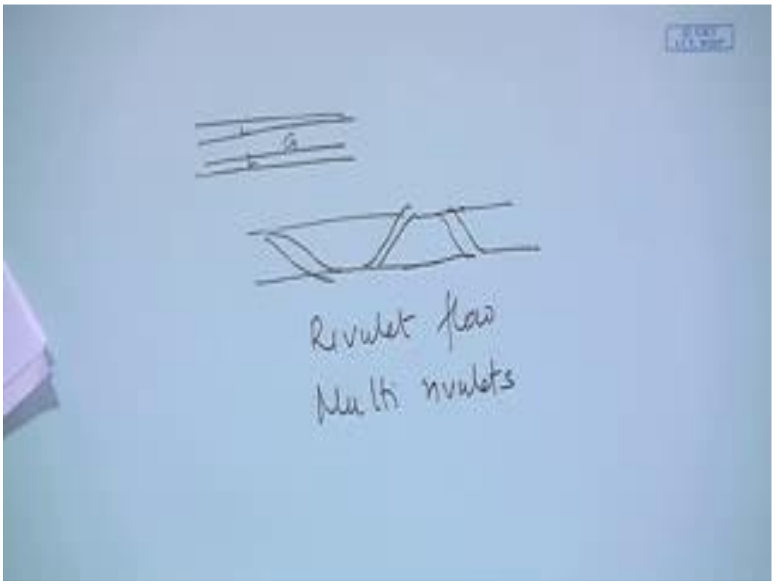


Now, in this particular case what happens is, that instead of annular flow suppose you are having a micro channel right. At high gas or other high mixture velocities, what should we getting we should we getting a gas core and a liquid film, but it is very difficult to maintain the continuity of the liquid film on the wall. It would like to minimize it is contact. Very frequently what happens is the liquid it does not flow as a film at the wall, rather it tries to flow as a rivulet sought of a thing which (Refer Time: 13:56) around the channels and it flows like an irregular rivulet, it is not as regular as I would drawn, it flows as an irregular regular rivulet through the gas core; minimizing it is contact with the wall and suppose we go for higher velocities, at a wet ability then instead of a single rivulet flow we might come across a multi rivulet. We can also come across multi rivulets.

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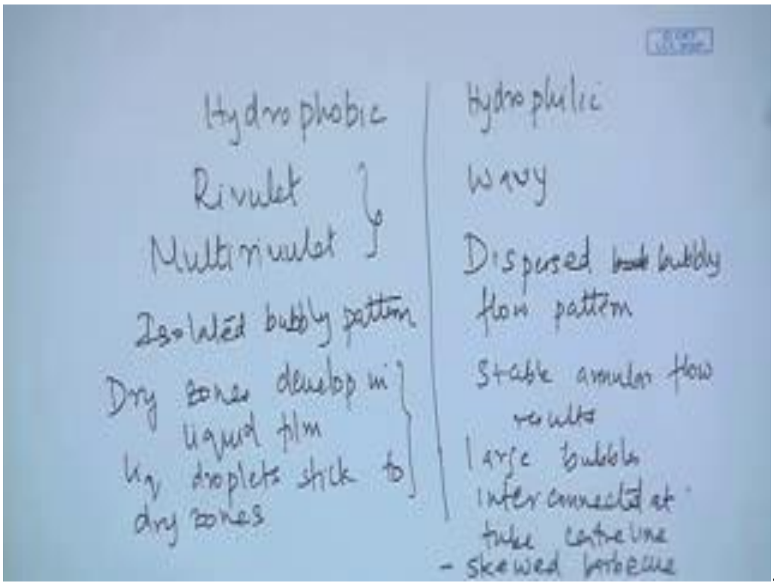

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Now, this I would like to see this is not something very common for hydrophobic pipes. Therefore, I would just like to job down the flow patterns which we get for hydrophobic and hydrophilic cases. This is hydrophobic and this is hydrophilic. In the summery I would just like to job down the 1st thing is I do not have a good photo graph, but this is something very important for hydrophobic tubes, while we have a wavy type of a flow in this particular case, which is not exactly a rivulet type, but it is a wavy type.

Next is, here we have a dispersed flow pattern it is better to write as a dispersed bubbly flow pattern let me write it down in this way, while in the previous case we had something like the isolated bubbly pattern. The other differences are hydrophobic these things I have already discussed, dry zones develop in liquid film and liquid droplets stick to dry zones while in this particular case stable annular flow results right and we also have another very unique flow pattern in this particular case where we have large bubbles, the flow pattern can be evident I think that all. I do not have this is more or less of sought of this, I will just write down. In this particular case we have large bubbles interconnected at tube center line, to form a bubble clean flow; if look something like a skewed barbecue; this particular flow pattern we do not get in the hydrophobic case.

Therefore, what we see that, instead of wavy sought of flow a something wavy interface we get rivulet and multi rivulet flow here, instead of a dispersed bubbly flow pattern we get an isolated bubbly flow; while stable annular flow results here we get here dry zones developing in liquid film, liquid droplets sticking etcetera. On the other hand since at from continuous liquid film is maintained; very frequently we get a flow pattern if a large bubbles are interconnected at the tube centers and they flow just like a bubble train flow it is looks like a skewed barbecue sought of a thing, but such phenomenon we do not find for hydrophobic tubes.

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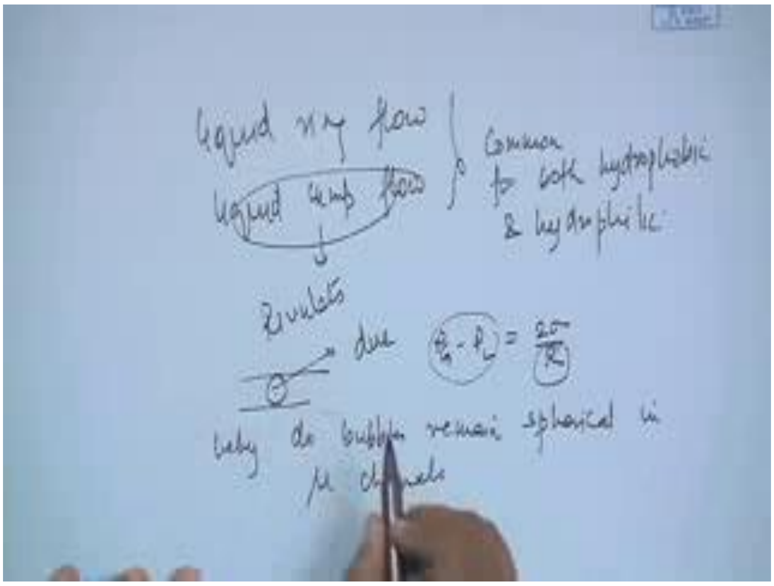


As for as the other type of unique flow patterns in micro channels, liquid ring flow, liquid lump flow etcetera. These are common for both type of flow patterns, common for both hydrophobic and hydrophilic and the liquid lump flow this develops in to rivulets for the hydrophobic case. And I would also like to mention that, in micro channels, if you remember; I had mention that the bubbles would remain more or less spherical in shape within the confined environment; this arises why do bubbles remains spherical in micro channels. The reason is that there is a very large pressure difference across the interface of the bubble, due to the very large pressure difference what we find is, the inter facial pressure B G - PL it is equal to 2 sigma by R. Since this is very large so therefore, the bubbles they tend to remain as small spherical droplets. That is why we find the flow pattern which has mentioned here, large bubbles interconnected at tube center line large spherical bubbles, this arises just because of 2 reasons.

The 1st reason is there is a large pressure difference across the bubble surface and due to this large pressure difference, the dispersed face tends to adopt the spherical shape; rather than the cap shape, elongated shape, ellipsoidal shape which we and which we come across in macro channels. And this also explains one more thing which had been repeatedly telling you that, Taylor bubbles in micro systems have a rounded nose and rounded tail; while in macro system they have a rounded nose and a flat tail. The primary reason is because the pressure difference due to capillarity it is very high so from young Laplace equation we find that, the stable shape it has to be a circular in order to be stable.

The other thing is because of the rigidity of the micro structured bubble, so once found did not tend to change their shape. So, this is one thing which we should be remember it while trying to understand 2 face flow through micro channels. well Now let us go to oil water flow patterns, do we expect anything extra or anything different in this particular case or is it more or less similar for your air water cases, we had we have the not rather we did not do this particular you can refer to this paper for the for further investigation in to the results, the (Refer Time: 21:37) here done they perform the experiments in 2 particular conduit materials one was quartz which as we know it is it has a higher contact angle with water has compare to glass, but in both the cases we find that the experiments were performed with an oil and water and in both quartz and glass we find the contact angle is lower for oil as compare to water, which shows that that it will be a natural tendency to for oil to wet the flow patterns and we had taken square quartz channel and a semi circular glass channel and of course, a range of (Refer Time: 22:14)

Of parameter I have also mentioned. Now, just try to understand one thing when I was trying to discuss that, flow patterns for gas liquid and liquid cases in conventional channel, conventional conduits during by introduction on multi phase flow I had mentioned one thing very clearly that is, that for oil water or liquid liquid flows either of the phases can wet the pipe wall. As a result what happens is we can have either of the phases dispersed in the continuous phase. It can be oil dispersed in water it can be water dispersed in oil. This depends upon the portion of the 2 phases in macro channels, along with that in micro channel it also depend upon the wet ability of the 2 phases and unlike gas liquid cases this case either of the2 can wet the pipe wall number one, the wet ability can be engineered by modifying the surface number one. Number 2 that we can start experiments either with oil 1st where the channel wall will be wetted by oil or by water first, where the channel wall will be initially wetted by water and oil is introduced.

Very interestingly we found in this particular case well experiments were done with horizontal micro channel, we found differences in flow patterns; when we performed experiments in glass and quartz micro channels we also noted that the researches had reported differences, when in both the micro channels the experiments were performed with oil as, with the channels saturated with the channels saturated with oil $1^{st}$ and when the channel was saturated with water1st. So, therefore, that called for some more unique features when instead of air water which we have been discussing. So, long if we come to oil water cases.

Let see what happens when it is initially saturated with oil, for horizontal micro channels it was observed, that the same flow pattern types were observed for quartz and glass because for both the cases we find that they have the contact angle of oil is less. Natural tendency in both the cases to be wetted by the oil phase. As a result what happens is when we introduce water here, the water 1st tries to remain as droplets then, qualise to form slugs and finally, this is an annular flow please remember, this annular flow is with oil film and a continuous motor core. And the flow range of flow patterns have been plotted in a flow pattern map where we find that, the transition from droplet to slug flow it occurs at more or less a constant void fraction of 0.03 and we also see that the slug to annulus flow it occurs at more or less a constant water velocity.

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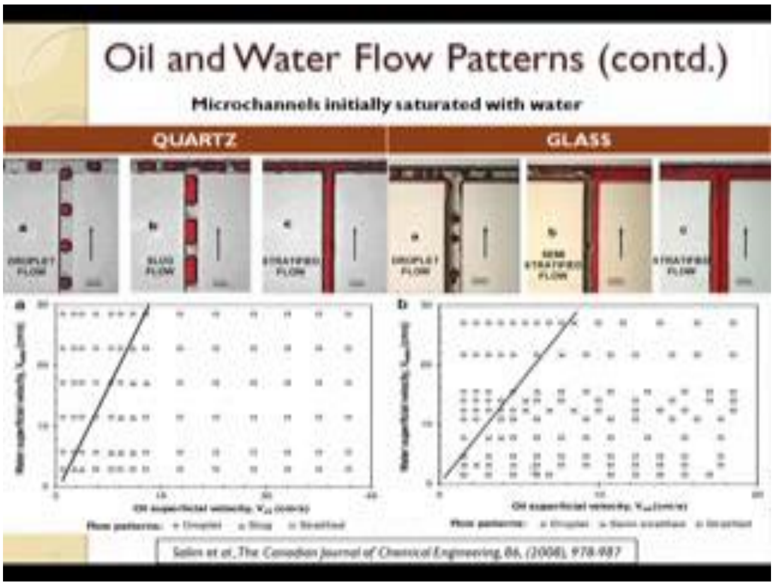


Now, suppose we shift and we go to the other researchers have performed experiments in micro channels, initially saturated with water and interestingly since water does not want wet either of the channel, we find different flow patterns for quartz and glass. In quartz what do we find just like in this particular case there was droplet flow, we have droplet flow here; we had slug flow here we had slug flow in this particular case, but in this particular case since it was initially saturated with water we have oil slugs in water.

Interestingly after that we had annular flow in this particular case, but here the water does not want to wet the pipe wall. Therefore, we had something rather they encountered something like the stratified flow pattern; where the water and the oil they were flowing one above the other.

On the contrary suppose we would be working at the glass micro channel, we observe that initially it was droplet then instead of slug it was sought of a semi stratified sought of a thing; where more or less the oil and water they were separated by an extremely wavy inter phase and then on further increase in velocity we obtain the same stratified flow, we did not obtain the annular flow which was observed; when the micro channel was initially saturated with oil and the primary reason being that, when it is initially saturated with water the water does not want to wet the pipe wall.

But since, it has already in contact with pipe wall. Therefore, it keeps on wetting a portion of the wall and leaves the remaining portion for oil to occupy. From this we find that we get completely different flow patterns for quartz and glass when that initially saturated with water and this is also reflected in the flow pattern maps, which have been plotted with the water superficial velocity and the oil superficial velocity as the 2 access well. With this I end this particular discussion series, as a very small portion left regarding the inference of wall wet ability and I will be doing that portion and then I will be going to the discussion of other hydro dynamic parameters namely the void fraction and the pressure drop. I think we had enough of flow morphology. Good bye today and we meet next week.

Thank you very much.