Multiphase Microfluidics
Dr. Raghvendra Gupta
Department of Chemical Engineering
Indian Institute of Technology, Guwahati

Lecture – 03
Gas-Liquid Flow: Flow Regimes

In this lecture we will talk about different flow regimes that may occur in gas liquid flow. So, to understand gas liquid flow regimes in micro channels or small diameter channels, first we need to look at what are the other flow regimes, or what are the flow regimes that had been studied that have been found in conventional channels. So, as to appreciate what is different in macrochannels and microchannels, let us look at the flow regimes.

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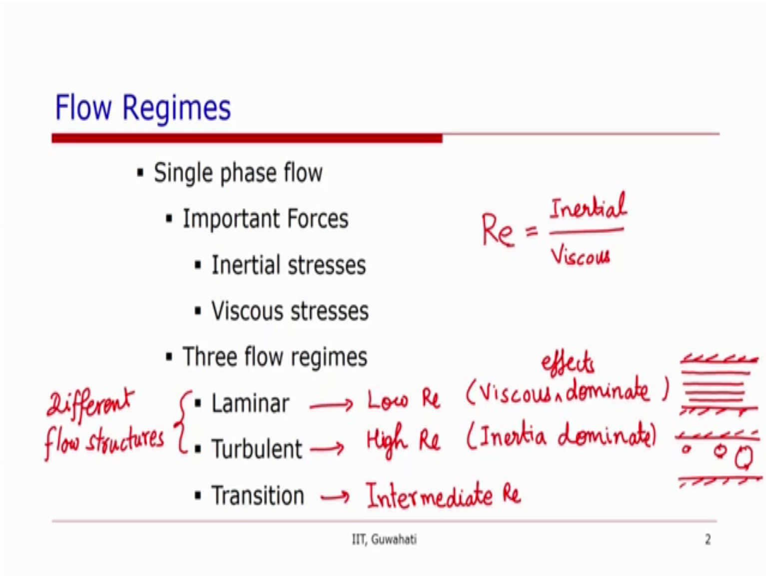

So, first this word flow regimes comes to our mind, and if we have had no exposure to multiphase flows. But we have studied single phased flow in a typical fluid mechanics course at an undergraduate level.

Then you would have been introduced to the terms such as laminar flow, turbulent flow and in between transition flow. So, our understanding of the flow regime will be with the when we say flow regime, then you will immediately think about laminar flow regime and turbulent flow regime. So, let us look at the why do we have laminar flow regime and turbulent flow regime. So, if you remember, we classify that a flow regime is laminar or turbulent by a Reynolds number. And this Reynolds number is a ratio of inertial as well as viscous effects inertial and viscous effects

So, the Reynolds number is a ratio of inertial effects, and viscous effects. And when see when we say that the flow is laminar. So, we say that it is at low Re and; that means, viscous forces are dominating, let us say viscous effects dominate. Whereas, in the turbulent flow, it happens at high Reynolds number and we have inertial effects, inertia dominate the flow. And this is in between at. So, in a single-phase flow because of the dominance of one particular physical force, or one particular physical effect we have different flow regime.

So, that is that a one thing that we can see from this that the flow regimes occur because of the dominance of one particular physical effect one particular physical force at certain flow conditions ok. Then if we look at the flow structure, we call it laminar, because if this is a channel and these are the channel walls the flow happens as laminar. These laminar might be moving with different velocities. So, the flow is happening as different layers of fluid, and these different layers of fluid do not have much mixing.

So, this is what we call because the flow happens in terms of laminar, and we call it laminar flow. Whereas, in turbulent flow we have number of ades, and then these ades can have different flow structures. So, they can be of different size and shown. So, in terms of the flow behavior or flow pattern, what we have is we get different flow structure; which is caused by the dominance of different physical effects in one particular flow regime.

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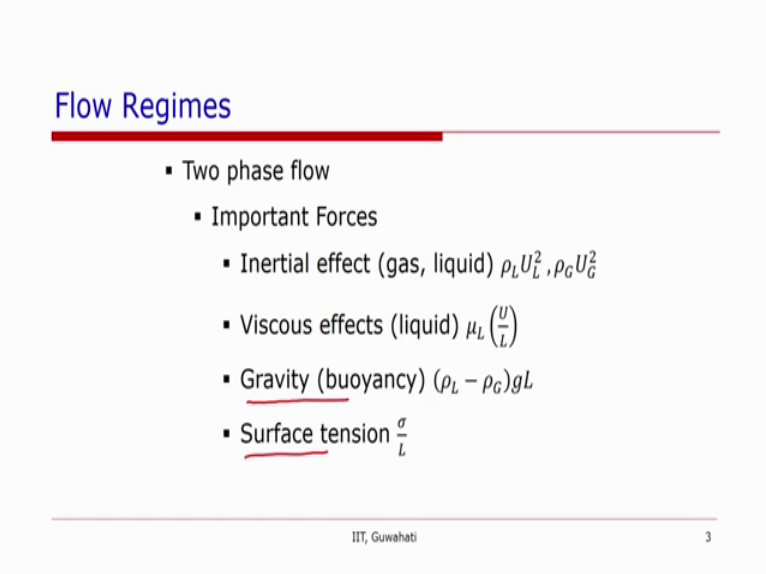

So now, moving on if we think about 2 phase flow, what else do we need to study in 2 phase flow? We already have inertial effects, but now we have 2 phases. So, depending on the phase flow rates, we will have the inertia of a gas, and inertia of liquid. So, we can have a inertial effects of a gas and inertial effects of liquid. Then we will have viscous effects, because viscous effects in general or at least in whatever we will be discussing in of flow in channels; viscous effects will be generally important for those of liquids.

So, we consider the viscous effects, one might consider because the viscosity of gas is sufficiently small or at least 1 or 2 order of magnitude smaller than that of liquid. Say, for example, if we are looking at water and air, the viscosity receives about 40, 50. Now one might argue that the inertial effects might not be important, or the gas inertial effects might not be important from the same argument. But in some cases, for example, in annular flow the gas velocity is very largeand the inertial effect is proportional to the velocity squared.

So, in such cases, where the gas velocity is very large the inertia of the gas and liquid can actually be of the same order of magnitude ok. The 2 additional effects which were not present in single phase flow are I have listed here, are gravity and surface tension So, the gravity one might say that the gravity is present for single phase flow. But because the flow is homogeneous a single-phase flow the properties are same everywhere. So, there is no buoyancy effect but when we have a body force, and there are 2 fluids, then because body force is a function of the density of the fluids. So, if the 2 fluids have different densities, then the 2 fluids will respond differently to this body force. For example, we have taken gravity here. But if there is a centri fugal force acting on the fluid, then the 2-fluid will have different response, because of this centrifugal force ok. Similarly, the other force is surface tension force. So, that acts at the interface between the 2 fluids, and that will be the stress by surface tension is sigma over l, and for buoyancy delta rho gl and that will be the stress.

So, these are the different effects that we need to consider, when we are looking at 2 phase flow. Now the things were simpler when we were looking at single phase flow, because we had only 2 effects. But now here even without considering any other effect for example, electrostatic force or magnetic forces, or centrifugal forces. We have our 2 more variables, or 2 more forces coming here. So, we have to consider all these forces. And this gives rise to different morphological patterns. So, that different morphological pattern means, the different arrangements of the 2 fluids in the channel of course, when these fluids are arranged in different manner they will affect the flow field as well.

So, we will have the flow to be laminar, and flow to be turbulent, we might also have that one phase is laminar, and another phase is turbulent, and they will interact and affect the other forces. So, it becomes very complicated for 2 phase flows and in 2 phase flow because the flow structure which is that how the 2 phases.

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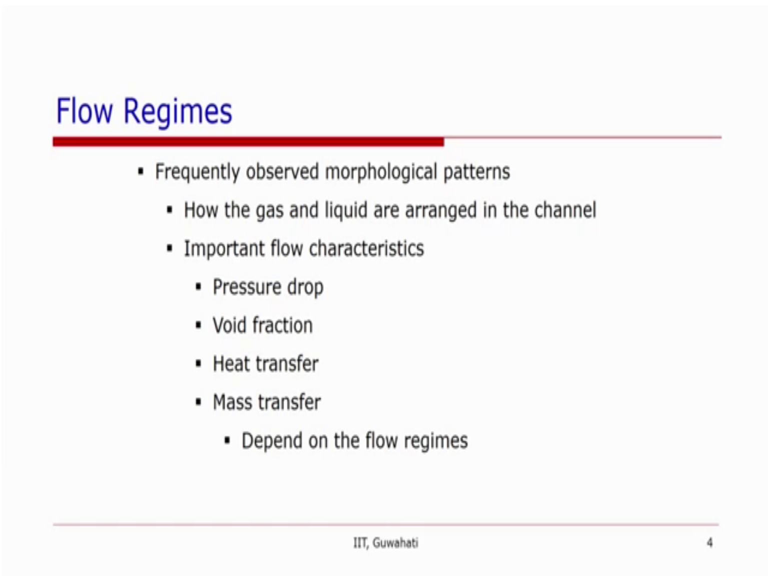

Because in this lecture we are talking about gas liquid flows. So, how the gas and liquid they arrange themselves will be a important criteria at the first end. But after that when we look at the modeling, we also need to understand the laminar and turbulent nature of the 2 fluids.

So, all the properties that are of engineering interest for us for example, pressure drop or energy loss or volume fraction after the fluids have been settled or the heat transfer. So, in a set number or mass transfer mass transfer coefficient and heat transfer coefficient, they all will depend on how the 2 phases have arranged themselves, while they are flowing through a channel. So, all these parameters depend on the flow regime. So, when we start looking at the 2-phased flow or gas liquid flow in a channel the first thing we need to look at that for a given set of conditions for the given set of a geometrical the channel geometry, what are the flow regimes that we are going to get.

Then we can study different flow regimes in detail, and try to understand; what are the different parameters of engineering interest, that we want to study or that we want to understand.

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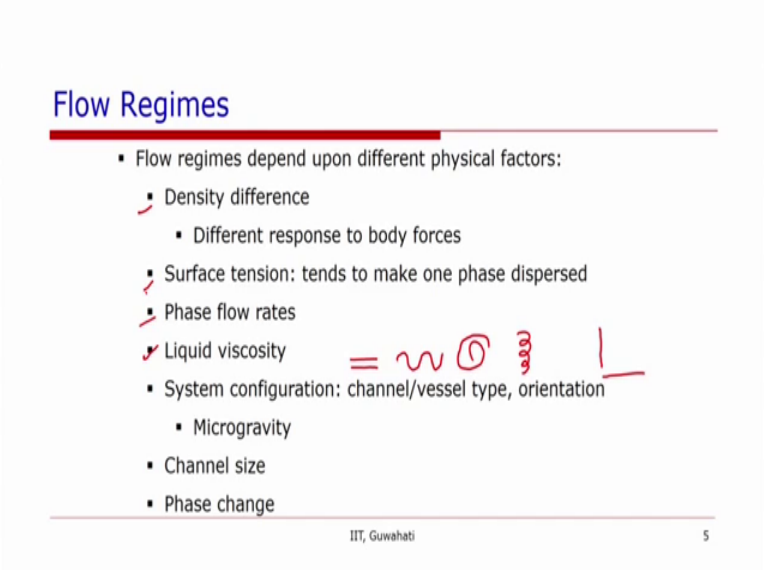

So, the flow regimes will depend on different physical factors, the first one I have listed here is density difference. So, as I said because of the density difference, the 2 fluids will respond differently to the body forces. So, the flow regimes will change, surface tension will again play an important role. And it will tend to make one phase dispersed.

Generally, for a gas liquid combination at a particular temperature one will have a constant surface tension. But if there are import is which are generally unavoidable in the in any industrial scenario. Then we will have surface tension variations also; which might affect the size of the bubbles for example, or the size of the droplets. And the temperature effects are there for example, if one has boiling or condensation then the temperature gradients in the fluid will also called surface tension gradient. So, that may have an effect on the flow regimes. Then one of the common things one will have is say phase flow rates.

So, depending on the gas and liquid flow rates, and the relative flow rates one will have different flow regimes. Generally, the flow regime map is plotted between the flow rates or superficial velocities of the 2 phases. It will also be a factor or it will also be a function of the velocity of the liquid because the gas velocity or the gas viscose effects are generally negligible. So, it will depend predominantly only on the liquid velocity again, the system configuration. So, what kind of channel one has exerted a straight channel or if it is a serpentine channel for example, or if it a channel of circular cross section, or if it is a helical channel, the flow regime will vary.

The orientation will also play a role. The orientation is connected with the effect of gravity. So, if you are doing these experiments on earth a vertical channel, and a horizontal channel will have a different responses to gravity. So, you will have generally the flow to be axi-symmetric if you have a vertical channel. But that will not be. So, in a horizontal channel, and if you have inclined channel then you will have depending on what is the angle of inclination. You will have different flow regimes.

So, extending over that, if you are doing those experiments on moon say; where the gravity is 1 by 6 that is on the earth, then you will have different effect of gravity. So, the flow regime map will change. So, people have done a lot of experiments for microgravity, where the gravity is almost negligible, and that is generally achieved by parabolic flights. So, people have done experiments in parabolic flight to understand the 2-phased flow behavior for space applications for example.

Then channel size will also have an effect and that is the reason exactly why we want to study here it for micro channels. And where if there is a phase change, so that means, if during the flow the phase is changing. So, the volume of that 2 fluids are changing, then we will have a different flow regime or we can even have a flow regime transition. So, considering all these effects we will not consider phase change right now, we will consider this during when we look at the boiling or evaporation. So, let us look at the different flow regimes.

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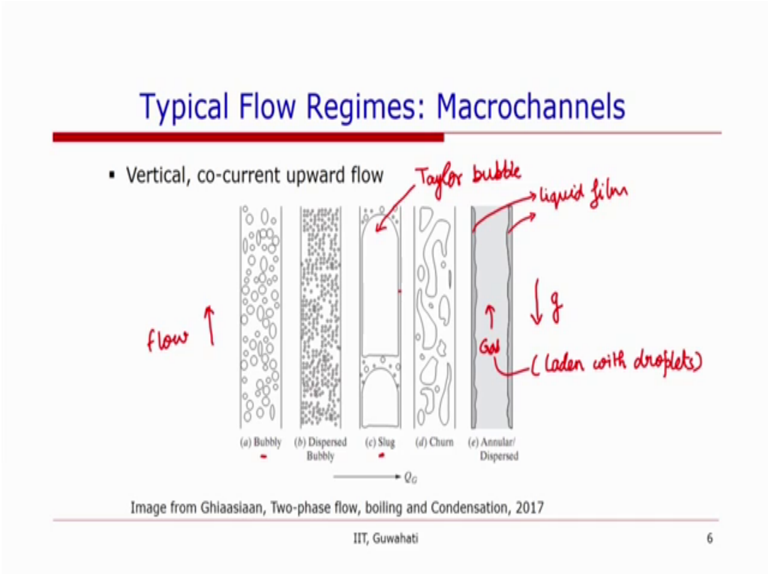

In conventional channels. So, if we have vertical co current upward flow. So, that means, the gravity is acting opposite to the flow, flow is happening in the upward direction, and the gravity will of course, act towards the downward direction. And depending on the gas and liquid flow rates, one will have a different flow regimes. So, in this typical flow regime map at a constant liquid velocity, if we have a small amount of gas introduced in it, then the bubbles will be generated and then these bubbles at low volume fraction of gas, these bubbles will start rising.

When you increase, further increase the velocity of the gas, then one will get slug flow; these bubbles will start increasing the velocity. And they the number of bubbles will increase and the number, when the number of bubbles will increase they will coalesce. And then they will become larger bubbles and then these bubbles, what we call generally it is important to know the name of these bubbles, they are generally known as Taylor bubbles. And they are very important in microchannels. So, it is better to understand and recognized them early on.

So, these bubbles Taylor bubbles are of the size of the channel, and there is a; very small thin liquid film, that separate them from the channel wall ok. Further increase in the gas velocity, we might have a churn flow, and once the velocity of the gas has increased to very high values. One we will have is annular or dispersed flows. So, where gas is in the core, and there is liquid film on the wall. We will also have this gas will have droplets into it. At high liquid velocities, specially when the liquid flow is turbulent, these bubbles are broken into a smaller bubbles, because of the turbulent effects of the liquid. And now one will have a dispersed bubbly flow where the bubble size is small.

So, that is finely dispersed bubbles in bubbly dispersed bubbly flow. So, these are the 5-major flow regimes that one can classify in a vertical co current of upward flow. There is this thing with the flow regimes in macrochannels, in microchannels that different people have seen different flow regimes. And at the transition, one will have a different flow structure coming into picture. So, sometimes of flow regime a same flow regime might be given a same name a one flow regime is given one name, by one sort of research and another name by another set of researchers.

Similarly, the 2 different flow regimes way which are morphologically different, might be given the same name by 2 different researchers. So, one need to understand and look into the flow regimes what flow regime is being talked about. But the research on say, a flow regime in macrochannels have matured and people have looked at into these flow regimes for last 60 years or so now, and they have agreed upon some of the broad flow regimes that are there.

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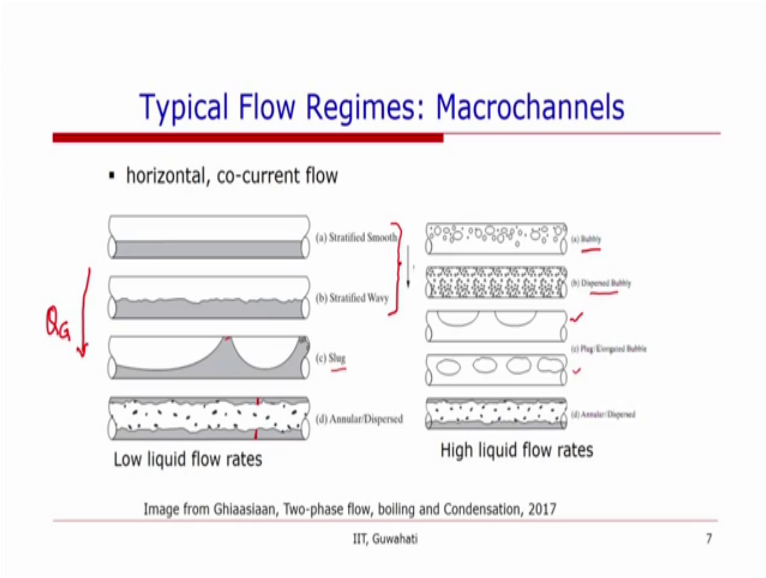

So, in the horizontal co current annular flow as one will think intuitively, that at low liquid flow rates one gets a stratified smooth flow. So, for example, we have the flow in the drains, where the liquid flows at the bottom and the air if it is flowing with a small velocity it will flow, and then the interface which is smooth.

When the gas flow rate is increased further, there will be some waves that appear on the on the liquid surface. And if the gas flow rate is increased further. So, all these flow regimes have been plotted with increasing gas flow rate. And if that gas flow rate is increased further then the amplitude of these waves will increase. And then one will once the amplitudes will increase, they will at one point they will start touching the wall. So, one will get slug flow. So, if you remember in the previous case we had slug flow; where the flow was axisymmetric, and the bubbles are not touching the wall.

Whereas in this case, we have the bubbles touching the wall, and they are not axisymmetric, but the same flow regime is termed as slug flow ok. At further high gas flow rates, we will get annular flow. Again, it will not be axisymmetric the film thickness at the bottom, and the film thickness at the top you can see from this schematic itself, that it is non-axisymmetric. The film will be thicker at the bottom, and actually there will be some drainage that might that will be happening.

So, when they have dispersed annular flow in which the gas code you will have droplets disperse, that is what have been shown here. Whereas, in the when the liquid flow rate is high. So, if it occupy the entire channel, then at low flow rates one will get bubbly flow, but because of the density difference and because of buoyancy, these bubbles will be first appearing at the top of the channel. If the gas volume fraction increases, and the liquid flow rate is very high, then these bubbles will be finely dispersed. So, one get dispersed bubbly flow.

Further on when the bubble volume or the gas volume fraction increases further, and then these bubbles will have to coalesce, because there is not much space for them to move on. So, this start coalescing and a slug flow, or what has been given as name as plug or elongated bubbles. So, one can have this flow structure, or one can have these bubbles separated from the wall but located towards the upper side of the channel. So, again Taylor bubble kind of a structure one will observe, and then again at high liquid flow rates one will have a high gas flow rates, and high liquid flow rates one will have annular flow ok.

So, you might notice here, that in the vertical flow we did not have stratified flows. In the vertically upward flow what we studied there was no stratified flow in the channel for the simple region, because the gravity is not acting in such a manner that it will allow or the buoyancy is not acting in such a manner that the phase separation can happen ok. So, this is one of the differences between the large channels was a vertical flow and horizontal flow.

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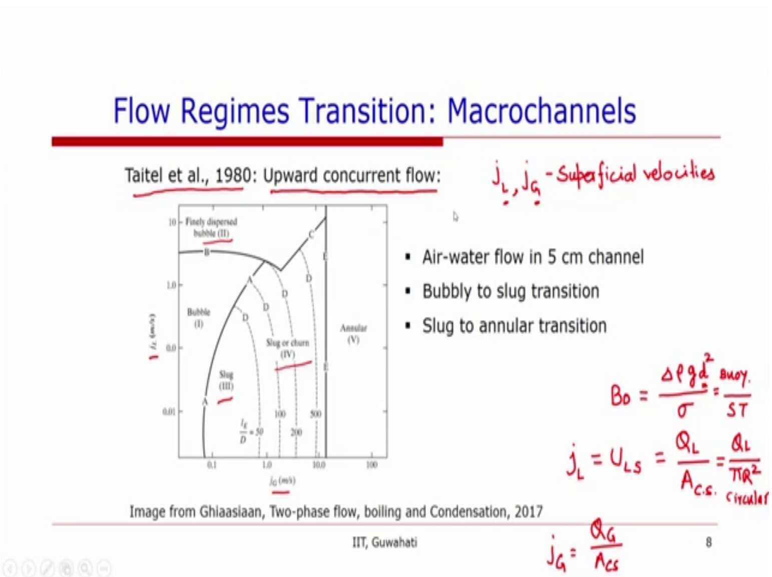

So, based on this now the question comes for example, one is looking at a particular flow, then the first thing in terms of the models or in terms of the prediction one would like to have that can I have a tool, where I can give my input parameters of the flows for example, gas flow rate, liquid flow rate, the properties of the fluids, viscosity, densities, and the surface tension, and the temperature, and a pressure conditions, and the channel size etcetera.

And one can is it possible to come up that for these set of conditions one is going to grant these flow regime. So, this is the first thing than one would like to have. So, based on those experiments that people have done over last 30, 40 years or maybe anymore, some flow regime maps have been prepared and one of the common and frequently used for upward co current flow. So, why we are studying only upward co current flow or why we will look at only upward co current flow, because there are some similarities in the flow in micro channels and upward co current flow.

So, as we have seen just now, that in the vertically upward channel, there was no stratified flow, and the flow was axisymmetric. Similarly, in the micro channel, the effect of gravity will be less ok. So, we will discuss that maybe in detail when we look at the flow in microchannels, but let us look at this delta rho g d square over sigma. And that is ratio of buoyancy and surface tension, because this is proportional to d. So, as the d becomes smaller, the effect of buoyancy will become smaller. So, at lower bond number; that means, when the buoyancy force the importance of buoyancy force start decreasing at lower bond number, and the effect of gravity will be reduced, and finally, become negligible as the channel size decreases.

So, some of the effect that comes because of that buoyancy effect for example, stratified flow asymmetric flow, that will be not observed in microchannels, which is similar to at least visually what we have observed in vertical channels. So, we will look at the upward co current flow and try to see if we can understand something from it which might be useful for flowing microchannels. So, this is a flow regime map. This has been plotted between jL and jG. So, where jL and jG are superficial velocities, L and G refers to the phase. So, jL is liquid superficial velocity, jG is the gas superficial velocity.

So, for those who do not know what a superficial velocity is the superficial velocity sometimes it is represented at jL, or it has also been reported as ULS. So, u liquid superficial, that is Q liquid divided by channel cross sectional area ok. So, if it a circular channel, then one can have QL over pi R square for a cylinder. Or maybe or this will be saying it as circulars only. Similarly, the gas superficial velocity, or jG is equal to QG over area of cross section. So, this flow regime map has been plotted between liquid superficial velocities and the gas superficial velocities.

And based on the occurrence of the flow regimes, they have plotted that at low liquid and low gas superficial velocity, actually a high range or a very large range of a liquid superficial velocities what one observe is bubbly flow at very high gas velocities what one observe is annular flow and in between one observes slug. And after slug one can have slug or churn. And very high liquid velocities one observe finely dispersed bubbles. And this flow regime map or representative flow regime map is based on after publication sorry Taitels publication in 1980.

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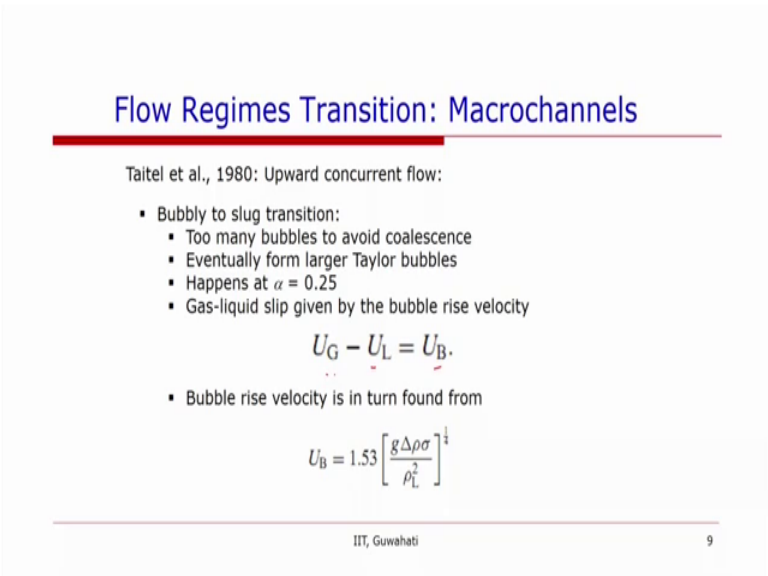

So, they have identified some of the transition regimes. Specifically, what we will be talking about here is bubbly to slug transition and slug to annular transition. So, from bubble flow to slug flow transition, which is this and slug to annular flow transition which is this. So, bubbly to slug transition, what happens that initially the bubbles are generated, and then they move. As the volume of the gas is increased, the number of bubbles will increase. And when the volume increases, so much that it is difficult to avoid the coalescence of some bubbles, then these bubbles eventually form and become larger than the bubbles. And Taitel has suggested that happens at volume fraction or homogeneous volume fraction of about 0.25.

Others have suggested that it happens about 0.3. So, that is about the range 0.252, 0.3 when this transition happens. Now because the gas liquid slip; so, slip means that if there is no slip between the gas and liquid, then the gas will be moving with the same velocity as that of the liquid, and that will be true for when the bubbles are finely dispersed because these bubbles in the flow around these bubbles between the stokes flow regime. And they will respond quickly to the fluid and you will have that they will move with the same velocity as that is of the liquid.

But for larger size of bubbles, there will be a certain amount of slip and mostly in general the bubbles will rise especially in the upward flow the bubbles will rise faster than the liquids. So, this slip is defined here, that UG minus UL is equal to the bubble velocity. So, the bubble rise velocity is defined by UG minus UL or slip between the 2 phases is given by the bubble rise velocity. And this bubble rise velocity from the literature, it can be found as a ratio of delta rho G sigma, over rho L square to the power 1 by 4. So, when this is the bubble rise velocity.

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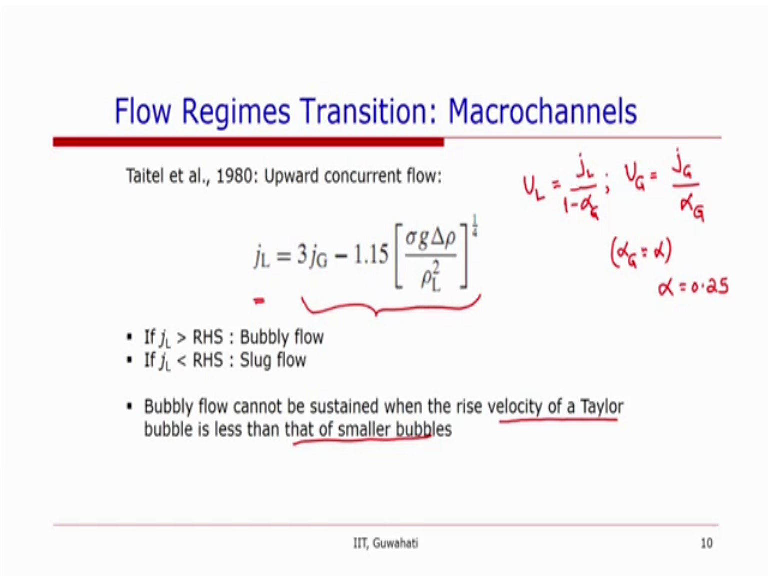

And one substitute the bubble rise velocity, and the fact that UL which is liquid velocity is equal to jL a superficial velocity over alpha and UG is equal to j G over alpha which is alpha is the one reflection of gas, and this is one reflection of liquid.

So, let us write this is 1 minus alpha G or you know we can just write alpha as alpha G is equal to alpha. So, you are going to substitute. So, when we substitute this here, and then take alpha is equal to 0.25 one will get this expression. So, from this if the liquid superficial velocity, when come one can compare the 2 terms; which is liquid superficial velocity on the left, and this term on the right. if the liquid superficial velocities is greater than the right-hand side, then one gets a bubbly flow, and if the liquid superficial velocity is less than the right-hand side, then one gets slug flow.

Another observation that has been made and it is relevant for us that this bubbly flow cannot be sustained, when the rise velocity of a Taylor bubble is less than that of the smaller bubbles. So, if somehow there is a bigger bubble a channel size bubble has been formed. So, that means, the volume fraction is already significant. And when this larger bubble has been formed, and it is moving slower than the smaller bubbles then what will happened these bubbles will come and entrain into the larger bubble, and when we will get a larger table Taylor bubble forming.

So, that simply means that when that has happened that, the bubble velocity is larger than the Taylor bubble velocity, then the bubbles will or will not be sustained and they will merged into the tailor bubble ok. So, they have suggested this or they have pointed out Taitel et al that it is difficult to sustain bubbly flow in smaller tubes.

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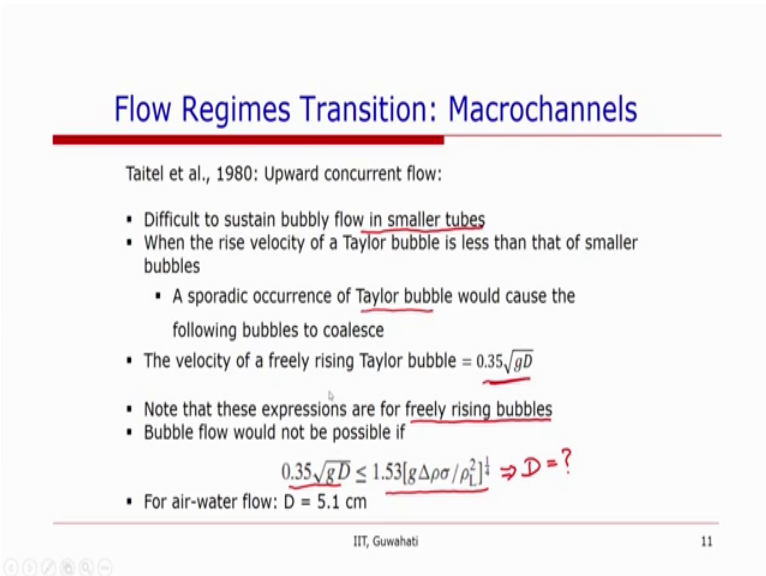

And when the rise velocity the same fact than the when rise velocity of a Taylor bubble is less than that a smaller bubble is sporadic, that it sometimes once upon you know once in a while occurrence of a tailor bubble. That will caused the bubbles to coalesce and the tailor bubble flow will there.

So, the velocity of a freely rising Taylor bubble because of this in a quiescent liquid just because of buoyancy the velocity of a rising Taylor bubble is given by 0.35 root gD ok. So, you will need to remember, that this is for freely rising bubble that is why it is only the function of gravity and the channel. And so, that means, we have an estimate for the bubble rise velocity in a channel, which is a function of the channel diameter. And the bubble velocity that we have seen just before that this bubble velocity can be given by this expression.

So, if the Taylor bubble velocity is less than the bubble rising down velocity, then we will not have a bubbly flow. So, the next question will come to mind ok, let us find out what is this D. And it turns out if you substitute this the D is 5.1 centimeter for a freely rising bubbles. So, but remember that this condition depends on that one should have a sporadic occurrence of Taylor bubble. So, once you have a significantly large bubble, and which can be Taylor bubble, which can have this velocity, then one will have this thing be valid ok.

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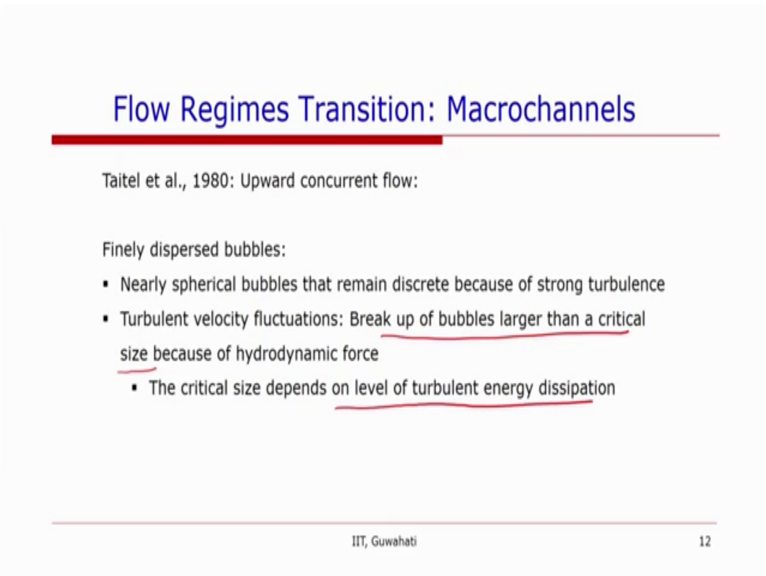

Now, looking at finely dispersed bubble, which is the boundary between the 2 bubbles, or the finely dispersed bubble; and the bubbly flow and slug flow, then this when can this happen, that these bubbles are nearly spherical bubbles, and then they remain discrete because of a strong turbulence effect. So, there are bubbles when the liquid is a strong the turbulence is strong in the liquid the inertial effects are high the fluctuations they break up the large air bubbles.

So, the larger air bubbles are broken because of the turbulent effects, and at a beyond a critical size these bubbles are break up because of the hydrodynamic forces or the inertial forces or the turbulent fluctuations. So, this critical size of the bubble will depend on the level of turbulent energy dissipation containers in factors that we have. So, in non-dimensional numbers that can be a Weber number.

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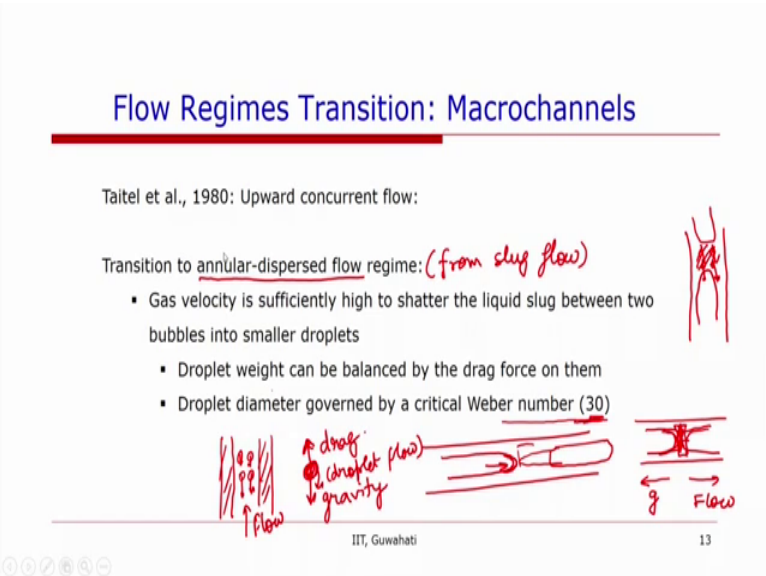

Then another important transition, for us is annular to disperse all or from slug to annular from slug flow, to annular flow or annular disperse flow regime transition, that will happen, because when we have Taylor flow then we have the gas bubbles which are of the size of the channel and they are arranged in a periodic manner and between 2 bubbles are the liquid slug.

So, as the gas volume will increase what will happen? The size of this bubble will become larger and larger, and the liquid that is there between the 2 bubbles or 2 conjugative bubbles, the size of that liquid or liquid slug will become a smaller. So, eventually because the gas velocity is becoming higher, when we move from slug flow to annular flow, the gas inertia will be larger. And this the shape of the bubble, what we have is say, the bubbles shape is like this, and there is a bubble at the front which is like this. And this shape is because of surface tension and the inertia is a thing rho u square.

So, at a particular and we increase the gas inertia. At a particular Weber number, the gas inertia will be able to overcome this the diameter the that will overcome the liquid bridge that is there between 2 bubbles, because when before coalescence or just before transition, when we have something like this.

So, this liquid will be broken up. Now the other thing is the other factor that comes into factor the other effect that comes into factor, that gas velocity is sufficiently high to shatter the liquid slug between 2 bubbles into smaller droplets. So, what will happen when this liquid slug when it is thicker let us say is sufficiently thicker. Then if the gas inertia is sufficient and it can break it up a smaller droplets, and then these droplets can be sustained.

So, remember we are talking about vertically upward flows if we are talking about vertically upward flow, then the gravity is acting in this direction, and the flow is happening in this direction. So, for a vertically upward flow, this is my bubble and this is the tail of another bubble. And this liquid is breaking up, when it will break up it will have a smaller droplets. So, because of buoyancy because of the gravity these drops will start dropping down, because when that happens one will have a annular flow. And in the annular flow one will have gas.

So, they will because of the gravity these droplets will try to come down. So, they took at a droplet it will have a gravity acting on it and it will have a drag because the flow is happening in this direction. So, the flow overall flow is happening in this direction when the droplets will try to come down. So, this is droplets flow direction. So, the drag on the droplet will be acting in the opposite direction. So, when the drag is sufficient, that these droplets can be held there. Then or can overcome the gravity, only then this flow regime can be sustained.

So, there is a critical Weber numbers what he gave that at a Weber number of 30, this can happen the droplet weight can be balanced by the drag force. So, that transition to slug annular slug to annular flow regime happens ok.

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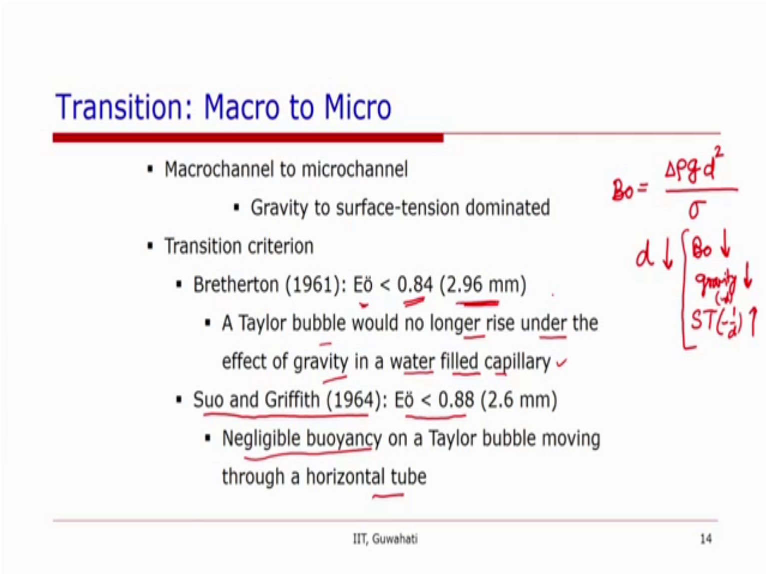

Now so, based on this what we have learned until now is the flow regimes in large channels and the different flow regime transition criteria more specifically we have looked at, the transition criteria from bubbly to Taylor flow, or bubbly to slug flow and from slug to annular flow.

Now, in this the slug and slug annular have been merged together, or the slug and associated flows what Taitel map has a slug or channel flow they have been put together ok. So now, what we just briefly discussed before that, when the transition is from large channels to small channel, the relative importance of the gravity force and surface tension force will change. So, when d decrease bond number will decrease, gravity will gravity effect will be lesser dominant and surface tension effect which is proportional to 1 over d and this is proportional to d.

So, they will be dominant. So, based on this there are 2 transition criteria that have been discussed in the literature. So, for example, Brotherton in his classical paper he said that the Eotvos number; which is same as bond number, and if the Eotvos number is less than 0.84, then a Taylor bubble would no longer rise under the effect of gravity in a water filled capillary. And this, the for a air water flow the channel diameter corresponding to this comes as 2.96 mm. So, he has given this and the and say transition from where one can start looking at that what flows is start dominating. So, a Taylor bubble would no longer rise under the effect of gravity in a water filled capillary. Then the another criteria has been given by Suo and Griffith in a 1964, where they said that when the Eotvos number is less than 0.88, very close to one Brotherton has predicted.

The buoyancy on a Taylor bubble moving through a horizontal tube can be neglected. So, they were looking at a horizontal tube. Whereas, they were looking at the a vertical channel and the criteria that they have suggested is quite there.

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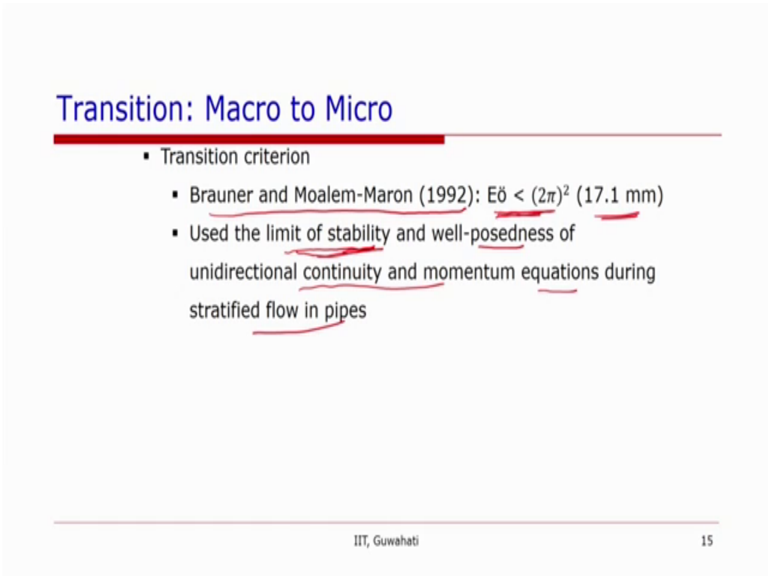

Then another work that was done by Brauner and Moalem and Maron and they suggested I mean what they were looking at the stability and well-posedness of unidirectional continuity momentum equation is stratified flow in pipes. And they have suggested, that the stratified flow will be observed, this the it will be stable only when Eotvos number is less than 2 pi square with 17.1.

So, they have not suggested than the stratified flow will not occur, only on the limit of the stabilities are in this number, that the transition happens. So, one can see from there that and about few millimeters. specially the one that the limit has been given by Suo and Griffith and by Brotherton, that when the when these effects or the microchannel effects or the size effect to small diameter size effects, have started coming into picture is at about few mm. And they have they have both are saying that about between 2 to 3 mm one can see such effect for air water flow.

I would like to talk about another effect, or another type of channels, which are not micro channels. But it is important or they are relevant the flow regime in these channels, or under these conditions is important, to understand the micro channel. Because there have been lot of studies on micro gravity effects. So, people have gone into parabolic flight done the experiments and try to analyze the data.

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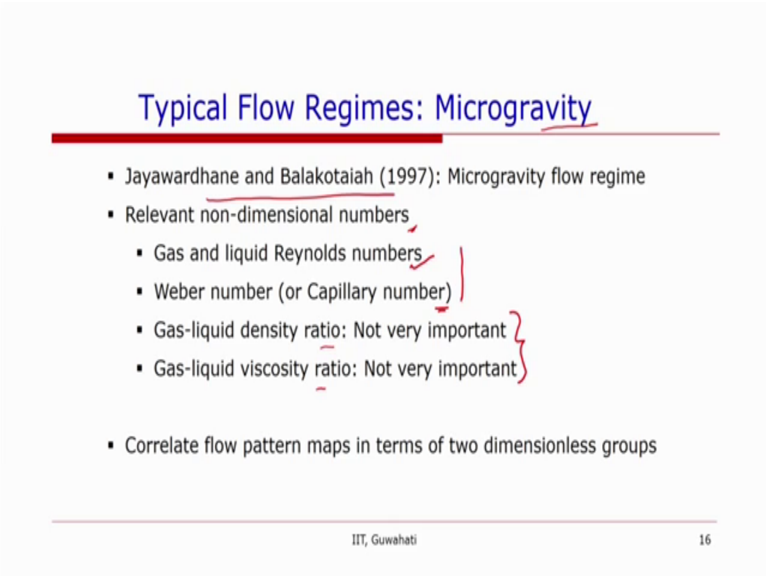

So, one of these studies has been done by Janardhan and professor Balakotaiah in the microgravity conditions where the effect of gravity are not present. And what they observe generally they are all the effect of gravity is not present.

So, then relevant non-dimensional numbers depending on the physical effects, that are present we have gas liquid Reynolds number and the so, gas inertia and liquid inertia. And the Weber number or by combining this Reynold number one can have capillary numbers. So, either of those, and the gas liquid ratio and viscosity and density usage but these 2 things do not seem to have much effect, because the gas liquid ratio and gas liquid density and viscosity ratio they do not seem to have much effect on as a variable on the flow patterns.

So, they correlated the flow pattern in terms of these 2 dimensionless groups. So, if you go back to our few slides back, and the at the start of this lecture when we talked about that there are a few effects present the inertial force is viscous forces and the gravity and surface tension forces. So, in microgravity there is no gravity present. So, one is looking at the inertial forces, inertia might be of the gas inertia might be of the liquid. So, those Reynolds numbers, and the Weber number which is the inertia and a surface tension

So, it is taking upon taking into account the viscous forces, inertial forces and the surface tension forces. So, based on these dimensionless groups they have tried to correlate things.

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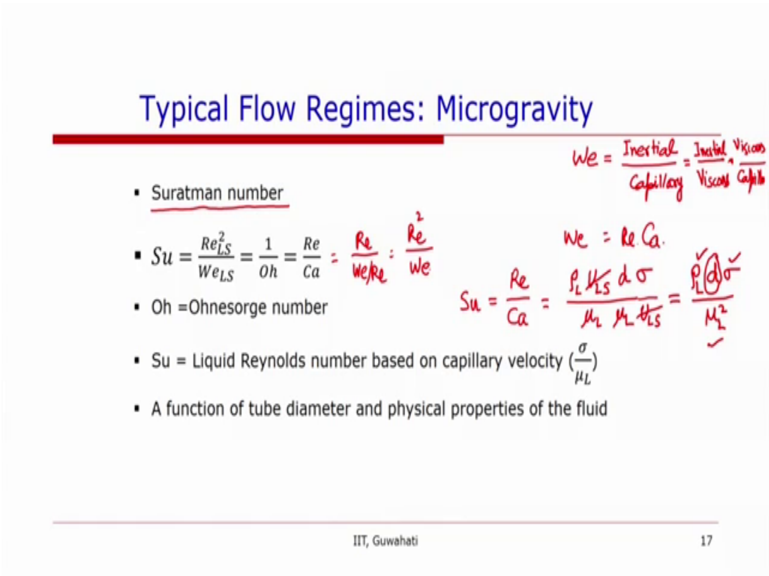

Now another non-dimensional number using this they have plotted the flow regime map is called or what is called as Suratman, Suratman number; which is the ratio of Reynolds number and capillary number or Reynolds number by a Weber number. So, one can look at say you have to see the relationship of these numbers.

So, Weber number is inertial forces, or inertial effects divided by capillary effects. We can also have that surface tension ok. Now if you divide by viscous force viscous here. So, one will have inertial divided by capillary sorry, inertial divided by viscous multiplied by viscous, divided by capillary, then we will have the Weber number is equal to inertial over viscous is Reynolds number into viscous or capillary is a capillary number. So, we have this Weber number is equal to Re into Ca. So, this Sutratman number is Re over Ca if we substitute that here, when this becomes equal to Re over Ca is equal to Weber number over Re. So, that will becomes Re square over Weber number.

So, one can use either of this definition and this is also 1 over Ohnesorge number; which is also frequently used. And let us see what we get this in terms of properties. So, if we write Su is equal to Re over Ca mu, sorry Re is rho L u LS diameter over mu L divided by mu L ULS sigma. So, the velocities will be cancelled out. And what one will have is rho L d sigma over mu L square. And one can see that rho L sigma and mu are mu L are properties from the fluids. And d is the channel diameter. So, this is not a property of the fluid velocity, but the properties of the fluids and the channel diameter ok.

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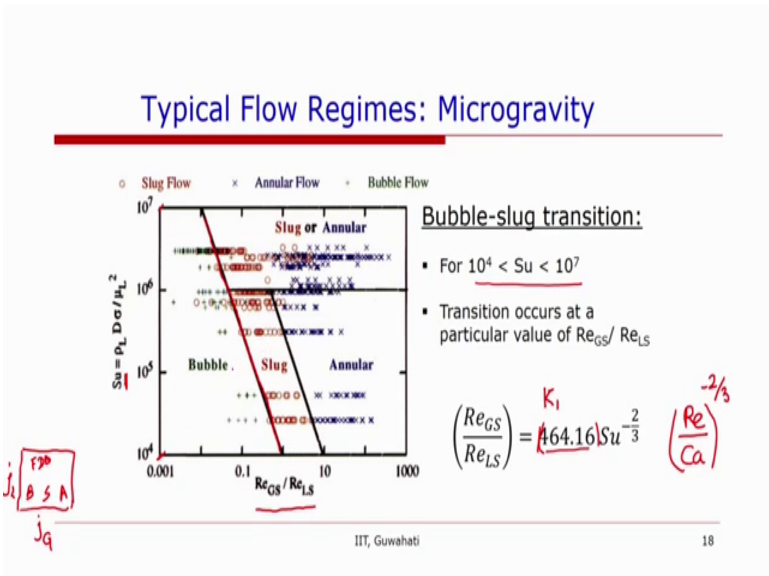

So, they have plotted a flow regime map based on; remember, just to remind you that the earlier flow regime maps that we have seen is based on gas and liquid superficial velocities. So, jL and jG that we have for lateral and then there we have different flow regimes in bubbles slug annular and they are finally, we will discussed ok. So, what they observed that in this of course, there is no gravity. So, they did not observe that is stratified flow. They had bubbly flow, slug flow, annular flow and they also had a what is the transition regimes. So, sometimes you call it wavy annular or slug annular. So, they have this.

But in this the in this flow regime they have not shown those transition data points or they have not taken into account those transition data points. So, they have plotted this on the x axis the ratio of 2 Reynolds number. So, the ratio of a gas Reynolds number and a and liquid Reynolds number, with the Sutratman number, the Sutratman number for the conditions they have done the experiments, it comes from 10 to the power 4 to 10 to the power 7. And look at this line which is the transition line between the bubble and slug.

So, this line when they have identified in 2 different regimes. So, you can see here, that this transition occurs at a particular value of ReGs by ReLs. So, this the slope on this line that they have found is ReGs by ReLs is equal to 464 point. So, this is some constant and you can call that or one they have called it as k 1. And then by looking at the experimental data from this value to be 464 and this is Re over Ca. So, this is Re over ca power minus 2 by 3 Ca power 2 by 3 is an important factor when we look at Taylor bubble. So, I would like to remember it that that this power is 2 by 3.

So, this and the slope of this line is given that. So, all the range of Sutratman number whatever they have studied from 10 to the power 4 and 10 to the power 7. The transition between bubble and slug happen. Or it can be given by this line for slug annular transition.

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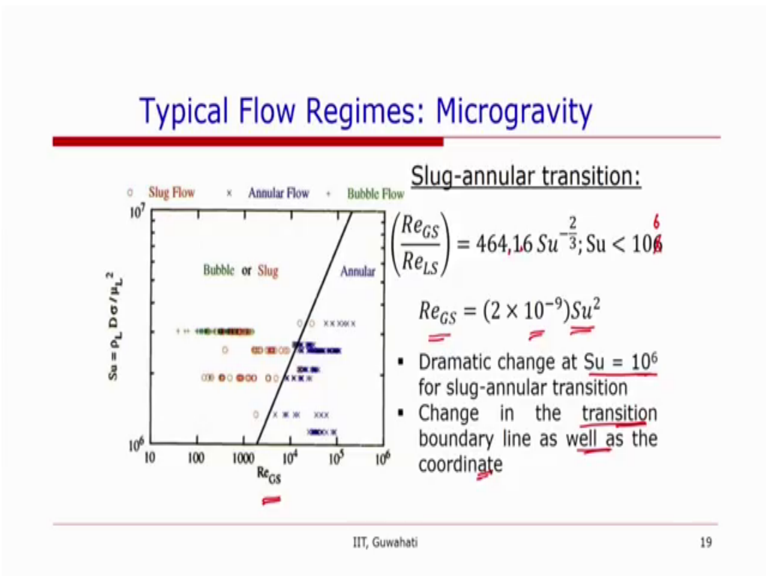

So, if I go back and look at this slug annular transition there are 2 different behaviors at about 10 to the power 6, you have a similar line which is parallel to this and you can keep this transition by a similarly one.

However, for the other case, which is 10 to the power 6 when the Sutratman number is more than 10 to the power 6, there is a different this does not if we extend this line. This does not really define the transition between slug and annular flow regimes. So, they have looked at this more closely and plotted this graph now between Sutratman number but on the x axis only the gas superficial velocity. So, this dramatic change had happens at Sutratman number of about 10 to the power 6. And then again, they have been able to plot a line which gives that Reynolds number is proportional to Su square ok.

So, one might see that this number is very significant, but then one have to look at sorry this is 10 to the power 6. And one get this value I think this is 464 1.6 10 times of that; and this is ReGs is equal to 2 into 10 to the power minus 9 Su squared. So now, this ratio is 10 to the power 6. So, this numbers is going to be significant 10 to the power 12 or more. So, this will be 2 into 10 to the power 3 or more ok. So, this dramatic change happens at about Sutratman number 10 to power 6 for slug and annular transition.

Now, changing the transition boundary line what happens that at 10 to the power 6 Sutratman number a change in the transition line as well as the coordinate ok. So, this was the transition criteria for a microgravity regime. So, what we have looked at in summary today ah.

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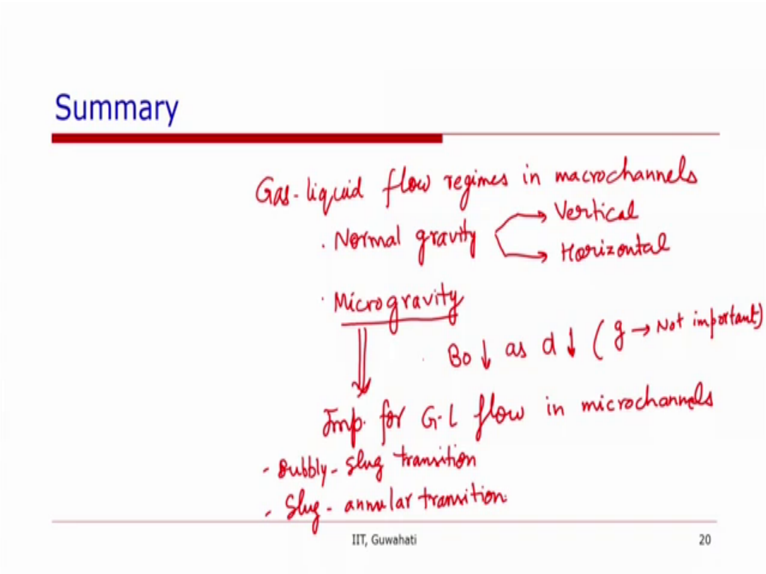

Gas liquid flow regimes in macrochannels under 2 conditions, one is normal gravity, and in the normal gravity we have looked at channel orientation is vertical and when the channel orientation is horizontal. The other one is microgravity.

So, one can look at the flow regimes under these 2 conditions. Now we also looked at that in micro channels the bond number start decreasing as channel or in not what we should say that. the bond number starts decreasing d as d decreases; that means, gravity not important. So, the lessons that we have learned for microgravity that might be also important for gas liquid flow in microchannels.

We have looked at the flow regime, but we have also looked at the transition lines. So, what we have looked at bubbly to slug transition and slug to annular transition. and I believe that these 2 transitions are most important, because the slug flow is the most important flow regime in which people want to work in a microchannels. So, in order to maintain slug flow regime, one need to know the both the boundaries; when it can go to bubbly flow, and when it can go to annular flow. So, in the next class, we will look at in detail the flow regimes in microchannel ok.

Thank you.