Adiabatic Two-Phase Flow and Flow Boiling in Microchannel
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Lecture – 06
Pertinent Dimensionless Numbers in Two Phase Flow

Very good day to all of you, before I processed further, we have already learned the criteria for confinement and how and rather the dimensionless groups or dimensionless number will define the micro channel. Now I would just like to be little more systematic and first discuss the different important dimensionless groups which are important for micro channel flows.

Now, when I would be talk about any flow system flow of water through a pipe whatever we talk about the first dimensionless group which comes in our mind is the Reynolds number right? What is Reynolds number? As all of us know it is basically the inertial force ratio of inertial force.

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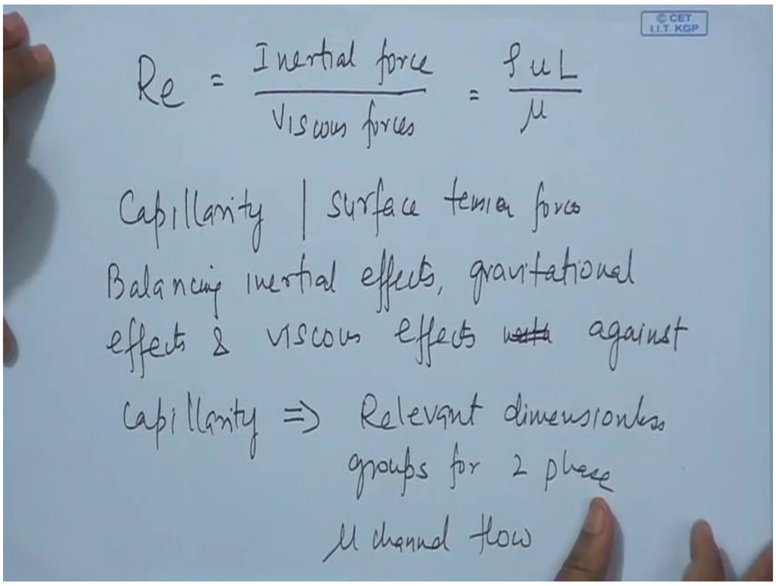

And viscous forces usually we define it in terms of some particular average or characteristic dimension, some particular average or characteristic length and the fluid properties. This has been very important in single face flows primarily because it gives us criteria of transition between the laminar and the turbulent flow pattern we know it. Whenever we talk of single face flows Reynolds number is the first dimension group which come our mind.

Let us see whether Reynolds number is equally important for this particular case or in other words what are the other numbers which come into picture for micro channel flows. Now whenever we are talking about micro channel the most important force which come into being is can be said as capillarity or the surface tension forces and viscous effects with or against should be against capillarity well from this particular balances should evolve the relevant dimensionless groups for two phases. Micro channel flow is not it this is something very logical that in micro system inertial force and viscous forces are important.

Naturally Reynolds number came up as a consequences whenever we are going to the micro scale naturally, we have been discussing we have bored by hearing that surface fluids has become important as compare to gravitational forces etcetera. So, naturally surface tension forces should be dominating here. Therefore, other forces they should be balanced against the surfaces tension forces and only from those balances we should be getting a proper representation of the different dimensionless groups.

Also we have come to know that rather in the last to last discussion. We also come to know that in micro channels the major flow pattern is the pluck flow pattern and then under very high gas velocity we come across to the annular flow pattern, now in annular pattern what we have seen there is a gas core and the thin liquid film and in pluck flow there are short plucks which occupy the entire characteristic dimension right? So, therefore, keeping this in mind and balancing the different forces we come across the different dimensionless groups which should be pertinent for micro channel flows.

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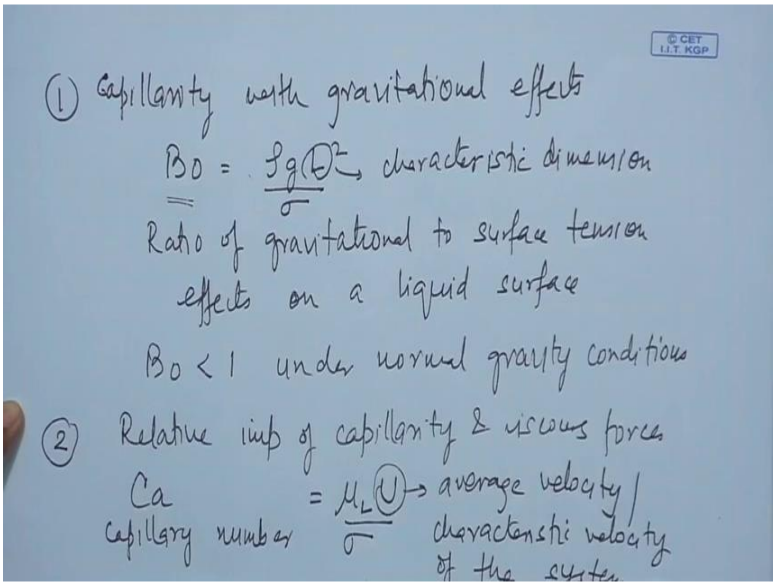

Now, suppose we balance capillary against say the gravitational effects then in that case, what do we get maybe suppose we balance your capillarity with gravitational effects we have already come across this particular number which, we call as the bond number and this actually define as row gL square by sigma where this particular L this is a characteristic dimension for most of the cases it is the tube dimension or a contour dimension and this gives us the ratio of gravitational two surface tension effects on a liquid surface right. So, from here we can know that when gravity will be dominating over surface tension and vice-versa.

Now, from here it is very evident that low bonds number can be attend either by reducing very sorry increasing sigma or by reducing g. Therefore, low rather small bond number systems can be achieved either under micro gravity conditions or by decreasing the channel length. For example, the situation which happen under capillary tubes, therefore, usually the characteristic length is define such that under normal gravity conditions bond number is less than one this is the primary group for micro channel flow. Therefore, this can be achieved as I have already said under micro gravity condition or for very low dimension for normal gravity condition and so, whenever still now you have seen whenever, we are defining a micro channel it was on the bases of bond number, but if you observe the particular expression you will find that it is applicable for a stationary or a static system it does not have any velocity component in it. Therefore, although can define micro channel flow, but it does not say anything about the flow characteristic in a micro channel for that, we need to introduce the inertial term or we need to have some particular velocity term.

For achieving that the most other the most commonly used number is which discusses the relative importance of capillarity and viscosity this is the most pertinent viscous forces, this is the most pertinent non dimensional group in flow system and this is non as the capillary number define as mu liquid u by sigma, where u is some particular characteristic or average velocity average velocity or characteristic velocity of the system.

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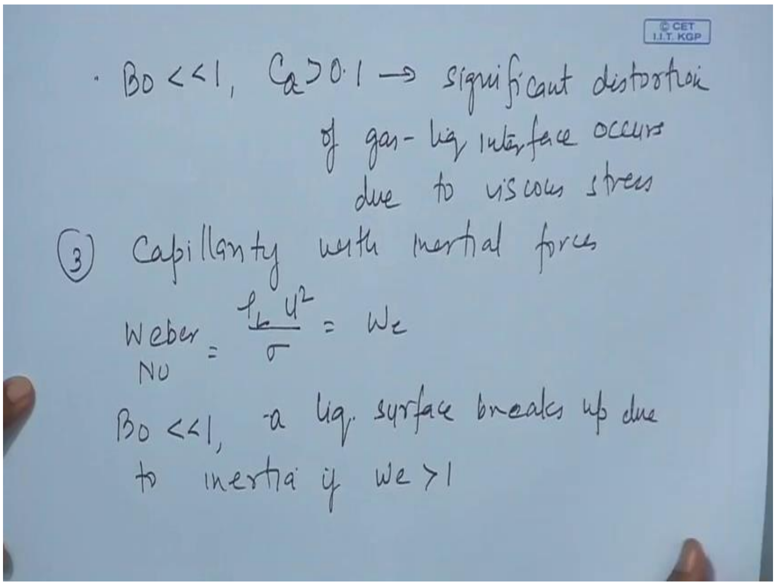

We find that more or less when we have a small bond number much less than one and your capillarity number greater than 0.1 for what do what happens significant distortion of gas liquid interface occurs. While due to viscous stress is not it. We find that when bond number is for low bond number system only suppose capillarity number is much greater than 0.1 than only its naturally that shows that viscous effects are much more important sense viscous effects are much more important it quit natural that the gas liquid interface the sufficient distortion occurs due to this particular reason.

Now, this was my balancing capillarity and viscous forces the next thing, which we can do is we can balance or we should be balancing capillarity with inertial forces what does this give us in this particular situations, we find this gives us a number as row l u square by sigma which is which can be define as the weber number I do not know whether you are familiar with this number or not this gives a major of inertial effects to capillarity effects again for small bond number systems when bond number is much less than one. We find that when weber, number is high what should happen inertial forces should dominate and the liquid surface should breakup is not it. For small bond number systems a liquid surface breaks up due to inertial, if weber is greater than 1. While capillarity number it showed us that significant distortion of gas liquid interface occurs due to viscous stress or other in words good amount of waviness sets in on the same time weber number tells us that liquid surface will break up due to inertia. If weben number is high well, these were the important numbers, if you observe here the weber number the capillary number and Eotvos number which are useful for micro channel flows.

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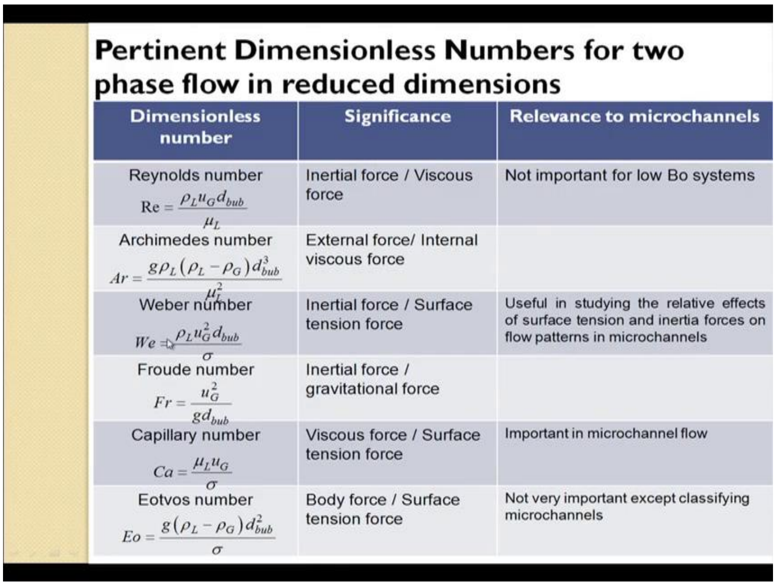

Pertinent Dimensionless Numbers for two phase flow in reduced dimensions

Dimensionless number	Significance	Relevance to microchannels
Reynolds number $Re = \frac{\rho_L u_G d_{bub}}{\mu_L}$	Inertial force / Viscous force	Not important for low Bo systems
Archimedes number $Ar = \frac{g\rho_L(\rho_L - \rho_G)d_{bub}^3}{\mu_L^2}$	External force/ Internal viscous force	
Weber number $We = \frac{\rho_L u_G^2 d_{bub}}{\sigma}$	Inertial force / Surface tension force	Useful in studying the relative effects of surface tension and inertia forces on flow patterns in microchannels
Froude number $Fr = \frac{u_G^2}{g d_{bub}}$	Inertial force / gravitational force	
Capillary number $Ca = \frac{\mu_L u_G}{\sigma}$	Viscous force / Surface tension force	Important in microchannel flow
Eotvos number $Eo = \frac{g(\rho_L - \rho_G)d_{bub}^2}{\sigma}$	Body force / Surface tension force	Not very important except classifying microchannels

Now, if you observe the Reynolds number which I already written down here, you will find that in the Reynolds part we have the inertial forces as well as the viscous forces now we observe that Reynolds number. It does not give a very good representation of the flow in micro channels the primary reason being the length parameter and the average velocity parameter that we select to define Reynolds number, they are not very appropriate for micro channel flows.

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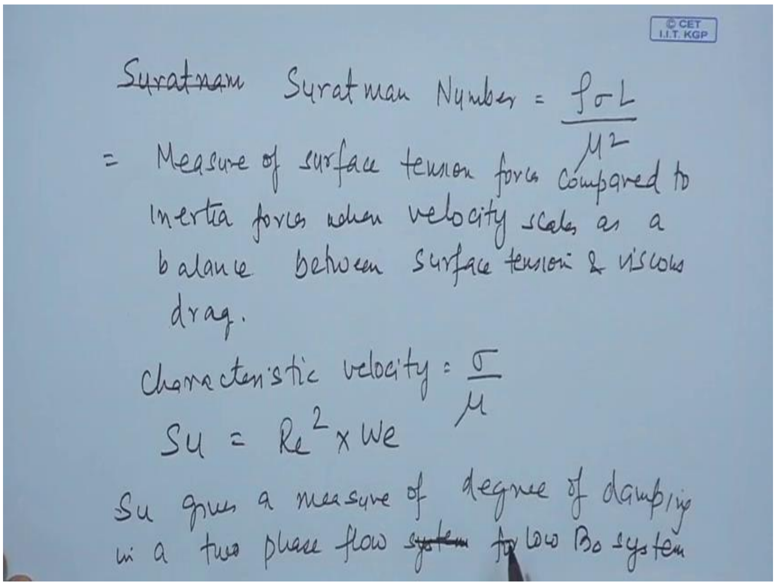

On the other hand, there is another number which is now as the Surat number this particularly number, Suratman number sorry it is not nam, it is su I will write it properly it is Suratman number. Now this number you find that this is the very interesting number this number is basically define as row sigma l by mu square this is actually it can be referred as measure of surface tension forces compare to inertia inertial forces. When velocity scales as a balance between surfaces tension and viscous drag what does it means in other words it means that in the Reynolds number, if we replace the characteristic velocity of Reynolds number with sigma by nu then we get this particular Suratman number. Therefore, the thing which I was telling that Reynolds number is not appropriate for two phase flow in macro channels primarily because, it does not capture the physics of the flow in this micro channel system this is because, the characteristic length and the average velocity which we select for defining Reynolds number are not suitable for micro channel flows.

On the other hand if the velocity is replaced by the capillary by the velocity in the capillary number that it is replaced by sigma by mu than we find that, this Suratman number this gives us a much better representation of flow characteristics in macro channel flows and if you observe the number you will find this is nothing, but Reynolds number square into weber number. So, therefore, this gives a very good idea about the major of surface tension force compare to inertial forces when the viscosity as define as a scaling parameter between surface tension and viscous track. So, it is nothing it basically its Reynolds number define with a proper characteristic velocity now if you observe this number very well what do you observe you observe that the number this Sumatran number it gives a measure of degree of damping in a two phase flow system for low for a two phase flow low bond number system is it clear to you? What we find is that this particular Suratman number it has got several particular physical interpretation one is the number the physical significance then it is basically Reynolds number with u, replace by sigma by mu thirdly it is Re square into weber number and in general it gives us a measure of the degree of damping in a two phase, system provided it is operating at low bond number.

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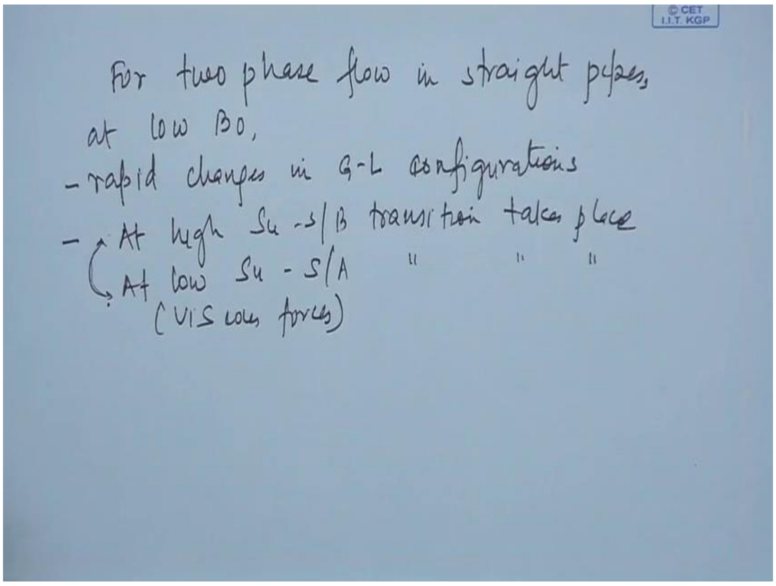

For low bond number system what do we find that if, two phase occurs in a straight pipe write for two phase flow in straight pipes at low bond number. We find that rapid changes in gas liquid configuration take place or rather flow pattern they keep flow pattern they keep on changing and what happens we find that at high Suratman number slack bubble transition take place is not it and at low Sumatran number your slack annular transition take place why because, we find that at your high Suratman number and low bonds number what happen the pinching effects it forms. So, when we have low Suratman number it means that viscous forces are important and as a result of which we find that under this particular condition you are the annular flow it breaks down to form slack flow. Therefore, 1 particular range of Suratman number should define the range of existence of the slack flow pattern if the number is higher than that, then the slack bubbles they break-off to rather the liquid inertia is sufficient to break off the slack bubbles into smaller bubbles and form bubble flow. If the number is below any particular critical number than under that condition viscous forces start dominating and the annular flow is form with continues gas core and the your continues gas core and then annular liquid film.

Therefore, we find just like Reynolds number was. Very important in micro scale flows Suratman number almost assume and equal importance for micro channel flows now after this we would just like to see initially, what we did in the first place we define or rather we discussed the importance of micro channel flow we discussed the specialties of the different flow pattern which occur in micro channel micro channel flow. Now there are two aspect we should remember first thing we should know what is the distributions just like in lamina sorry in single face flow, we should know what are the distribution we know that distribution can be either laminar or it can be turbulent. If the distribution is laminar we would be using the relationship of friction factor as f equals to sixteen by Re if it friction factor or 64 by Re if it is drasy friction factor and suppose the flow is turbulent we have an large number of equations any of them we can use.

And next thing is when should we use Fitch equation or in other words when will be the flow be laminar. If the flow is laminar what is the equation we know, but when will the flow be laminar and when will the flow be turbulent or in other words what is the critical Reynolds number to identify the transition between the two we usually depict this as moodies plot which plot r versus Re. Now similarly in 2 phase flow it is very important to know what are the different distributions along with that it is very important to know when each distribution exist, that we can know that when the flow condition are, and so. We would aspect this particular flow pattern and accordingly some specific word fraction and pressure drop model is going to be applicable for that case, now in order to range of existence of the different flow pattern usually two dimensional plots are adopted these plots with suitable coordinates they identify or they divide a 2 dimensional area into different regions were each and every flow pattern exists.

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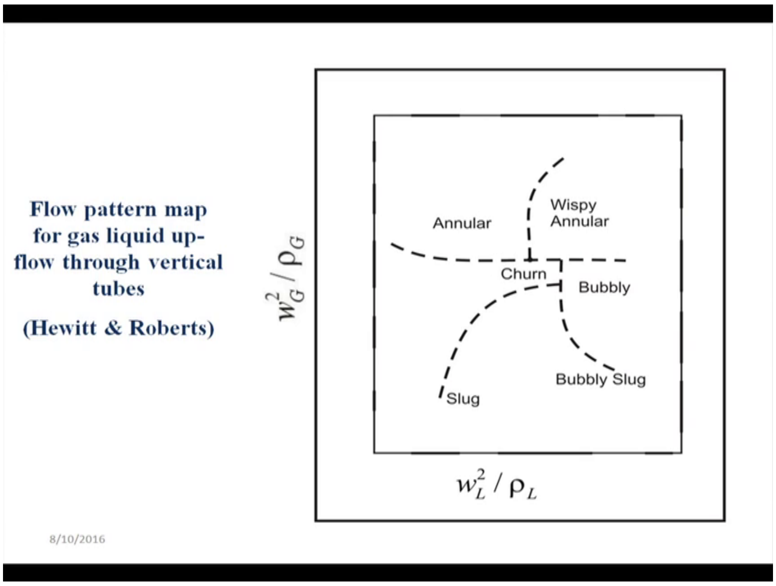

1 of the oldest flow patterns for gas liquid up flow in vertical tubes plots the flow patterns in a two dimensional plot with superficial movement flux of the gas and the liquid face as the access and naturally, they show that at high momentum flux of the liquid bubbly flow exists at high momentum flux of the gas the annular flow exists.

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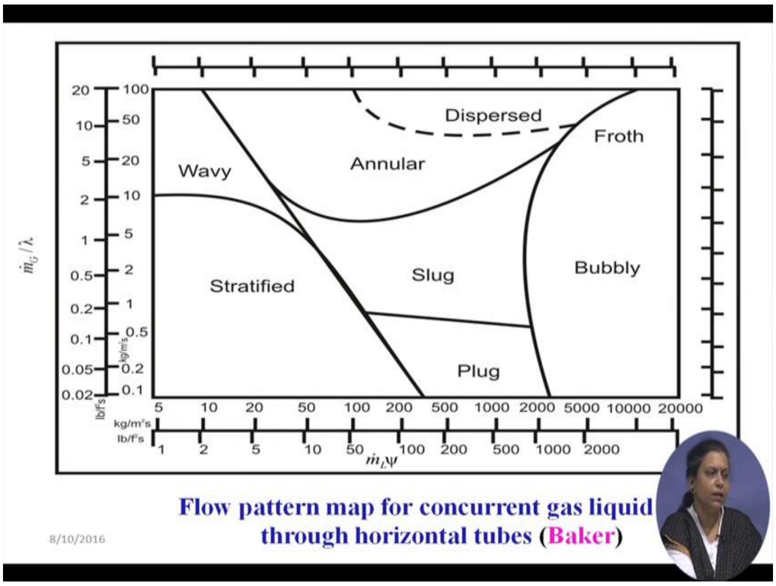

Similarly, the oldest flow pattern map for horizontal pipes was proposed first by backer and then; obviously, much more modified and that also gives us the divides the entire two dimensional plots into areas the marketing different flow patterns using two different access which, consider the mass flow rate of the gas and the liquid along with dimensionless groups defined in terms of the properties of the two phases.

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Flow pattern maps for vertical up flow of air-water based on generalized co-ordinates

Author	Fluids	Pipe Diameter	Coordinate Parameters
Kosterin (1949)	Air-Water	1 in.	β, j
Kazlav (1954)	Air-Water	1 in.	$(\beta, j^2/gD)^{1/2}$
Galcgar ct al. (1954)	Air-Water,-Kerosene	0.5 & 2 in.	G_g, G_f
Ueda (1958)	Air-Water	2 in.	W_g, W_f
Hewitt & Roberts (1969)	Air-Water	1.25 in.	$\rho_f j_f^2, \rho_g j_g^2$
Nishigawa et al. (1969)	Air-Water	1 in.	j_f, j_g
Govier & Aziz (1972)	Air-Water	Data from others	Y_{j_f}, X_{j_g}
Oshinowa & Charles (1974)	Natural Gas-Oil		$(\beta / t - \beta)^{1/2}, Fr_{TP} / \Delta E$
Spedding & Nguyen (1980)	Air-Water	4.55 mm	$j/(gD)^{1/2}, j_f / j_g$
Weisman & Kang (1981)	Freon-II3 Vapor-Liquid	1 in.	$j_g / \phi_1, j_f / \phi_2$

Now, if we go through literature we find that people have again lot of confusions regarding the most appropriate dimensionless group to be used. For defining flow patterns this is quite obvious because, we find that when the transition occurs between different flow patterns there is no one mechanism which governs the bubbly slug, slug churn, churn annular all the all the transition mechanisms. For example, bubbly slug occurs when the qualises between the bubbles is, high that they form the elongated Taylor bubble. Naturally in this particular case your bubble qualisense should be the dominant phenomena on the other hand if you observe slug churn transition what do we find we find in the Taylor bubble region there is a downward flowing liquid film and the upward flowing Taylor bubble. Therefore, there is counter current flow in this particular region and focus there is a liquid slug which flow upwards.

In churn flow we find that the whole system becomes chaotic the counter current flow is no longer maintain. So, people have postulated that possibly flooding is the mechanism of transition and again from the churn flow; you should go to annular what you find both the gas core and the liquid film are flowing in the upward direction which shows that initially flooding has occurred and now flow reversal has occurred. So, naturally its quite evident that bubble Qualisense flooding flow reversal all of them cannot be predicted by the same physical mechanism or the same dimensionalist or dimensional numbers cannot be used to bring about all the transition together that explains the confusions in selecting the access of the different flow pattern maps, and as a results of which we find that the large number of coordinate excess have been adopted for vertical as well as horizontal flow pattern maps.

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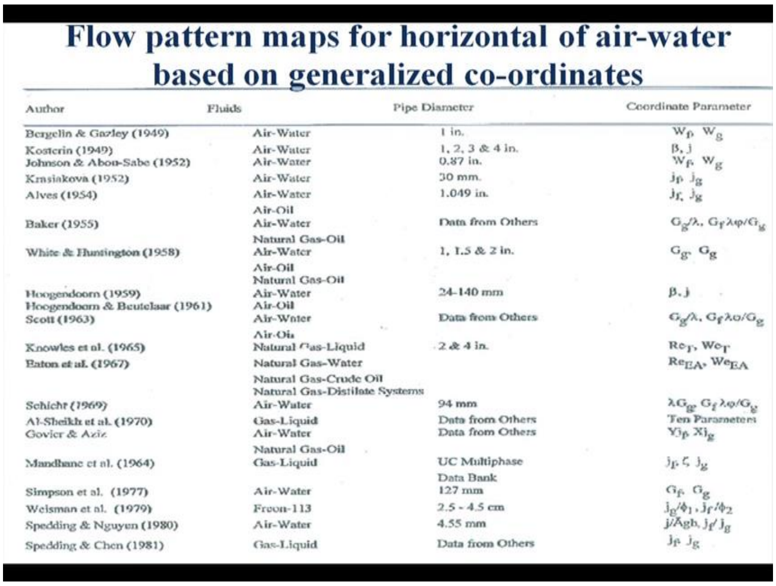

Flow pattern maps for horizontal of air-water based on generalized co-ordinates

Author	Fluids	Pipe Diameter	Coordinate Parameter
Bergelin & Gazley (1949)	Air-Water	1 in.	W_f, W_g
Kosterin (1949)	Air-Water	1, 2, 3 & 4 in.	β, j
Johnson & Abou-Sabe (1952)	Air-Water	0.87 in.	W_f, W_g
Krasiakova (1952)	Air-Water	30 mm.	j_f, j_g
Alves (1954)	Air-Water	1.049 in.	j_f, j_g
	Air-Oil		
Baker (1955)	Air-Water	Data from Others	$G_g/\lambda, G_f\lambda\psi/G_g$
	Natural Gas-Oil		
White & Huntington (1958)	Air-Water	1, 1.5 & 2 in.	G_g, G_g
	Air-Oil		
	Natural Gas-Oil		
Hoogendoorn (1959)	Air-Water	24-140 mm	β, j
Hoogendoorn & Beutelaar (1961)	Air-Oil		
Scott (1963)	Air-Water	Data from Others	$G_g/\lambda, G_f\lambda\psi/G_g$
	Air-Oil		
Knowles et al. (1965)	Natural Gas-Liquid	2 & 4 in.	Re_T, We_T
Eaton et al. (1967)	Natural Gas-Water		Re_{EA}, We_{EA}
	Natural Gas-Crude Oil		
	Natural Gas-Distilate Systems		
Schicht (1969)	Air-Water	94 mm	$\lambda G_g, G_f\lambda\psi/G_g$
Al-Sheikh et al. (1970)	Gas-Liquid	Data from Others	Ten Parameters
Govier & Aziz	Air-Water	Data from Others	Yj_f, Xj_g
	Natural Gas-Oil		
Mandhane et al. (1964)	Gas-Liquid	UC Multiphase Data Bank	j_f, ζ, j_g
Simpson et al. (1977)	Air-Water	127 mm	G_f, G_g
Weisman et al. (1979)	Freon-113	2.5 - 4.5 cm	$j_g/\phi_1, j_f/\phi_2$
Spedding & Nguyen (1980)	Air-Water	4.55 mm	$j/\sqrt{gh}, j_f/j_g$
Spedding & Chen (1981)	Gas-Liquid	Data from Others	j_f, j_g

And this entire confusions what people have finally, decided is that the superficial or the inlet velocity of the two phases are the best coordinate maps or in other words they are the most popular excess.

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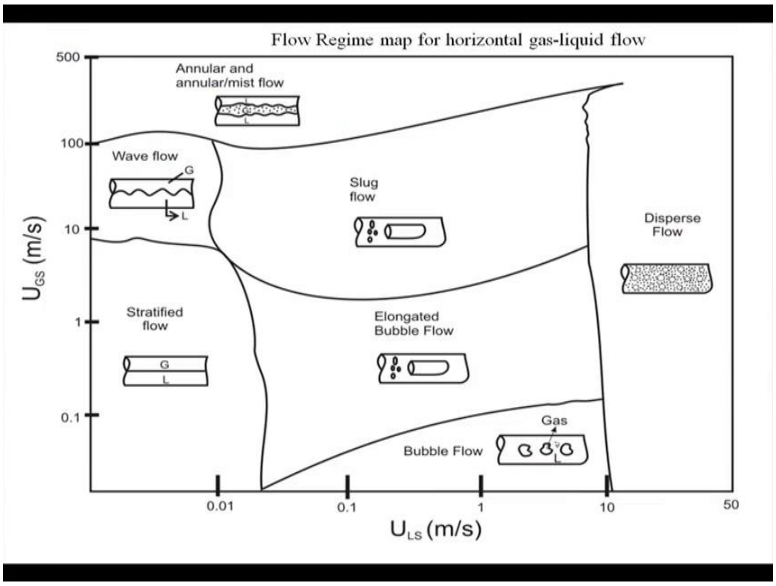

Accordingly we find that a large number of flow pattern map have been predicted with the gas and the liquid superficial velocities this is one typical map for horizontal gas liquid flow as accepted as low gas and low liquid. We have stratified in a high liquid we have disperse at high gas we have annular. It simply has divided the entire two dimensional regions into some areas dominated by different flow patterns.

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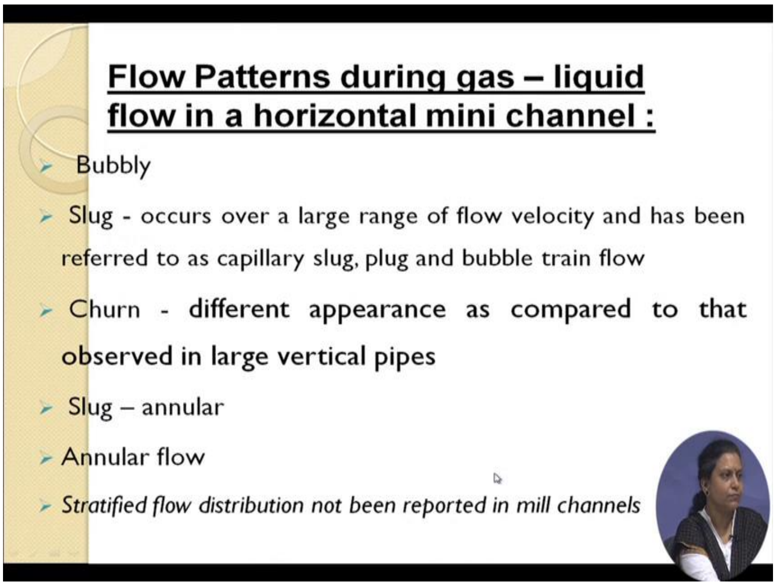

Now, in the next class we will be discussing the relevant flow pattern maps for micro channels and what are how they are represented, what are the problems of this particular flow pattern maps. Finally, we will be discussing an analytical modal based on basic physics which governs the transition criteria in micro channels.

Thank you very much.