Adiabatic Two-Phase Flow and Flow Boiling in Microchannel
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Lecture - 03
Two Phase Flow through Micro Channels

Well hello everybody. Welcome again to the 3rd Lecture on Adiabatic Two-Phase Flow and Flow Boiling in microchannels. This is the second topic that we are going to cover. In the first topic what we covered I just gave a brief introduction regarding multi phase flows so that after this it will be easier to grasp the concepts or the reasons why multi phase flow is different in micro and macro channel.

Today we will be going through rather we will be making a journey or will be I will be introducing you to 2 phase flows through micro devices.

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The first thing is this current trend of miniaturization, why has this come into being. There are some specific advantages of miniaturized systems.

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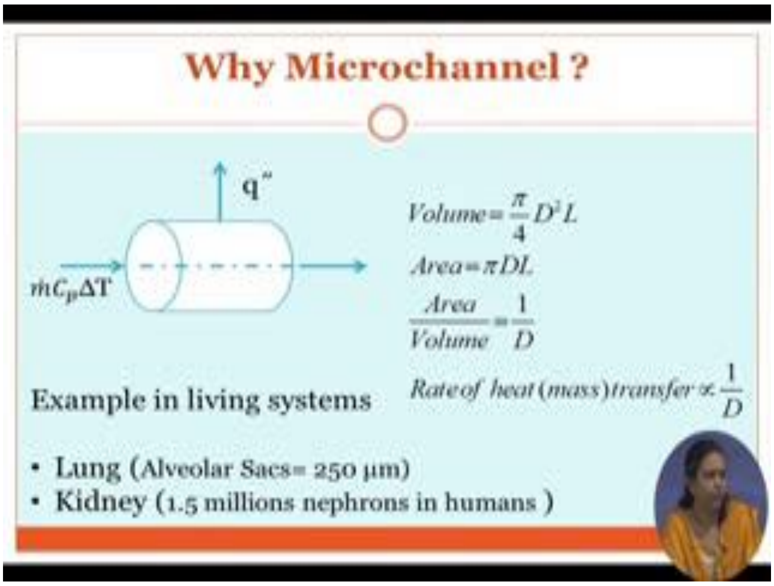

And the first thing is as we know that there is an extremely large surface to volume ratio which will be clear from this particular slide which you see we find that your area to volume ratio is inversely proportional to diameter. When the diameter goes down, this area to volume ratio it increases. What happened as a result of that? Due to the extremely large surface to volume ratio there is a short transportation path and naturally that implies the high rate of transport processes. It can be mass transfers, it can be mass transfer, it can be heat transfer and it also leads to the enhancement of mass transfer limited chemical reactions.

Therefore, as a result of this firstly due to the fast mixing we have enhanced transport and then this leads to more compact device, and therefore heat transfer can occur across a very less temperature difference. Naturally when you are dealing with less volume it automatically implies that there will be a smaller amount of inventories for process development. This is particularly important for 2 types of materials; one the making is very expensive we require a less capital and inventory cost, the other thing is if you are dealing with hazardous material it automatically assures an intrinsically safe reactors. And well less weight less volume, less power consumption for mobile systems they go without saying.

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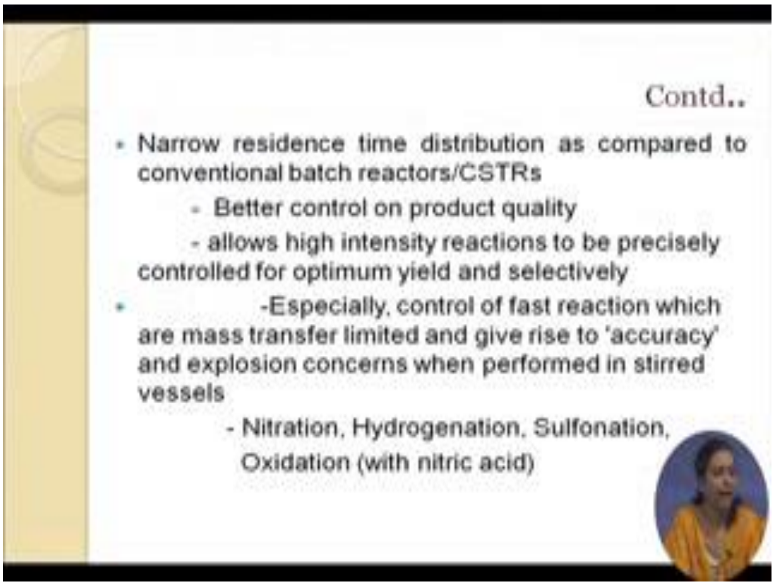

And also we find that in this particular case we have a very narrow residence time distribution. The reason for this will be clear as I go further, but due to this narrow residence time distribution as compared to conventional batch reactors or CSTRs. Therefore, we have a better control on product quality number one. And number two, it allows high intensity reactions to be precisely controlled for optimum yield and selectivity.

And this is particularly useful as I was just mentioning a few seconds ago. It is particularly useful for the control of fast reactions which are mass transfer controlled, mass transfer limited and they give rise to accuracy and explosion concerns when they are performed in stirred vessels. To be specific these reactions just a few examples I have given there are many more reactions which are facilitated by performing them in your micro reactors. Few of them are nitration, hydrogenation, sulfonation, oxidation, and so on and so forth.

Well, and naturally since we are dealing with very small amount of fluid so what it implies a smaller pump and a lesser pumping part.

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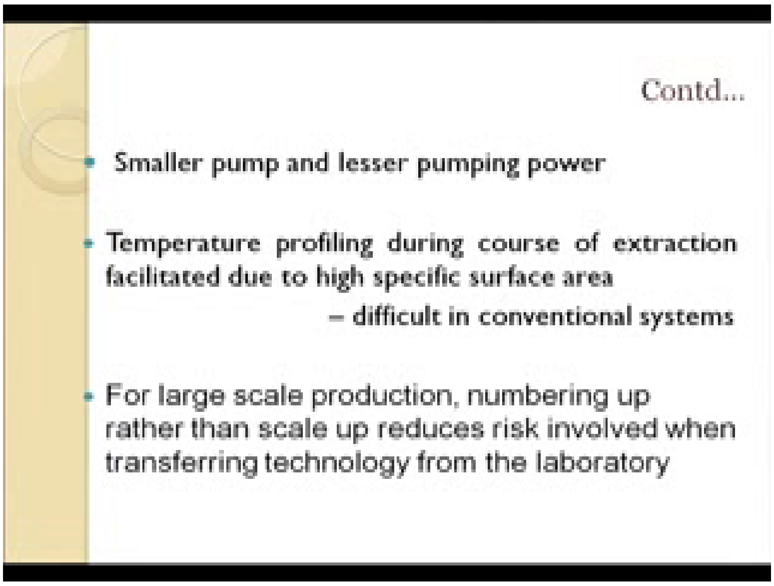

It also tells you that temperature profiling during course of extraction is facilitated due to the high specific surface area. This is difficult in conventional system. And another interesting part is, suppose you want to scale it up for a large scale production. Genuinely for macro systems what we do, we increase the dimension of the system and then we apply several scaling laws to find the dimension of the macro the large scale system with respect to the pilot plant prototype which has been developed in the laboratory.

Now for micro systems there is no question or there is no story of increasing the dimensions. In this particular case the concept of scale up comes from numbering up concept rather than scaling up concept. And therefore, since large scale production we go for this numbering up it reduces the risk involved when transferring the technology from laboratory to the commercial scale, which is always we as engineer the scale up is quite a challenge for us.

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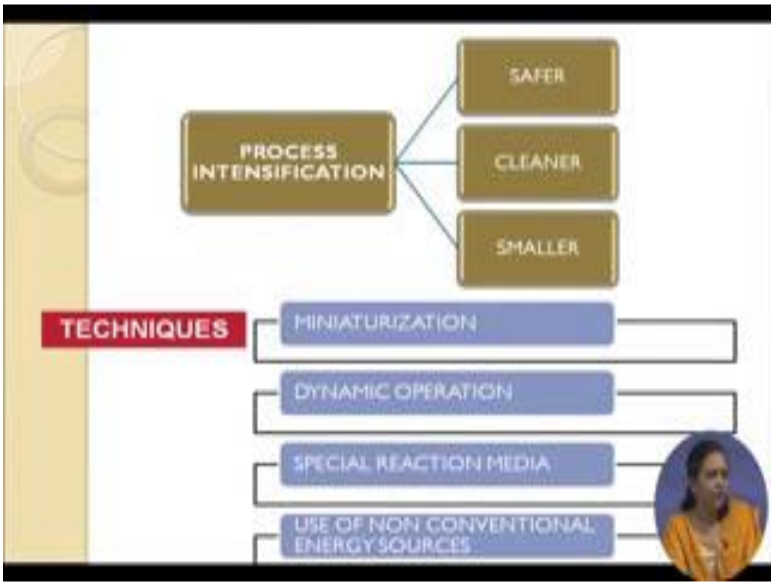

Well, so with all the applications a well with. Therefore, in a nutshell, what do we find; we find that micro reactors they provide a large surface to volume ratio. As a result of which it intensifies different transport processes and also mass transfer limited chemicals reactions or in other words it leads to process intensification which signifies not only a large amount of production at reduced cost, but it also ensures safer and cleaner environment as well. And among the different process intensification techniques if you find, you will find that miniaturization is one of the techniques that is followed. The primary reason is that just as I have mentioned the larger your surface area to volume ratio.

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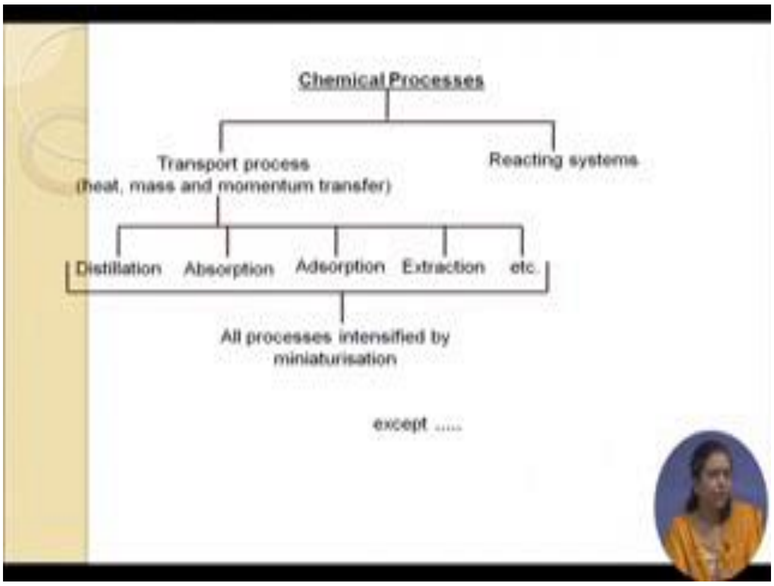

And in fact, in the last to last introduction I was mentioning while I was talking about the application of the multiphase flow I was mentioning that whatever chemical processes we come around, be it reacting systems or in non reacting systems all of them they involve multiphase flow. That we have already discussed. All of them they involve the contacting of 2 phases and then ensuring that one phase is completely dispersed or as very fine films where the maximum transport takes place.

And if you observe you will find both for reacting and non reacting systems almost all the process they are intensified by miniaturization. There is just 1 exception to it, that exception I will leave you to guess but anyhow it will be quite evident to you that the exception is distillation you do not have a micro distillation column, because there we actually need that particular temperature difference. Therefore, except distillation all other processes beet it in reacting systems or in non reacting systems they are intensified by miniaturization.

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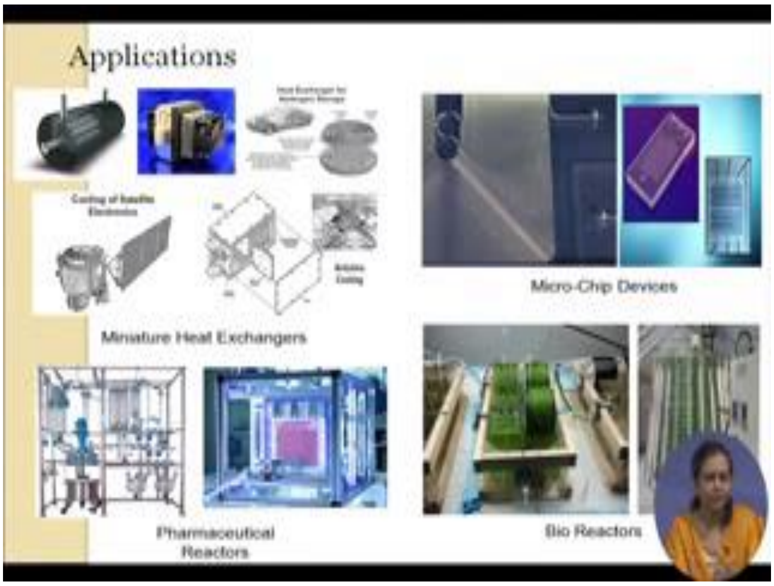

Apart from your micro reactors there are also rather a large number of other applications of miniaturized systems. For example, in compact heat exchanges, now it is we find that there has been a thrust of excessive cooling or rather since you have gone through this miniaturized systems. Therefore, there has been increased need of studding 2 phase flow and heat transfer through microchannels, because of the rapid development of micro scale devices which are used for several engineering applications.

Now these micro scale devices they pertain to maybe medical devices, your high heat flux compact heat exchangers as I have shown in this particular slide and cooling systems of various types of equipments, such as high performance micro electronics, super computers high power lasers and so on and so forth. Now, in these particular applications which demand good amount of memes cooling or micro chip cooling or whatever, we will find out that the cooling does not occur by the conventional heat transfer process like conduction conviction radiation etcetera, due to the very small amount of volume of fluid available so that the convention current cannot set up in that case.

But in these particular cases the chunk of cooling occurs by phase transfer. And therefore, the moment the greater amount of cooling has to occur by phase transfer naturally 2 phase flow a liquid and a vapor flow occurs in these applications, so unless we understand the distributions or the typical characteristics of the 2 phase flow we cannot go for an efficient cooling system. This is 1 part of the application in several types of cooling of compact devices or in other words the cooling of electronic chips etcetera; this is 1 part. The other part is from the chemical engine aspects, where we find that micro reactors are being increasingly used for production of several chemicals as I have said, more importantly in the pharmaceutical industries and as bio reactors.

Now, in this particular case the use is primarily because rather it is possible in these particular reactors to ensure a narrow residence time distribution so that we have a better control on the product quality. With the large number of coupled advantages high transport characteristics, then narrow residence time distribution, then again we have this temperature profiling possible, numbering up impossible. With all this combined characteristics we find that microchannels they are a very good potential area of process intensification. And also for several new engineering devices which are coming up in the way the advent of electronics and super computers and so on and so forth.

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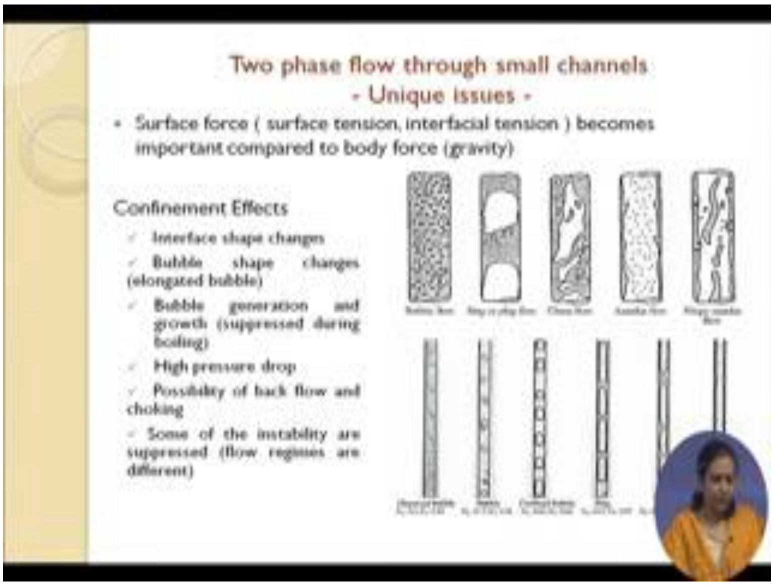

Well, now the next thing is that what do you expect will be the differences when the 2 phases; for the time being let us assume a gas and a liquid phase flow when they are flowing through a large system and when they are flowing through a miniaturized system. Now whenever there are 2 phases they interact rather due to a large there is an interaction of a large number of forces. What are the forces that we encounter?

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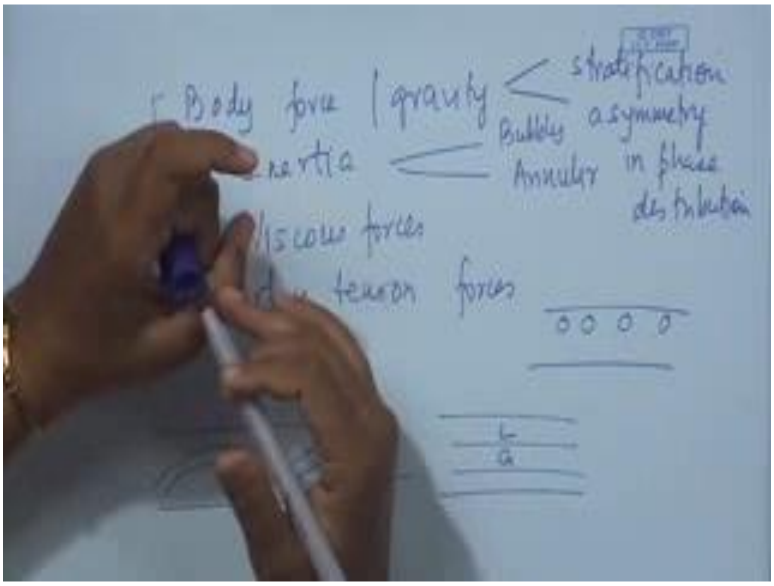

1 is definitely body force or gravity. Then there is inertia force definitely in flow system inertia is going to be quite important. Then viscous forces also come into picture. And normally in macro systems this surface tension forces are not very important, but mainly these are the four forces due to which we encounter the different flow patterns. When the liquid inertia is high it can break the gas phase into small bubbles and as a result of which we get bubbly flow pattern.

Inertial dominant flow patterns are bubbly on 1 side and on the other extreme, what do we have? The gas inertia is sufficient, it forms a gas core and the liquid film is pushed at the sides. Therefore, the inertia controls we have you people inertia controlled regime 1, regime 2; 1 comprises of bubbly and other dispersed patterns on the other extreme it is the annular pattern. When gravity is important what do we have first thing what we have is stratification in horizontal and near horizontal systems; this is number 1. What is the other thing we have symmetry in phase distribution?

As long as we are dealing with macro systems generally if it is a gas liquid system or a liquid liquid system with one of the liquids or both of the liquids it is not very viscous generally we deal with rather there is an interaction between body forces and inertial forces. Viscous forces is coming to be when we are dealing with high viscous oils like crude oil lubricating oil and something of this sort. Now whenever we have reduced the dimension, what happens? The first thing which is very evident to you is gravity forces get suppressed. When gravity forces gets suppressed the affects of gravity they tend to become less or in other words they will be lesser and lesser tendency of stratification.

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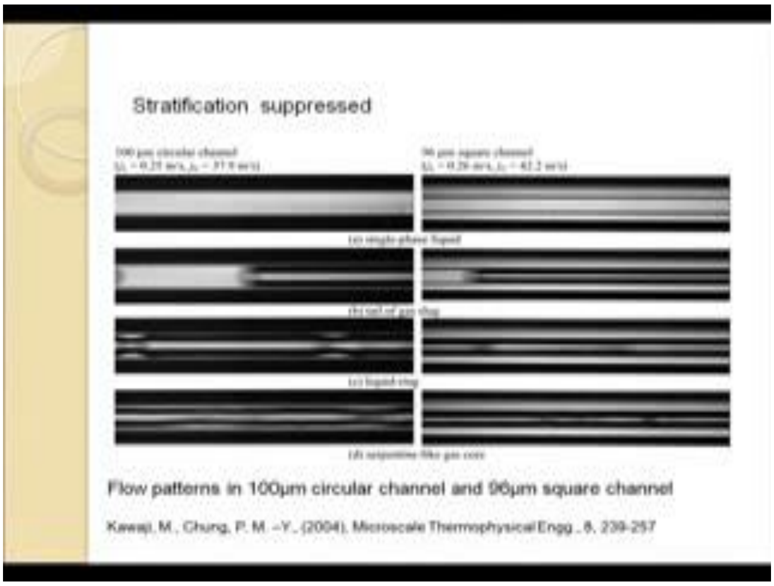

Or stratification is suppressed we say. This will be evident from the flow patterns which have been observed by the researchers Kawaji M Chung, in a 100 micro meter and until 96 micro meters square and circular channels. You will find out I do not know how evident it is, you will find that what we have here is we are having some slug sort of things and then when the slugs become bigger then they get bridged at regular intervals and the gas liquid interface it is marked by a waviness of a smaller and periodic inter facial wave. And at regular intervals the gas it forms a neck in region where the neck is much more narrow and there the liquid it appears to be as a ring, because the liquid is not very large or rather the liquid slug is not sufficient it just appears to form a ring between successive tailor slugs or tailor bubbles. This is known as liquid ring flow.

Then gradually what we have? We find that gradually when the gas velocity increases naturally the gas flows very fast and we have; I do not know whether it is clear, we have something of the serpentine like gas core they say. Here in this particular case what we have is more or less it is sort of in this particular way the gas core it becomes thinner and it flows in a serpentine like fashion, but due to the inter facial waviness, but the normal annular flow we have in macro channels where the gas core and the liquid film that does not happen except gas velocity is very high and the liquid velocity is very low.

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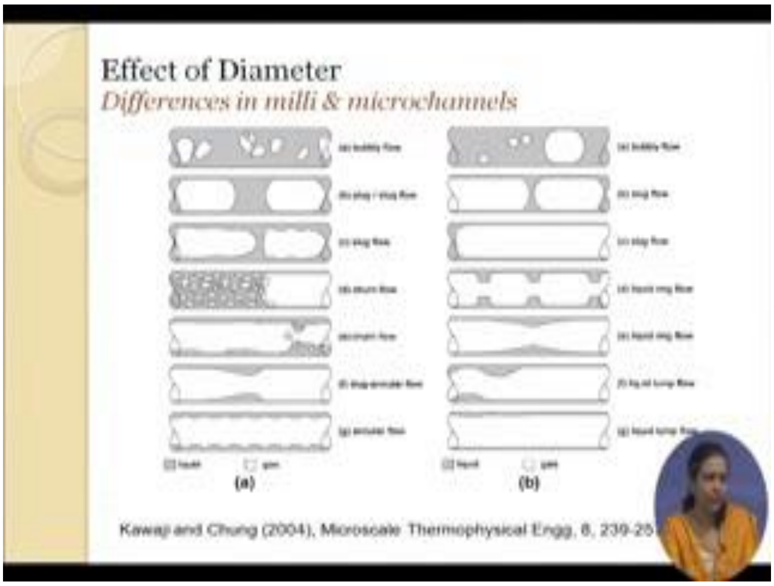

This concept of stratification being suppressed is also evident from these flow patterns which has been taken from a mini channel or may be in a millimeter size channel and in a microchannel. Even in a millimeter size channel we find that initially more or less the flow pattern in a mille channel they are more or less what we had discussed regarding the flow patterns in a macro channel, but there are some additions and deletions. For example, we find that when the gas flow rate is very less we have bubbly sort of flow patterns, but definitely this bubbly flow pattern does not comprise of finely dispersed bubbles which we had observed in the for the macro systems.

Therefore, here the bubbles they are quietly elongated disk shaped or cap shaped. And you will find that unlike horizontal conventional channels they are more or less distributed uniformly throughout the flow passage, and tendency of being confined to the upper region is comparatively less. Now this particular tendency it decreases as the conjured dimension starts decreasing. And after a time we find the gas velocity increase then naturally these bubbles they come very close and they for the plug bubbles like in conventional channels. But this bubble to plug transition occurs at a lower gas velocity as compared to conventional channels number one.

Number 2, if you have remembered the video which I have showed you yesterday, you would have seen how erratic and irregular the Taylor bubble was, while in this particular case we find the Taylor bubble it has a regular shape with a rounded nose and a rounded tail. Well, I can show you a video after some time where it will be more evident that how rounded the Taylor bubbles are as compared to macro channels. Again you keep on increasing the low rates naturally the gas bubbles will get elongated there will be waviness along the interface etcetera, etcetera.

And after sometime they start qualising and a flow pattern emerges which the researchers call as joint flow. But let me tell you this joint flow is distinctly different from the periodic chaotic joint flow which has been observed for large diameter pipes. In this particular case usually I find that there are three types of phenomena associated which people club together and if they see any of the phenomena they say it is joint flow. What are the things which happen?

1 thing is that the bubbles become quite large and they start shredding smaller and smaller satellite bubbles and therefore more or less a churning mixture is found here. The other thing which happens is the bubbles they start getting longer and may be a churn sort of a thing that sweeps the interface and due to this particular churning wave more or less their interface appears to be irregular. And this particular flow pattern also people are unable to decide what it is. There are long gas slugs people are most convinced that well it is the annular flow and then the fine that know there is some amount of liquid breathing.

Therefore, they cannot define it as slug, they cannot define it as annular since this good amount of waviness at the interface they call it the joint flow pattern. There is another thing also which people call as the churn flow pattern which is when the gas plugs become quite large and they almost merge with each other, but we find that the gas core it is marked by a periodic wave it is sort of this sort of a thing.

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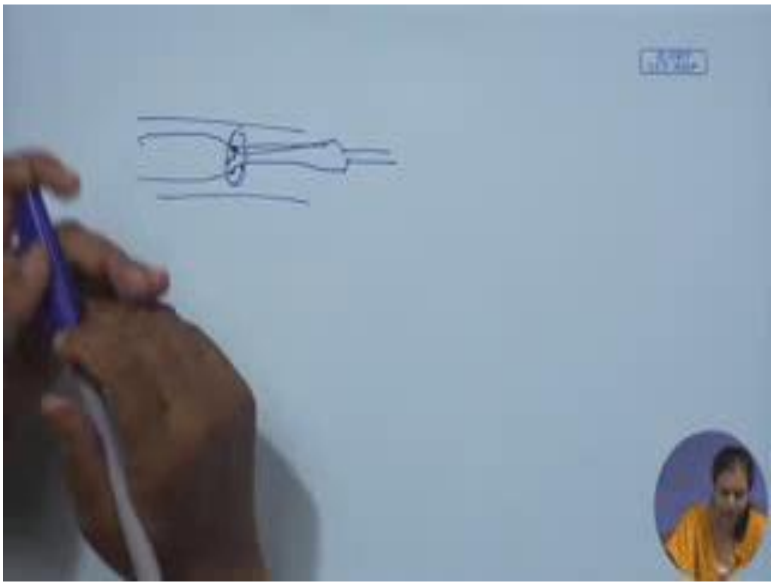

The gas core, there are large bubbles. Here there is a small necking sort of a thing and it goes in this particular wave. Therefore, there is a gas core which is possibly continuous, but there are very short liquid slugs and these liquid slugs rather these liquid churns they form a bridging sort of a thing better it is called necking than bridging. And this particular thing also people do not know whether it is slug or annular so they call it a joint flow pattern.

Usually, we find that churn flow it is marked by three particular phenomena. The first one is serpentine like gas core and this is surrounded by a deformed liquid film. Now here I would like to tell you one thing, such a serpentine like core used to be observed for when high viscous oil and water used to flow in a circular pipe,

I will just show you a slide in order to highlight this particular situation. I will just show you this particular slide so that it will be easier for you to understand. Let us see this particular slide.

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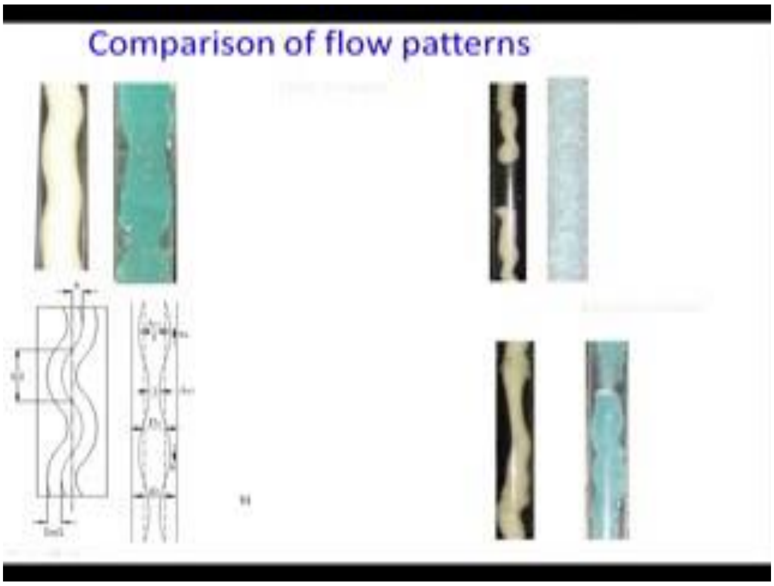

Here if you observe, here I have taken the flow patterns of this one is kerosene water and this one is your lubricating water. In this particular situation if you find you find a serpentine like lubricating oil core in the central portion and it is surrounded by an annular water film. And we find that this particular sort of corkscrew waves or whatever you call it they are absent for kerosene water flows. In this particular case you find that such types of waves are much more symmetric and they are not symmetric as this case.

Here we know that this happens because of the high viscosity of the oil or in other words viscous forces are responsible for this. From there, we call very well conclude that the situation. That we had caught for this particular case as well also arises because of the dominance of viscous over inertial forces.

Therefore, the first thing which has happened as I have said that the gravity inertia is more important or rather be sorry, the surface forces are more important as compared to gravity. When surface forces become more important with respect to gravity first thing stratification suppressed. We have already discussed; it is very evident if you see this horizontal flow patterns you can very well see that stratification more or less suppressed. The other thing is if you compare the flow pattern in this horizontal mille channels with the flow pattern in the vertical mille channel you find that they are more or less the same type of flow patterns are evident.

What do we have? We have dispersed flow, but this occurs only at a very high liquid and a very low gas velocity. At one particular extreme we do not have dispersed or rather dispersed flow is not very common in microchannels. Very frequently moment small bubbles are formed they quails and they form such type of disk shaped bubbles which are smaller than the channel cross section, but they are comparable to the diameter. Very frequently the bubble diameter comes comparable with the channel diameter as a result of which we have elongated bubble flows in this particular case.

Now for this elongated bubble case also we find that people have used different names. Sometimes they say it is isolated bubble regime, then they say qaulising bubble regime so lot of names are used. The basic thing is when the bubbles they have very less tendency to quails, they flow as separate entities then we call them the isolated bubble regimes. And then when more or less they start qualising and forming bigger and bigger slugs we call them the qualising bubble regime.

The main thing which I should say is that for the microchannels since we get very similar sort of distributions, but we understand there are a difference and the need to differentiate this and this flow pattern. We do not have sufficient words or in other words not much information from macro channel can be used in this case. For example both these 2 things, both of them are more or less bubbly or what to say your bubbly slug etcetera, etcetera. But there is a definite difference between the distributions. So how to differentiate them; some people call it bubbly, some people call it isolated bubbly, because there is very less chance of the bubbles qualising. And till this case they call them either qualising bubbly or confined bubbly, because in this case it appears as if the bubble it has been it has been compressed by the channel wall to take that particular shape and flow.

Therefore, most of the regimes you find that there is a periodic sort of appearance which characterizes this plug flow pattern. And then we find that after this bubbly, confined bubbly, etcetera the bubbles start getting larger and they assume the typical bullet shaped access symmetric shape of the Taylor bubbles, we call it the slug flow pattern. From this slug as the slugs the Taylor bubbles slot becoming larger and larger so they come into each other's wakes and they start qualising at 1 another. There is a portion where qualising yet there can be some liquid bridges the liquid that so short we cannot call them liquid slugs.

They form sort of rings around long Taylor bubbles. Sometimes they are called as liquid ring flow, sometimes these rings they become larger in proportion they form lumps which are again driven by the gas. People call them liquid lump flow. But basically they are different variations of the slug flow pattern. And only at very high gas velocity it is we get a situation where the gas is flowing at the center and the liquid is flowing as the core. Dispersed bubbly and annular flow regimes which are inertia flow regimes are very less or rather they are not very frequent in microchannels. We continue with our discussion in the next lecture section.

Thank you very much for it.