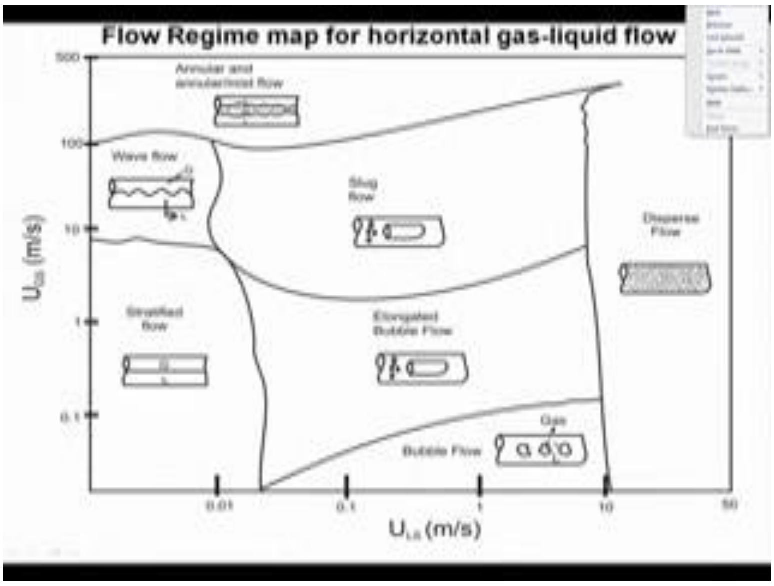
Adiabatic Two - Phase Flow and Flow Boiling in Microchannel
Prof. Gargi Das
Department of Chemical Engineering
Indian Institute of Technology, Kharagpur

Lecture -07
Flow Pattern Maps for Milli and Micro Systems

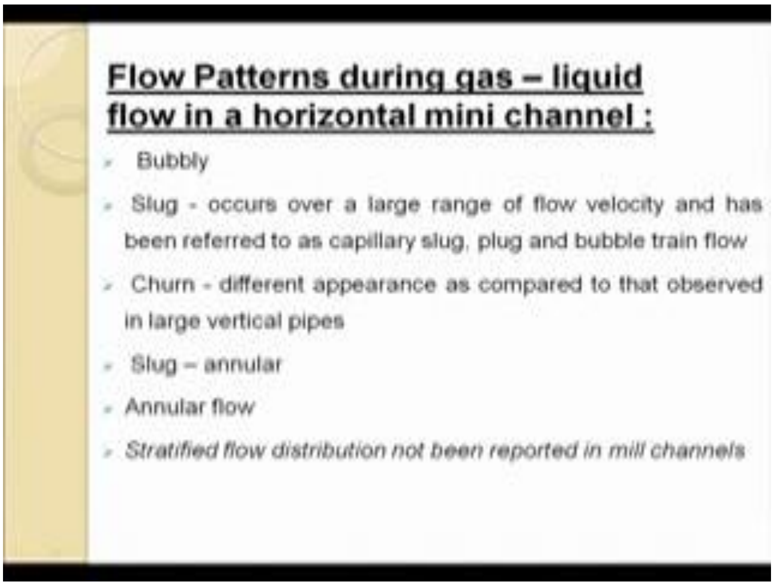
Hello everybody. We continue with our discussion on the flow regime ritual set, yesterday I had just mention to you that, when we first identify the flow patterns and then we try to depict the range of the existence of the different flow patterns on a flow pattern map and as I have mentioned yesterday; several different coordinates have been adopted for the flow patterns map in macro system and then finally, people have find out that no one pair of coordinate access was suitable, to predict all the transitions . Therefore, what was adopted was the most commonly adopted access for depicting flow pattern maps are; the superficial velocities of the 2 phases.

Now, let us see what happen for mini channels and micro channels, as I mentioned yesterday that, we will be focusing on micro channels.

(Refer Slide Time: 01:23)



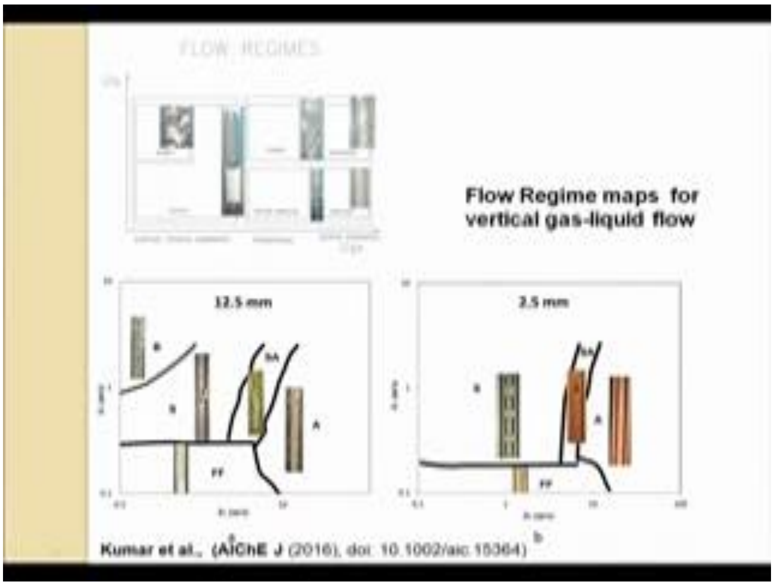
(Refer Slide Time: 01:30)



But will be also covering certain interesting aspect of the mini channel as well. In mini channels what do we see is that, just to recall yesterday we found out that more or less morphologically the different flow patterns in mini channels and micro system are similar; we finds bubbly slug, churn, slug annular and annular flow patterns, keep in mind that the slug flow occurs over the largest range of flow velocity and naturally depending upon the appearance of the slug flow they are refer to us as capillary slug, plug bubble train all of them they refer to the intermittent periodic flow pattern; which is commonly now as slug flow, and usually in slug flow we find that the liquid slugs are un narrated.

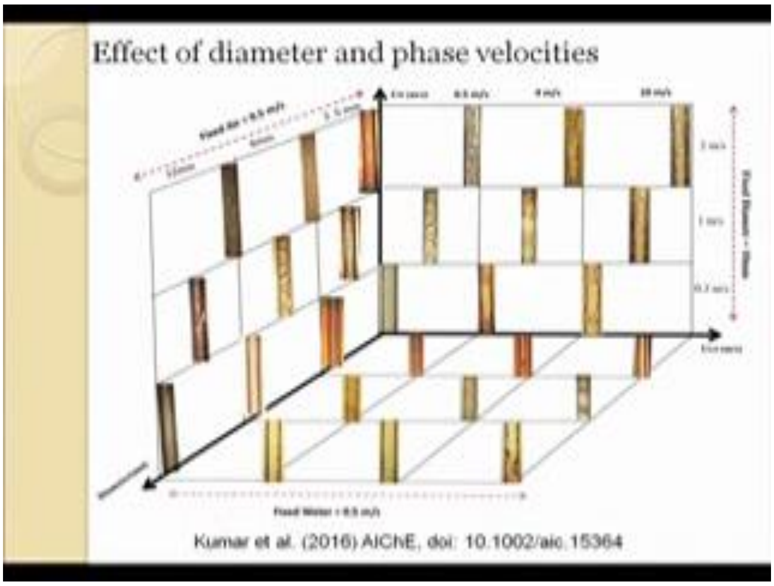
Therefore, it comprises of one 2 phase region, comprising of Taylor bubble and the counter current flowing liquid film or the adjourning liquid film and then un-narrated pure liquid slug. The other thing which we should remember is that, churn flow pattern, as we observe in the micro systems do not exist in macro systems, quit naturally. Because of the increasing influence of surface tension or surface forces, several different phenomenon; which mark the transition between the slug and annular flow patterns and termed as the churn flow patterns; and other thing which we should remember that stratify flow distribution as not been reported even for mille channels.

(Refer Slide Time: 02:54)



Now, with this in mind, again we find that the most commonly used flow pattern maps they use the superficial velocity of the gas and liquid as the 2 access and if it is liquid-liquid flow; then we use the discontinuous at the lighter liquid superficial velocity in the x access and the heavier liquid superficial velocity in the y access, for examples suppose it is water flow, then in that case water flow rate is y axis; tool in flow rate is the x axis. And the flow pattern maps and depicts as shown this 2 maps they have been developed in our laboratory and for gas liquid down flow in vertical pipes.

(Refer Slide Time: 03:40)



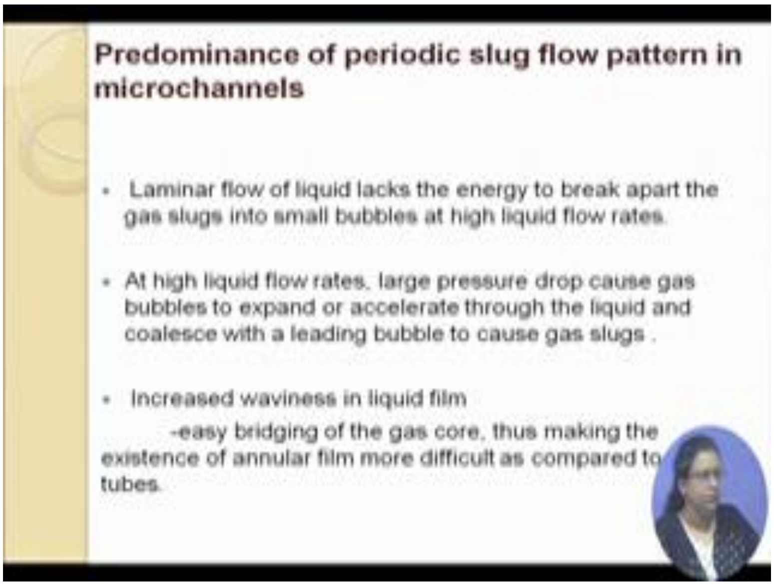
And this also 3 dimensional flow pattern map, that we are try to develop just in order to show the coupled effect of liquid velocity, gas velocity and pipe diameter.

From here if you observe gives you lot information. For example, it tells you that more or less at high liquid constant gas velocity, we find that for low pipe diameters 2.5 millimeters, it is more or less plug flow and as we come to lower and lower liquid velocities, the situation it becomes elongated plug or plug flow whatever you see, now as we increase the diameter, we find the tendency of plugging decreases and in the 12 millimeters, we have a dispersed pattern in contrast the plug flow pattern; which observed here. Same thing is noted for moderate or medium liquid velocities, in this case also we find that the well defined plug flow becomes deform plug flow and then we get something like a slug and annular transition, as we come to still lower liquid velocity, we find that this falling film flow or the annular flow pattern as it is called and to the interface of the falling film is much smoother in the 2.5 millimeters, as compared to the 12 millimeters.

Same thing if we see the variation of your gas velocity and diameter, we observe a similar trend; the existence of the larger proportions of existence of slug flow in the smaller diameter pipe and the lesser proportion of existence of slug flow in the larger diameter pipes and this particular situation this shows the typical flow pattern map which we are used to see in a fixed diameter of 10 millimeters.

Here we try to capture the effect of face velocities and diameter, for one particular set off air and water velocities expecting that it is going to give us much more information.

(Refer Slide Time: 05:55)

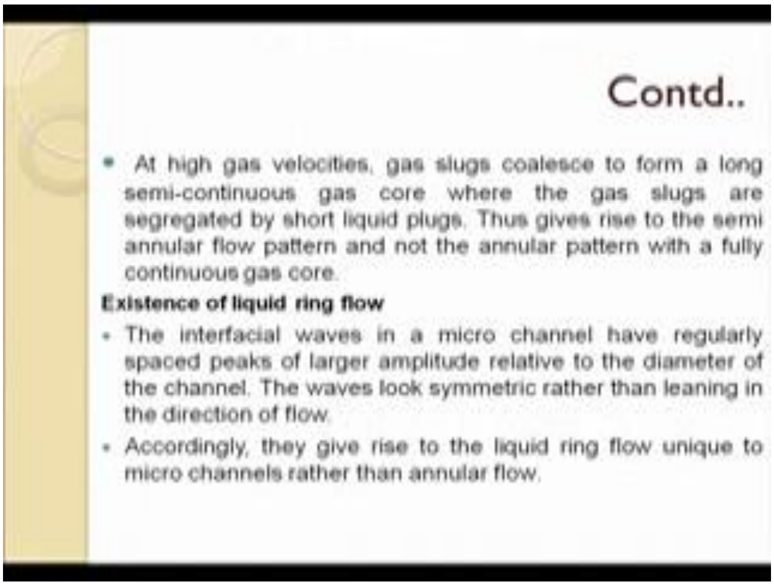


Now, we come to the micro channel part, in micro channel it was very evident that there is a predominance of slug flow pattern; just to summarize the reasons just in a nautical, I would just like to mention the reasons; which dominated periodic slug flow in or rather which elect to the dominance of slug flow pattern in micro channels and just as we all of us know that the surface tension was dominant; compared to in a body forces and also your viscous forces were much dominant compared to inertial forces.

Therefore, if you observe the first thing is that, since Renaults number was very low, so naturally most all most of the situations we had encountered laminar flow of the liquid. As a result the liquid did not have sufficient inertia to break the gas slugs into smaller bubbles even at high liquid flow rates also. Therefore, the bubbles once they formed at as slug flow, they did not have tendency to share and form the bubble flow pattern. Next even if you go for a higher liquid flow rates also, what happen, when we are in higher liquid flow rates; it cost a larger pressure drop and when the gas is trying to flow through this larger pressure drop, it had a tendency to expand or and accelerate to the liquid.

Naturally even if it shear to smaller bubbles they were flowing very fast, and coalesce with one another to form the elongated plug flow pattern; on the other hand if we find that, at higher gas velocities what happen there was increased waviness in the liquid film; when there was increased waviness in the film naturally, the amplitude of the wave was sufficient in order to bridge the continuous gas core and therefore, the existence annular flow was much difficult as compare to larger tubes.

(Refer Slide Time: 07:58)

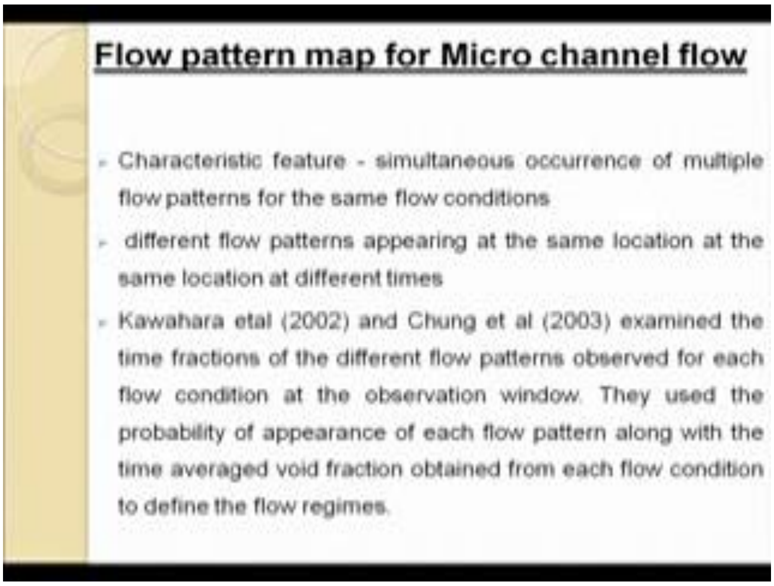


Again at higher gas velocities what we found was, the gas slugs they are coalesce to form a semi continuous gas core; where the gas slugs they were separated by short liquid plugs.

Therefore, this gives rise to the semi annular flow pattern, but the annular flow pattern with a continuous gas core was absent. Therefore, we find that the plug flow it was favored both at high liquid velocity as well as high gas velocities thus plug flow had obtained a dominance over both the bubbly flow pattern at one end as well as the annular flow pattern at the other end, both being inertia dominant flow patterns. Another unique feature which you observed micro channels was the existence of liquid ring flow and this also we have discussed already the interfacial waves in this particular case, they were regularly spaced and of larger amplitudes as compared to the diameter of the channel.

Relativity amplitude is quite high, so therefore, the waves they look symmetric rather than leaning in the direction of flow. Therefore, they give the appearance of a liquid ring flow which was unique to micro channels and this was not observed for many channels of larger channels for that matter.

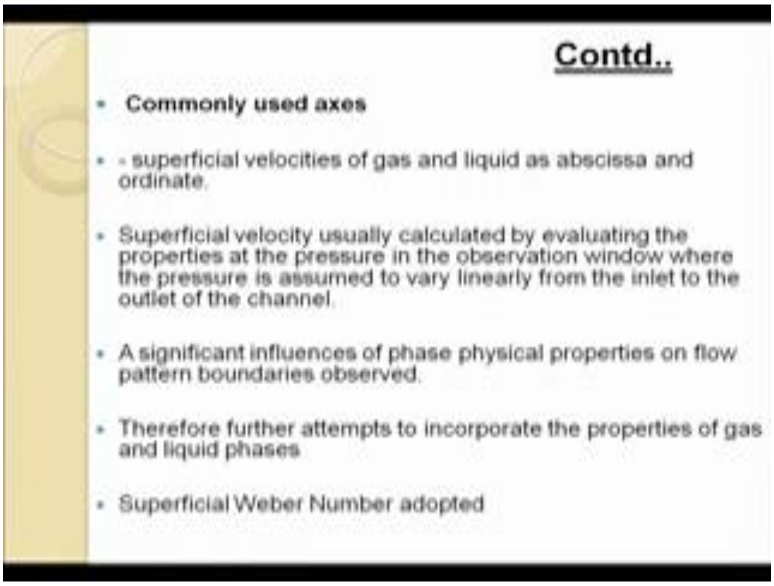
(Refer Slide Time: 09:21)



Now when people try to plot the range of existence of the different flow patterns in micro channels, what people observed were, that the main characteristic feature of micro channel was, the simultaneous occurrence of multiple flow pattern for the same flow conditions. Or in other words, even if we keep the gas velocity, liquid velocity everything as constant, if we observe the flow through the channel, then we find that different flow patterns appear at the same location at different types. So likely then how to identify, what is the exact flow pattern or how to denote the flow patterns on a flow pattern in a map. Accordingly kawakawa one particular group and Chung Et Al, they did, they went on examining the flow patterns for a sufficient period of time and then they examine the time fraction of the different flow patterns or other the time fraction of existence of the difference flow pattern, for each flow condition at the observation window they had an observation window. They were observing their and may be they were observing say 5 minutes. Out of the 5 minutes they found for different time instance, slug flow was occurring and may be the total time of existence was slug flow was say 4 minutes, for the other 1 minute some of the other flow patterns were existing including single phase liquid flow and single phase gas flow.

Accordingly they did, they plotted or rather they try to identify the probability of existence of the different flow patterns; along with the time average wide fraction. For example, the wide fraction is very large and if the probability of appearance of slug liquid ring and annular those more or less comparable and alpha is much greater than 0.8, then in that case it was denoted as annular flow pattern. For moderate wide fractions naturally it always happens that slug flow occurs over a large range, so then it was slug flow pattern; in this way the probability of existence of any particular flow pattern, was studded and the highest probability flow pattern was taken as the dominant flow pattern under this specified flow conditions.

(Refer Slide Time: 11:45)

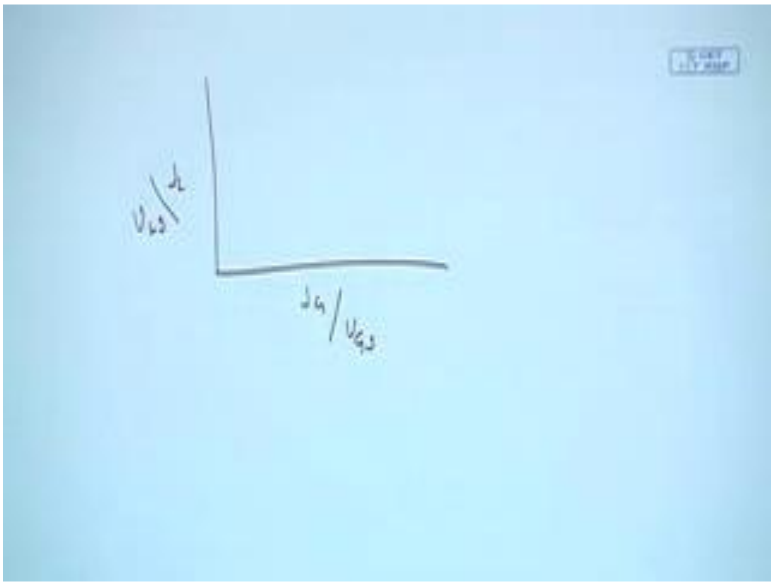


In this way the flow patterns are identified, and the flow pattern maps were made. In this case also we find that the commonly used axes of superficial velocities of the gas as abscissa and the liquid as the ordinate. 1 thing I would like to say that, in this particular case it is not the inlet velocity of the fluids, now for large diameter pipes the superficial velocity and the inlet velocities are the same we do not differentiate between the 2. Why inlet velocity is the velocity which is measured by the flow measurement device, which is there up stream to the section.

We measure the flow rate there may be in IPM either the mass flow rate or the volume flow rate and then we just divided by the cross sectional area and we get the inlet velocity. The superficial velocity is defined as the velocity, which the fluid will have if flowing alone in the pipe quite naturally it will be having this particular velocity only. Therefore, the superficial velocity is commonly taken as the inlet velocity for macro system. Now in this particular case there is a very large pressure drop as already I have mentioned.

The naturally superficial velocity should be the velocity, which the fluid will have if it were flowing alone in conduce, true; but at the condition at which it is flowing now. So, naturally it is now flowing at that particular location at a pressure which is not equal to the inlet pressure. So, therefore, the superficial velocity it is calculated by evaluating the properties of the 2 fluids, at the pressure in the observation window. And in this case it is assumed that the pressure varies linearly from the inlet to the outlet of the channel. Accordingly the pressure in the observation window is valuated and the superficial velocity is calculated accordingly.

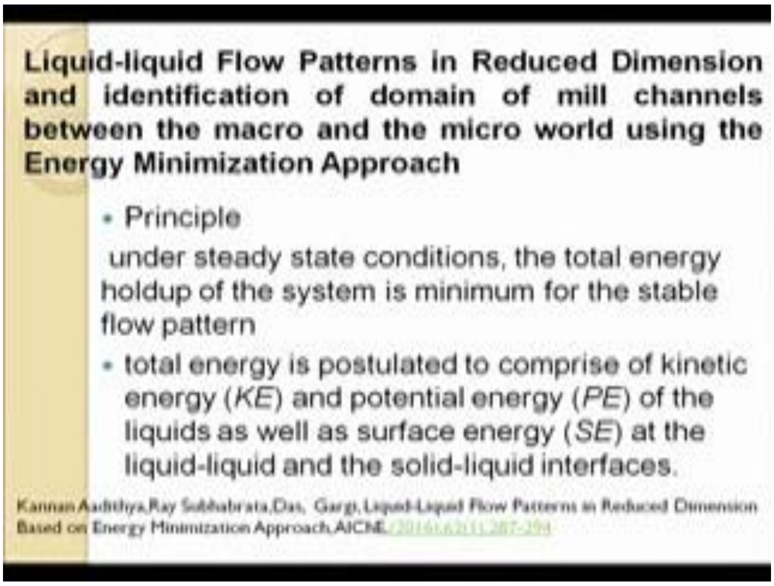
(Refer Slide Time: 13:52)



And there we have the typical plot of say, j l verses j g, or in what if you wish it to write it as the superficial liquid velocity to the superficial gas velocity, whatever you wish in any of this plotted and usual the flow pattern maps are depicted, but in this case you know that the main portion of the flow pattern map is occupied by the slug flow pattern. So, naturally there is not much information to be gathered from this flow pattern maps. Now people have also observed there is a remarkable influence of phase physical properties on the flow pattern boundaries observed.

In order to capture this particular dependence very frequently, some non dimensional groups have been adopted. Out of the commonly known non dimensional groups that have been adopted, we find that the superficial Weber number of the gas verses the superficial Weber number of the liquid is very frequently used as an alternate to the superficial Weber velocity.

(Refer Slide Time: 15:04)



With this more or less I have given you idea regarding the basics of the flow pattern in a micro channel, the flow pattern maps now I would want to discuss one particular analytical model based on basic physics which we have developed in the multiphase flow laboratory to predict the liquid-liquid flow patterns in reduced dimensions, we have used for liquid-liquid flow, but it its more or less general it can be used for gas liquid flow in reduced dimensions as well.

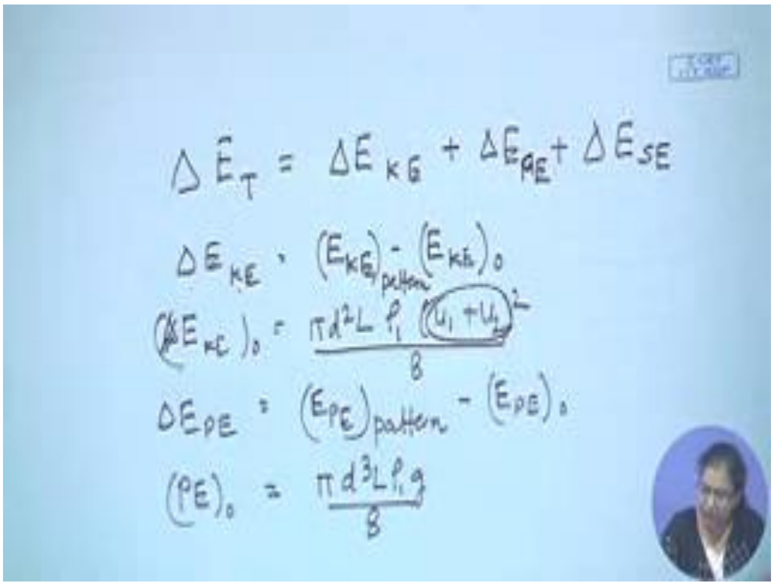
This model I would like to discuss because this is quite versatile the thing is it can predict the range of existence of the different flow patterns number one. Number two it can do this for both horizontal and inclined pipes and thirdly it has been modeled in such a way that it can you also identify the range of existence of the meso scale between the micro and macro domain and most importantly we find that, usually whatever analytical models have been developed for predicting the flow pattern transitions all of them they predict the transitions as occurring at a one fixed particular location, but in reality we find that the transitions they occur over a range of conditions or in other words in a flow pattern map, the transitions should be depicted as a zone or a region rather than a unique curve.

Why most of the analytical models they show transitions as a unique curve this is also taking care of in this particular model and this actually predicts zones of transitions between the different flow patterns. Now this has been based as on fundamental physics and this is based on the principle of energy minimization, which states that quite naturally all of us know the conservation of energy, which states that under steady state conditions the total energy hold up of the system or in other words the total energy content of the system per unit volume; should be minimum for the stable flow pattern.

What we do we try to estimate or evaluate the total energy content of the system that is a 2 phase flowing system per unit volume, for different flow patterns; then we try to draw curves of the total energy verses the wide fraction and then we find that, for each wide fraction the one particular flow pattern will have the minimum total energy and we postulate that, that particular flow pattern is the stable flow pattern under the conditions, when we change the conditions; it can be change of pipe diameter, it can be change of fluid velocities, it can also be change of fluid properties, then we go to a different set of conditions under that conditions again we evaluate the energy terms and then we find out what is the minimum energy under the changed condition. It can happen that if the conditions have not changed much, the same flow pattern continues to exist, if the conditions are changed to a large extent; then we might get a different flow pattern under the changed condition.

Now, how do we go about, the first thing we have developed this module for reduce dimensions. Accordingly what we postulate.

(Refer Slide Time: 19:21)

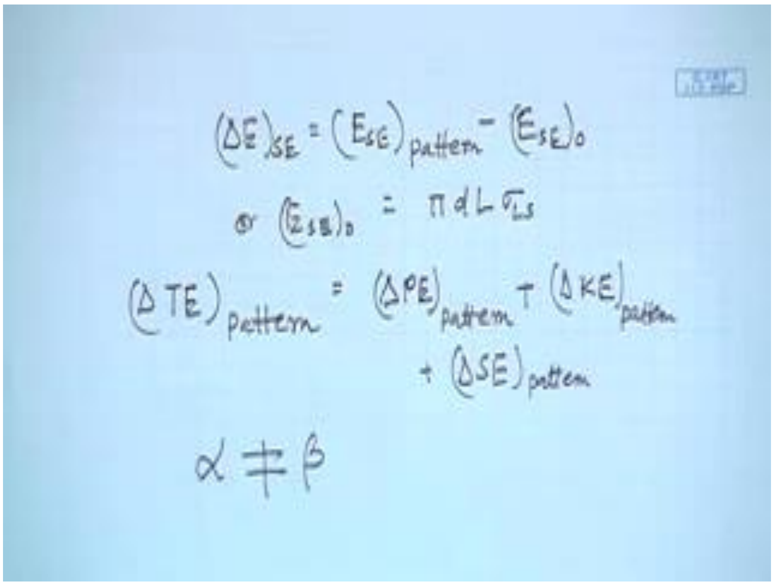


We postulate that the total energy. It is a summation of definitely kinetic energy is going to be there, it is also in macro systems also, then we should have a gravitational energy term, which will be gradually reducing in importance as a channel dimension gets reduced and along with this, there should be a surface energy term rather its not gravitational like write it down as potential energy term and along with that they should also be a surface energy term, due to the surface energies at the liquid-liquid as well as the Solid liquid interface.

Therefore, we write down the total energy in terms of the total energy change, for rather the energy kinetic energy change, with potential energy change, and the surface energy change. And each of this changes, they have to be evaluated with respect to some particular some particular standard, is standard it is taken in this particular case, it is the kinetic energy of the 2 phase flow minus; the kinetic energy reference, which is the kinetic energy of water flowing at the total mixture velocity . So, therefore, this has been considered in this particular case.

Accordingly what has been done; accordingly the kinetic energy term it has been written down as delta E ke for the pattern minus delta ke for the reference system where the delta E ke 0 for the reference, this is taken as pie d square l row 1, u1 plus u2 whole square, divided by 8. So, you can see nothing this is just the kinetic energy of water flowing at the total mixture velocity u1 plus u2, so the kinetic energy of that water. So, therefore, the total energy rather the kinetic energy change is taken with reference to the kinetic energy of water flowing, at the mixture of velocity. In the same way, the potential energy term it is taken as, potential energy for any set pattern whatever pattern we consider, minus the potential energy for the reference state; where the potential energy for the reference state it is given as the potential energy of water occupy the entire phi, and again if you take surface energy.

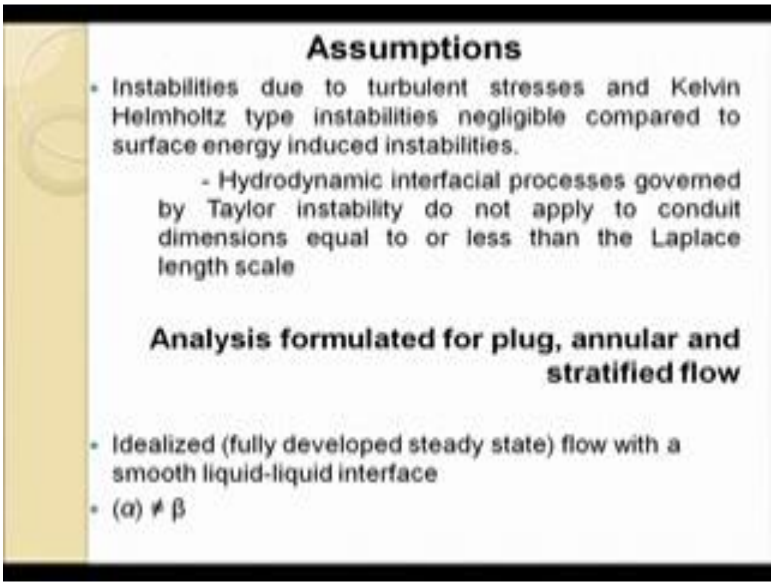
(Refer Slide Time: 22:52)



Its again the same thing, this will be also given with respect to the surface energy of the particular pattern, minus the surface energy of the reference substance which is again water flowing at the occupying the entire cross sectional energy, which is nothing, but the surface tension of water. Finally the total energy change for any particular pattern in non dimensional form, it is given as the delta PE for that pattern, plus delta kinetic energy for that pattern plus surface energy for that pattern.

In this way we formulate, it we develop expressions for study state total energy, we postulate the total energy terms under steady state conditions for per unit volume of the conduit, which has specify geometry and orientation. The postulates are the base rather than they primarily applicable to low diameter conduits, where we find that the instabilities due to turbulence stresses and Kelvin amounts of instabilities or negligible are compared to surface energy induced instabilities.

(Refer Slide Time: 24:55)

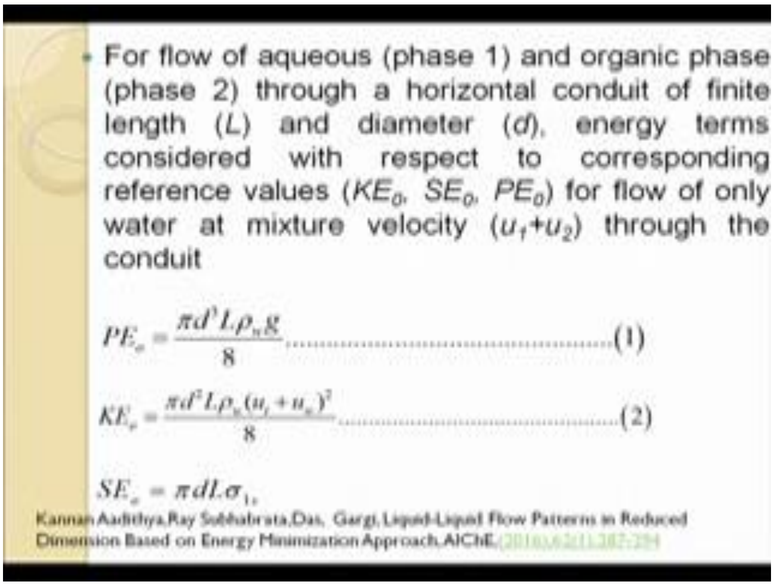


Therefore, there are 2 things which are taken care of here, one is that we have we are doing it for log conduit diameters where we can very well assume that the hydrodynamic interfacial processes governed by Taylor instability do not apply to condude dimensions equal to less than the length (Refer Time: 25:13) scale.

Therefore, this is number 1. Therefore, we the analysis is concentrated to low diameter pipes; the other thing is we have been working on low to moderate flow rates such that the kinetic energy term does not become very dominant as compare to the surface energy and the surface energy term. We would like to operate in the surface energy dominant condition, for low tube moderate pope diameters and accordingly naturally we do not consider the dispersed flow pattern in our case, since that occurs at high liquid velocity where kinetic energy is dominating.

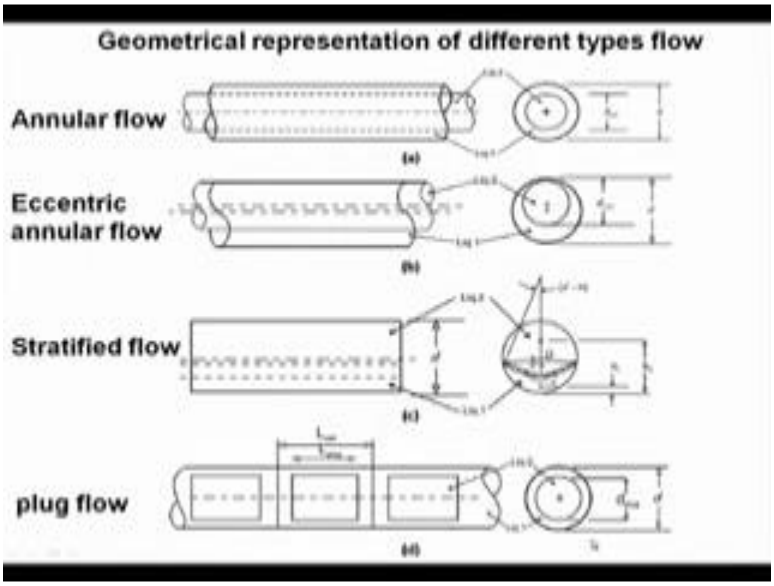
Therefore, this analysis is concentrated for the plug, the annular and the stratified flow pattern. Just like all analysis in this case also we have assumed 2 things, one is the idealized flow that is a fully developed steady state flow and to smooth liquid-liquid interface. And now this is quite relevant for micro and mille systems, because as we observed earlier also we have seen that, more or less the interfaces are smooth due to the due to the pronounce influence of viscous force here and other thing that we are introduced a slip here by assuming that the inlet and the incitu velocity are not the same or in other words as I have written down there the incite composition is not equal to the inlet composition.

(Refer Slide Time: 26:52)



On this particular basis the analysis has been developed and accordingly as I have told you that, we have considered a flow of an aqueous phase and a organic phase in this particular case, through a horizontal conduit of length of l and diameter d, and they are considered with respect to the corresponding reference values; for flow of only water and the this particular work as come out in the paper, which you can refer for your for the understanding of the work.

(Refer Slide Time: 27:21)



And the equations have been developed based on the geometrical morphology, of the different flow type flow types as has been shown in this particular figure.

In the next lecture we continue with developing the model and the interesting result which the model shows or gives us regarding 2 phase flow, in micro channels under surface tension dominant conditions.

Thank you very much.