Multiphase Flow
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Module No. # 01
Lecture No. # 02
Estimation of Flow Patterns

Well very good morning to all of you again.

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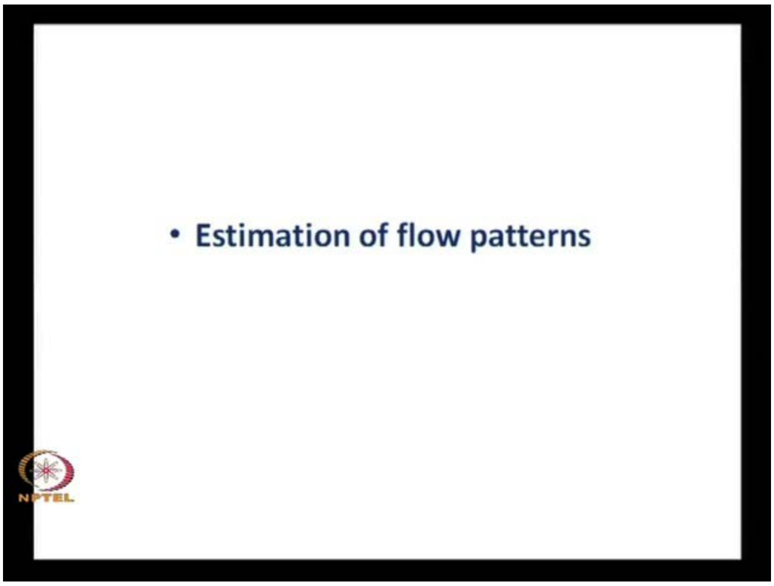

So, today in the last class what we did I had introduced multiphase flows to all of you is it not? I had told you what is multiphase flow and how is it different from single phase flow conditions. What are the applications of multiphase flow? Why do we need to study multiphase flow? Why is the need being more felt in the present day scenario as compared to the need which was felt previously? There were applications in the past also and the applications are increasing then there is an increasing pressure to improve the efficiency of the equipments. Now, we are governing or rather we are operating over several particular skills we have started to operate from the micro scale, nano scale level 2 to macro levels and to much larger ranges as compared to that.

And therefore, the need to study multiphase flow to understand multiphase flow to increase the efficiency of the equipment to bring about proper design of the operating equipments, to know the safe operating limits to diagnose faults, to correct faults in as a matter of fact even to alleviate some type of defects. For all these things we need to know or rather we need to know the hydrodynamics as well as the other characteristics of multiphase flow as the situation may demand. Now, when we were going through the applications in the last class I showed you that there are vast number of applications if you remember this they have started from say the applications. If I will just go through it in very short we will find that there are large number of applications starting from power system heat transfer process equipment.

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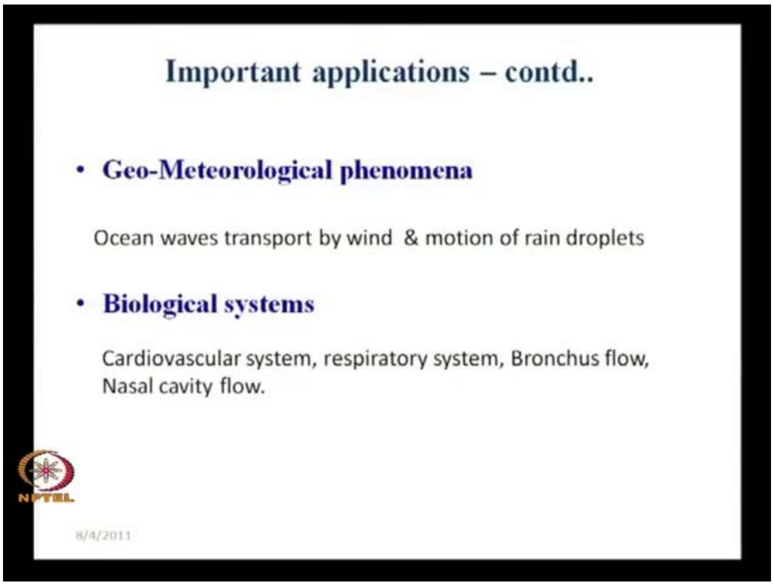

Till biological system geo-meteorological systems and so on and we find that there are large number of variations. Some where it is ocean wave transport, some where it is the respiratory system. So, these things they do not seem to be connected in anyway, but if they have to give about a unified approach to the particular type of study.

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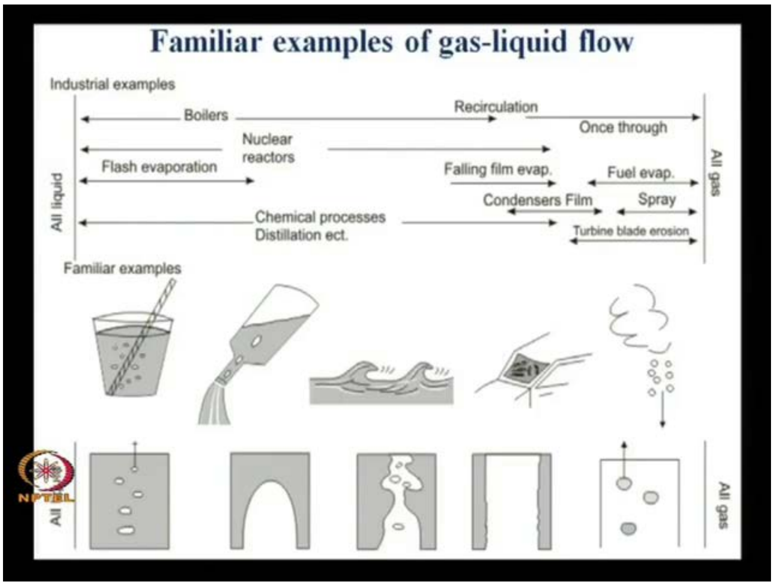

Then in that case what we have to do, we have to present some unifying principles. The first thing is we have to identify as I had discussed in the last class, how multiphase flow is different from single phase flow. Now we found out that in single phase flow the situation was either laminar or turbulent we have to find out whether it is laminar or turbulent which is already a very well defined technique to find it out. Once we know it there is no problem at all. In this particular case also we have to know the distribution of the two phases. Once we know the distribution because in this particular slide if you find in the first particular example we find that simply gas bubbles rising through a bottle of lemonade we find that small spherical gas bubbles are rising.

Next the other example these are just practical this common life examples which I have shown can you simply pour water from a bottle. We find that when you pour water from a bottle and through a narrow necked bottle rather, we find that as the water comes out large elongated bubbles enter here. Definitely the geometry the topology of these bubbles are different from swamp these spherical bubbles which are encountered in this particular case. So, this same physics the same governing forces cannot be governing the rise of spherical bubbles or rather certain forces are more important in this cases, certain forces are more important.

In this particular case at the other extreme if you see it is just rain drops which are falling or in other words a very interesting example. When there is rainfall you must have observed on the windscreen of the car, small revolute sought of patterns they come out and they flow in a very zigzag sought of a fashion on the windscreen it is known as a meandering motion. Lot of interest has come up in with respect to this meandering motion and this is also due to interplay of a different type of forces. Forces are the same, but some forces are important under certain circumstances something else is important for certain other cases.

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So, therefore we find definitely the physics of elongated bubbles rising through narrow necked bottles will definitely be different from the physics governing the meandering flow of revolute on the windscreen during a rainfall. So therefore, before we go to do anything for multiphase flow, or rather to be more specific two phase flow situations. First we will be dealing with after that we might touch up on some sought of three phase flow situations as well. First thing we need to know is the distribution of the two phases the first thing is the distribution what it does it governs the entire physics of the flow.

And more importantly we know that since the two phases have a different density as I have already told you. So therefore, what happens there is a slip between the phases as I had explained in the previous class as well.

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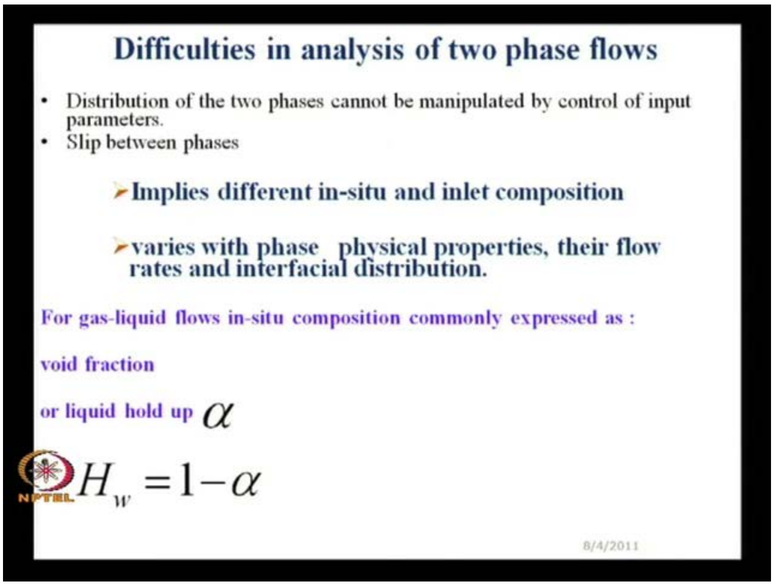

So, the lighter phase tends to slip passed the heavier phase and this particular slip velocity as I have already discussed in the last class. This particular slip velocity it depends also upon the distribution of the two phases and of course it varies with a large number of parameters as we have discussed in the last class. So therefore, since it governs this slip, it governs the heat mass reaction kinetics it governs everything of two phase flow. The first thing that we should study is the distribution of the two phases and how the distribution it varies with different phases say air water? What are the different types of flow patterns which are available instead of air if we use oil? How the flow patterns change? How they change with flow rate? And definitely how they change with the conduit orientation the conduit geometry and things like that.

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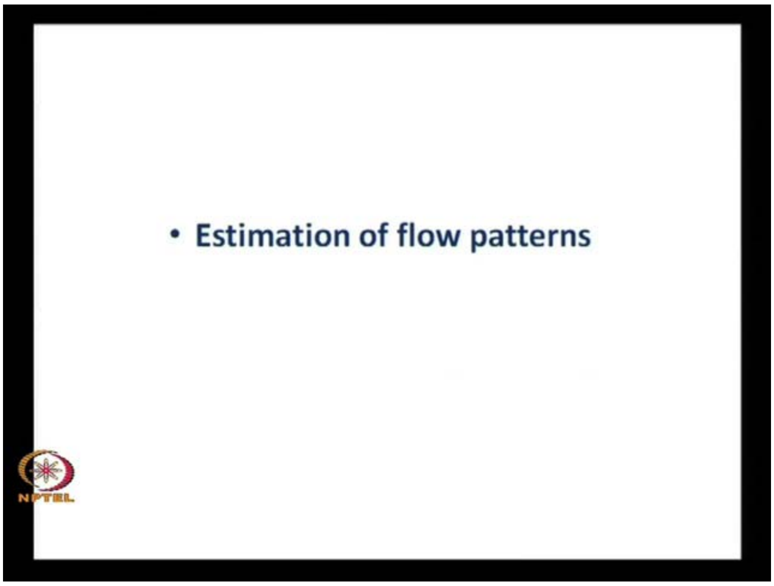

So, we will be proceeding systematically accordingly and today we are going to start the estimation of flow patterns. Now from whatever we have discussed it might appear to you that well there can be innumerable number of flow patterns and we have no control over them we cannot predict them at all. Therefore, the situation is extremely difficult. Well there are certain fortunate situations due to which some sought of delineation of flow patterns are possible.

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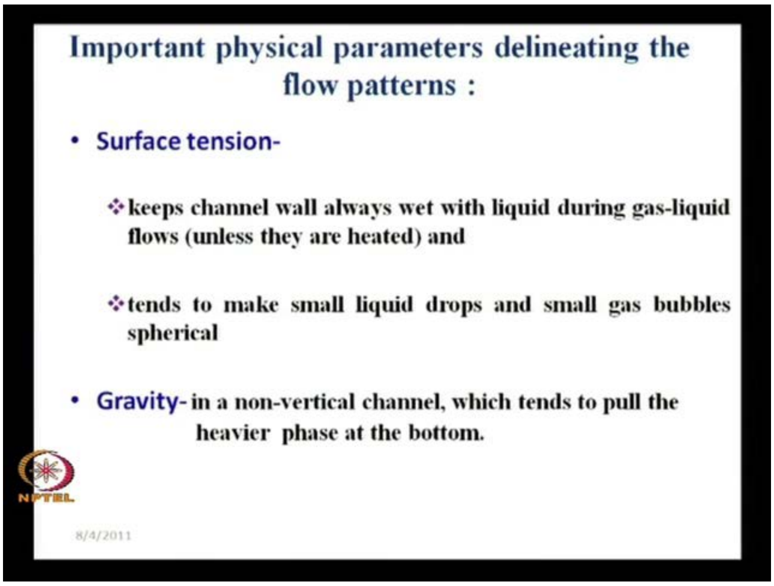

The main factors will be first thing is effect of surface tension what it does if there is a discontinuous phase then it tends to keep and the size of the discontinuous phase is small then it tends to keep those small discontinuous phases as spherical or spheres. Now, before I proceed I would like to clarify one thing, what is a continuous phase? What is a discontinuous phase? Any idea anybody of you? Well a continuous phase is that phase whose different parts can be joined by a curve which does not cross the inter phase. Is it clear? So, continuous phase is that phase which can be joined by any particular curved line where the curved line does not cross the inter phase at any point.

On the other hand the discontinuous phase is one that if you want to join two parts of the discontinuous phase then definitely that curved line or that particular line it has to cross the inter phase. So therefore, we find that the first thing or rather the basic factors which govern your rather which govern delineate the different flow patterns. Number one surface tension what it does, it tends to make small liquid drops and small gas bubbles spherical this is number one. And the other important thing is particularly for gas liquid or vapor liquid flows, there will always be a tendency of the liquid phase to wet the pipe wall. This you must remember this does not again hold when it is a liquid ,liquid flow there we get some other interesting situation which we will be discussing shortly.

But for gas liquid and vapor liquid cases surface tension plays two roles. First thing is, it keeps the channel wall wet with liquid during gas liquid flow and the second thing it tends to make small liquid drops and small gas bubbles spherical. Now remember one thing that this the first point which I mentioned that there can be certain exceptions to it. For example when the tube is heated and the wall temperature is much higher than the saturated temperature of the liquid under that conditions what happen? Vapors will be generated at the wall and they may try to stick to the wall till a particular distance.

So, for heated tubes this does not always hold there can also be some hydrodynamic instabilities due to which there can be gas phase or vapor phase sticking to the wall. But unless such a situation arises under normal circumstances it will always be the liquid phase which will be wetting the wall for gas liquid and vapor liquid flow situations. Well the other way important thing is gravity. Gravity is a non vertical channel naturally what it tends to do? It naturally tends to pull the lighter phase on the top. So therefore, we will always have some sought of a stratification where the lighter liquid or the lighter gas.

Whatever is the lighter phase that will be on the top and the heavier phase will be on the bottom. So therefore, due to these two factors more or less some order can be brought about in the totally apparently chaotic study of flow patterns which we see. So, what I would like to do is first I would take up say air water flow and we would like to see that it gradual increase of one particular flow rate. Keeping the other constant what are the different flow patterns that we will be observing. Then gradually we will be going to different situations.

Maybe we will be changing the pipe orientation the pipe diameter the fluid type, maybe we will be introducing one other fluid inside the pipe. Maybe we will be heating the pipe something we will be doing and we will be seeing, what are the corresponding changes? Which come about in this particular case?

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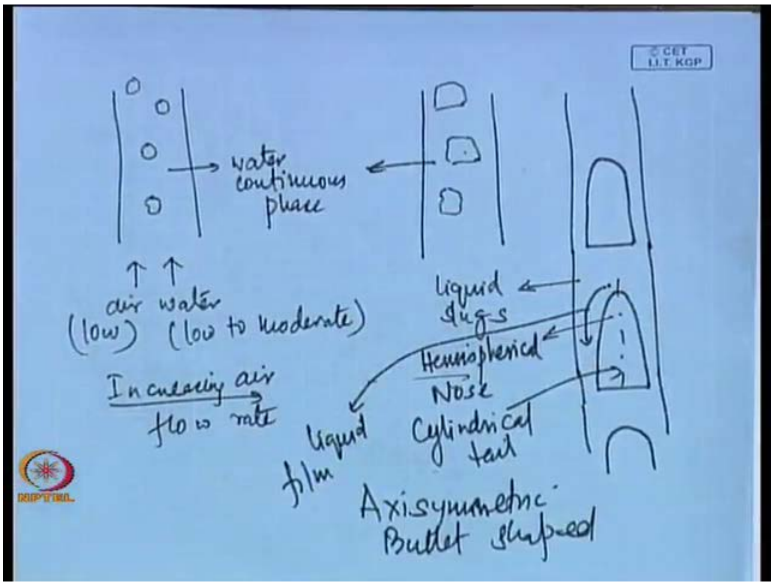

So, now let us see for a vertical case because gravity would not be occurring under that conditions for a vertical cube suppose we take. We introduce say any gas liquid we take for the time being air and water is being introduced here. Now we have very low air velocity and it is about low to moderate water velocity what do we expect? We expect that water flows as a continuous phase and discrete air bubbles are more or less dispersed in this continuous water medium. So therefore, these bubbles if they are very small then they are definitely spherical as they grow larger and larger they tend to become deformed.

Now, with time what we do we gradually increase the air flow rate keeping the water flow rate more or less constant. So, we are increasing the air flow rate what do we find gradually the number as well as the size of this bubble they start increasing. So, gradually we find they become much more deformed they deviate more from this spherical shape and gradually some sought of a cap shaped bubbles they come into being. Keep on increasing the air flow rate more and more, but in this particular case also we find that water is the continuous phase and gas is the discontinuous phase more or less gas is more or less uniformly or it is more or less disperse within the continuous water phase.

So, from here to here if we see we find that may be the shape of the bubbles have changed, but the basic characteristics remains the same. It is simply the water flowing as a continuous phase and the gas phase or the air phase it is dispersed uniformly as discrete bubbles in the continuous water phase. Where these discrete bubbles they maybe spherical they maybe non spherical they maybe oblate spheroidal ellipsoidal cap shaped and so on. And so forth now, as we keep on increasing the air flow rate further what we find these particular gas bubbles, their size as well as their frequency both increase and finally, a situation comes.

When we find that the gradually coalesce and they form such elongated sought of a bubbles whose size is comparable to the tube diameter. Whenever we have this we find that more or less now the flow pattern it is characterized by such elongated bubbles which a translating uniformly through the liquid phase. And in between these bubbles we have the liquid mass, which are usually known as liquid slugs now these bubbles I have a schematic of this. So, these bubbles if you see these elongated large bullet shape axisymmetric bubbles now these bubbles are very interesting now what we have observed is that.

This particular bubbles they are characterized by a hemispherical nose and a cylindrical tail they have they have two portions and they are essentially axisymmetric and bullet shaped usually this has been observed and under these circumstances what we find the liquid from the liquid slug is sought of this. The liquid from the liquid slug it actually flows downward as a liquid film it is an annular film between the bubble surface and the tube wall. So, here we find a number of things first thing is there are bullet shaped bubbles which translate periodically through the continuous liquid slug.

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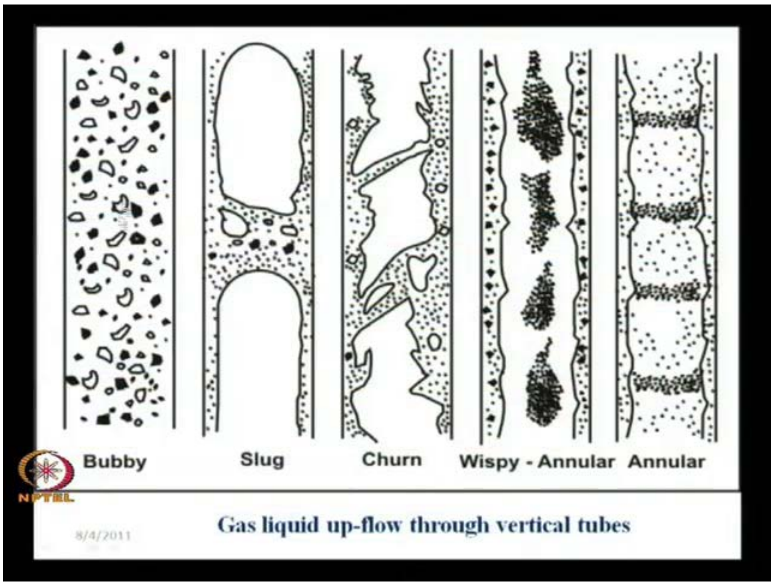

Now here we find that in this particular liquid slug there can be bubbles as shown in this particular figure or they might not be aerated at all. The liquid slugs may be aerated they may not be aerated. Now the tendency of aeration that decreases with few diameter as I will show from some photographs shortly and what happens is from the preceding liquid slug. The liquid starts flowing downward as the continuous liquid film along the surface of the bubble and it forms an annular continuous wetting film between the tube wall and the bubble surface. Then it comes down and finally, it meets the liquid slug beneath.

Often it meets naturally in this particular conference a good amount of vorticity is produced. Due to this particular vorticity some amount of air is sheered away from the surface of the bubble and they tend to aerate the liquid slug beneath now. Usually the aeration is more to just below the bubble as compared to further downwards. Now, remember one thing once these bubbles are formed their shape does not change further with more introduction of air. What happens as we introduced more and more air in this particular case both the frequency as well as the size and the shape of the bubbles were changing in bubble flow.

This particular case once the bubbles has been formed their shape does not change. If we introduce more air the bubbles become longer and longer, but this hemispherical nose and the cylindrical tail the axisymmetric bullet shaped shape, this remains unchanged. If you observe you find that in this particular case the flow it is characterized by a periodic flow phenomena it is periodic. If you observe any particular cross section what do you find we find that in any particular cross section.

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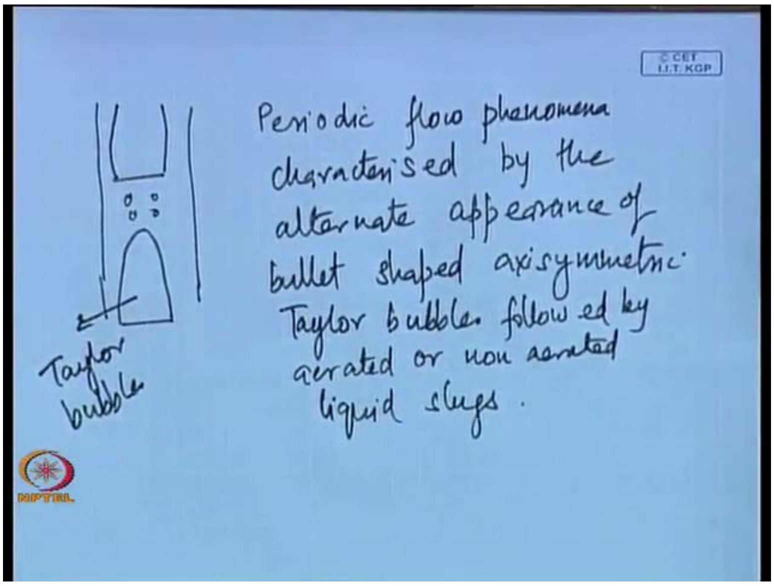

I will just draw the slug flow once more. So, that I can explain to you and we find that the periodic phenomena- this particular periodic phenomena suppose you observe any particular cross section you keep on noticing that particular cross section. What do you find? You find at one point there will be liquid flowing up or there maybe some sought of bubbly flow flowing up. Then at some other interval of time in the same cross section you find that air is flowing up and liquid is flowing down as an annular film. Keep on observing again you find that a bubble flow mixture or pure liquid is flowing up and after sometime again you find that only pure air is flowing up and liquid is flowing down as a annular film.

So therefore, the main characteristic of this slug flow pattern is the periodic flow phenomena or the intermittent flow phenomena. And this is characterized by the alternate appearance of bullet shaped axisymmetric this is very important taylor bubbles. These bubbles they were first observed and they were studied in very details by davies taylor and from hence forth they have been named as the taylor bubbles. Bullet shaped axisymmetric taylor bubbles followed by aerated or non aerated liquid slugs. So, the thing is if we compare the bubbly flow and this slug flows which has evolved from bubbly flow, just the increasing air keeping everything else constant.

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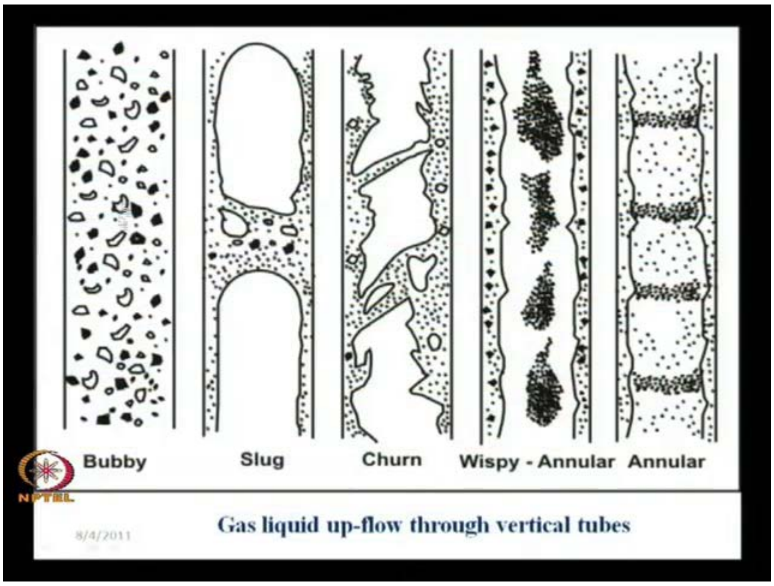

We find that definitely the distribution is widely different here, here it has a homogeneous appearance. If you observe one particular cross section you will find the same thing it is just the bubbly mixture flowing up flowing up liquid is a continuous phase and the bubbles are distributed there is no variation with time. If you keep on increasing the air flow rate you find you come to a situation where you get a periodic flow phenomena characterized by alternate appearance of bullet shape taylor bubbles and liquid slugs.

Now, again you keep on increasing the flow rate what happens these bubbles they become larger and larger as they become larger and larger they become unstable. and then finally, a situation arises when these bubbles they get sheered they get broken up and they keep on oscillating up and down in the flow passage. And they present a totally chaotic and random flow distribution which is termed as the churn flow pattern. So, what happens? That that very nice periodic flow phenomena that disappears altogether and what we get? We get a totally chaotic and random flow phenomena where we find that there are churns. Irregular churns of gases and irregular masses of liquids they are flowing up and down in a totally chaotic and random manner.

And it just presents you cannot predict the distribution like that it is simply a chaotic and random distribution that is termed as the churn flow pattern. Keep on increasing the air flow rate more and more. What happens these irregular churns what they do they gradually they start coalescing with one another now the gas flow rate is very high liquid is slow to moderate. So, these churns they keep on coalescing and then what it forms is it forms a continuous gas core. And what it does? The wall has to be wetted by the liquid phase. So therefore, it pushes the liquid towards the wall and it forms a continuous gas core as you can see here and it is separated from the tube wall by an annular film.

So therefore, from this chaotic and random churn flow pattern we find that we entered into the annular flow pattern. In the annular flow pattern we find that the gas forms a continuous gas core and the liquid is pushed towards the walls. It forms annular film just like the film which we had seen in the taylor bubble region and sometimes what happens? This film it is usually wavy when it is wavy then part of this particular film it is infringed by the gas phase. And it flows as droplets or as irregular churns or irregular wisp sought of a thing in the gas core. So therefore, the annular flow it can be characterized by a smooth inter phase or undulating inter phase depending upon the relative velocity of the two phases.

And we find that main characterization is that there is a continuous liquid film on the wall and a continuous gas core between the two liquid films, there may or may not be droplets of liquid or wisp of liquid in the gas core. Some researchers they have tried to differentiate between the wispy annular and the annular flow, but we are not going to do this for our particular purpose. We will be primarily be concentrated into dividing air water flow in vertical pipe in primarily four types of flow. One is bubbly next slug churn and annular flow.

What is our intension is we would like to keep the definition of flow patterned to a minimum as well as taking care that each flow pattern can be governed by a definite set of characteristics and they have the same physics. So that the same laws of fluid mechanics governs them. So therefore, broadly speaking what we have done we have first differentiated into bubbly flow where liquid is continuous and bubbles are uniformly dispersed. So, it is a more or less uniform mixture of the two where the gas phase is dispersed in the liquid phase.

Next we divided into the slug flow pattern where it is definitely it is characterized by the intermittent presence of gas and liquid. Gas appearing as stellar bubbles and liquid as liquid slugs which may or may not be aerated. Interesting part of slug flow is slug flow is very interesting in the sense that it is hydrodynamics is comparatively more complicated and it occurs over a wide range of flow conditions. And more importantly as you keep on increasing the decreasing the size of the tube their range of existence of slug flow increases.

So therefore, as you proceed toward miniaturization maybe you get slug flow over a much larger range as compared to normal size tubes. So, that is why slug flow is gaining more and more importance in the present day scenario of micro fluidics and things like that. So therefore, in this particular case we find the number of interesting things. Firstly, is the periodic flow phenomena. Secondly, if you observe slug flow you will find that in slug flow there are regions where the liquid is flowing downwards and the regions where the liquid is flowing upward. So therefore, if you if you notice the wall shear space you will find that the wall shear space keeps on changing direction with the passage of bubble and the liquid slug.

In this particular region the wall shear space is towards the upward direction and in this partcular region it is in a downward direction again here upward again downward. So therefore, with time we find that or rather with position we find that the wall shear space keeps on changing its direction. This is also one particular way of differentiating distinguishing or identifying slug flow from the other flow patterns. Well next after that we come to churn flow pattern which is the least understood least studied flow pattern. I should say there is plenty of scope to study churn flow pattern for the time being it is a totally random chaotic erratic mixture of two phase flow not very well understood.

And after that again we get the annular flow pattern which is again a very well ordered structure with a gas core and the liquid film. So, these are usually the four types of flow patterns which we encountered in a vertical tube for unheated conditions. Now, simply keeping everything constant instead of the vertical tube we just make it horizontal. What are the changes that you would expect? Immediately you would find that gravity would start to act differently on the two. Naturally the lighter fluid the air phase will be on the top and the water phase will be on the bottom. And so therefore, immediately something which was not observed in the previous case will be observed here that is stratification. So therefore, if we go to if we just make the pipe horizontal.

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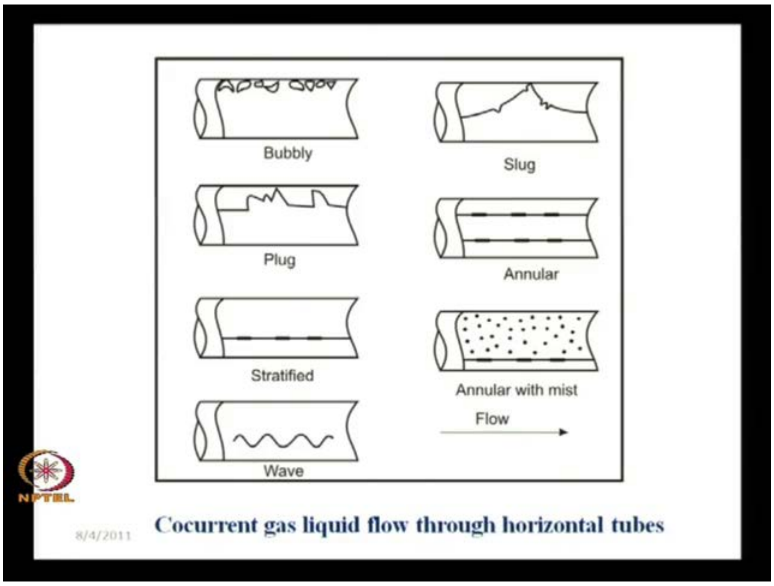

What we observe is an immediate tendency of stratification at low flow rates of the two phases we find stratified flow and then gradually as the increase the liquid flow rate or the gas flow rate. We find a waviness sets in and we come across a wavy stratified flow, as we keep on increasing the velocity then we find out the water velocity we find out that gradually these waves they become larger and larger. And then a time comes when these the amplitude of the waves becomes so large that it can actually catch the upper wall. And again if you keep on increasing the water flow rate, we find that it touches the upper wall and then it these particular gas phases they start breaking up from one another.

And then we have definite gas slugs separated by liquid slugs, but the gas slugs are usually concentrated or confined towards the upper portion of the tube. So, this gives rise to the slug flow pattern as we have observed for the vertical case, but here definitely slug flow pattern it has got an axisymmetric sorry asymmetric characters. Bubbly flow which we had already observed, there annular flow which we had already observed, there generally churning it is not very prominent. But churning can also be observed under these conditions, but all these bubbly annular slug they are all characterized by one thing here that is the asymmetry in the flow distribution.

Because the bubbles the taylor bubbles as well as if you observe the liquid film, in this particular case also you will find that the liquid film will be thicker at the lower side. It will be thinner at the upper side. and with gradual increasing of the liquid flow rate we find that gradually we the effect of gravity decreases and more or less there is a uniform distribution. So therefore, the moment we made the tube horizontal by not doing anything else we find that stratification sets in. So, we get two additional flow patterns or in other words one additional flow pattern that is the stratified flow it is usually differentiated into two types one is the smooth stratified flow, the other is the wavy stratified flow.

Just because of the difference in the wave characteristics some different treatment is necessary for the two and therefore, we distinguish between the two. Here other flow patterns are more or less same as we had observed in the vertical tubes. The only difference being that all the flow patterns have a tendency of asymmetry which reduces with increasing phase flow rates. And interesting thing we come to see also reduces with decrease in the tube diameter as well under that condition also gravity does not play much role in this. Well the next thing which I would like to deal with is suppose we deal with a heated tube same vertical tube is standing now we start heating it with a constant heat flux at the walls.

So, here what happens here certain additional factors start to come in. What are the additional factors number thing is as this tube is heated. What happens gradually say initially we have introduced liquid at below saturation temperatures. So, the liquid it starts getting heated as the liquid starts getting heated a point comes when vaporization starts to occur. When vaporization starts to occur then gradually the vapor bubbles they are formed at certain preferential sites and they start getting detached and flow upward in the liquid phase forming the bubbly flow pattern.

Gradually the weight of vapor generation increases and these vapor bubbles they become larger they start coalescing and they form taylor bubble like structure giving rise to the slug flow pattern. Again the heating continues so therefore, these bubbles they steller bubbles taylor like bubbles is elongated bubbles they become larger and larger. Till finally, the coalesce and they become a continuous vapor core and they form the if you can see this picture it is much it will be much more evident.

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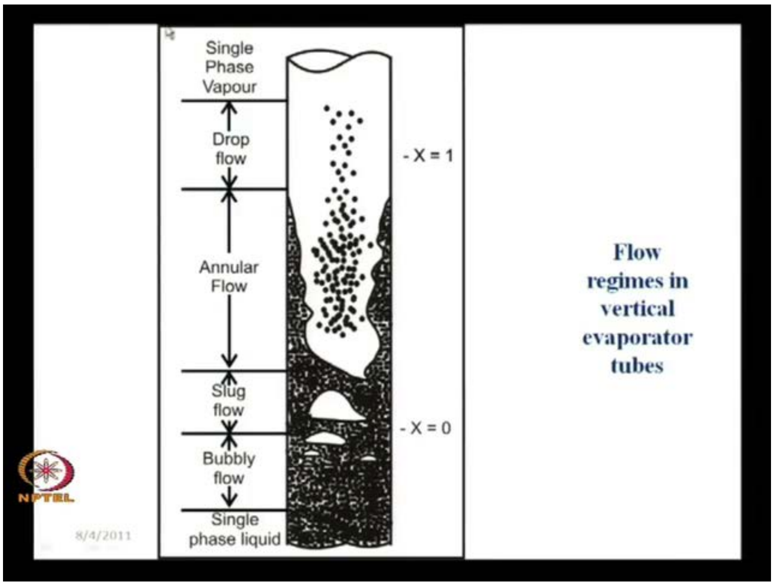

Initially we have single phase liquid where liquid is below the saturation temperature then gradually bubbles start forming and bubbles gets detached from the wall they flow up in the liquid. The bubbly flow pattern then gradually we get a slug flow pattern and finally, we find that these slugs they become larger and more numerous they then form a continuous gas core with a liquid film and the annular flow patterns sets in. Now, after the annular flow pattern sets in we find that now the vaporization it starts to occur not more at the walls, but predominantly from the vapor liquid inter phase. And gradually the liquid film it starts getting depleted, remember one thing in this particular phase the liquid film gets depleted by two mechanisms.

What are the two mechanisms? Firstly, some amount of the liquid it gets vaporized into the vapor phase and secondly, there is a liquid vapor shear. Therefore, some amount of the liquid it gets entrained in the vapor phase. So therefore, due to the coupled effect of entrainment and vaporization the liquid film it starts to get depleted. And then finally, a situation arises when there is no liquid film and there are only liquid droplets in the vapor phase this gives rise to the droplet flow pattern after the droplet flow pattern. After the droplet flow pattern the entire liquid film it has vaporized we come to the single phase vapor region as shown here.

So, in this particular case, in the case of a vertical heated tube, what you find? What are the basic differences as compared to flow in tube which are not heated? What are the difference that you find? In unheated tubes and in heated tubes what are the differences which we observe? Number one is the amount of that liquid it keeps on changing along the length since the amount of vapor and liquid keeps on changing the flow distribution also keeps on changing along the length. And as far as the flow distributions are concerned what we find is that here we find there is no churn flow which is very prevalent in unhealed flows.

The other thing is there is the presence of some droplet flow which was not there in that particular case. As I had already told you that, there is an inherent tendency of liquid to wet the pipe wall. So therefore, this droplet flow patterns does not occur under normal circumstances in unheated tubes. So, these are the two basic differences between flow patterns in heated as well as unheated tubes.

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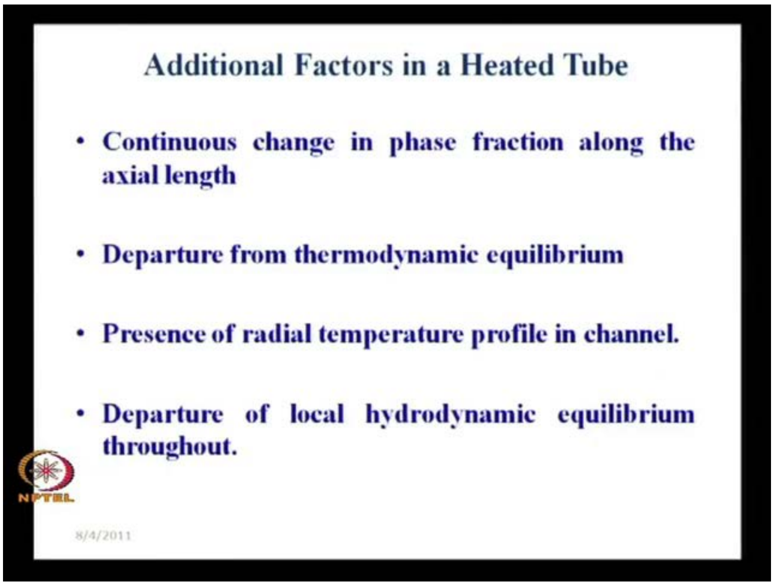

So, what are the additional factors in a heated tube as we have already discussed in a nut shell, if we have to mention continuous change in phase fraction along the axial length. So therefore, there is a continuous change the vapor phase keep on increasing the liquid phase keeps on decreasing just the reverse situating occurs if there is condensation. Next there is departure from thermodynamic equilibrium. next there is a presence of a radial temperature profile. So, for this particular thing what happens is even if we find that the liquid mean temperature is much below the saturated temperature, but vapor start to occur because the wall is at a much higher temperature.

The wall has exceeded the saturated vapor temperature. Therefore, vaporization starts, but if you find that the mean temperature at any particular cross section that is below the saturated temperature. So, the next thing is presence of radial temperature profile and departure of local hydrodynamic equilibrium throughout. So, due to these four factors we find that certain extra things come up in a heated tube when it is in a vertical position. Now same heated tube you think and tell me same heated tube I just make it horizontal what do you expect under these conditions in.

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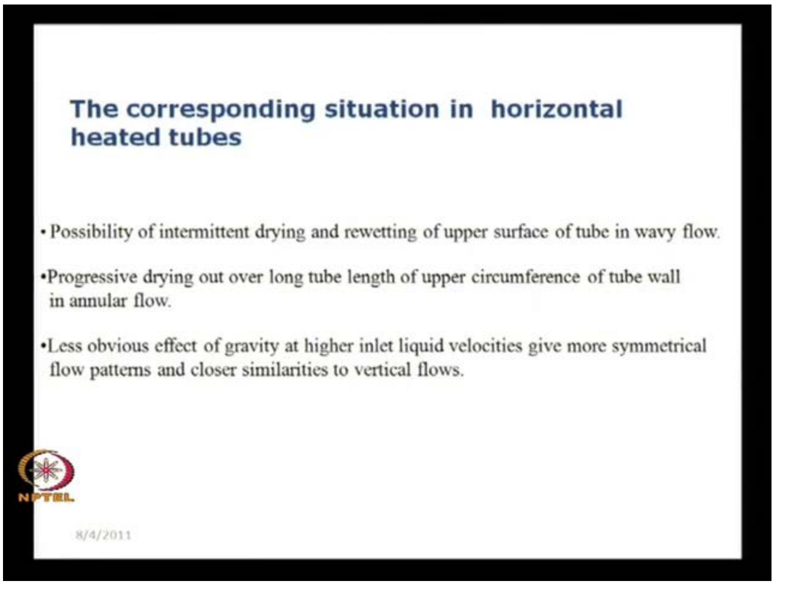

This particular situation we find what happens is that gravity well this slide we will see later. We find that gravity also starts to play a part in addition to the factors which we had already mentioned for vertical heated tube that means their presence of an asymmetric temperature profile. And then the other factors continuous change in phase fraction along the axial length, departure from thermodynamic equilibrium from departure from local hydrodynamic equilibrium presence of radial temperature profile. In addition to this, gravity also sets in and therefore, adds to the asymmetry of the flow situation. This flow situation if we imagine it will be something of this sought.

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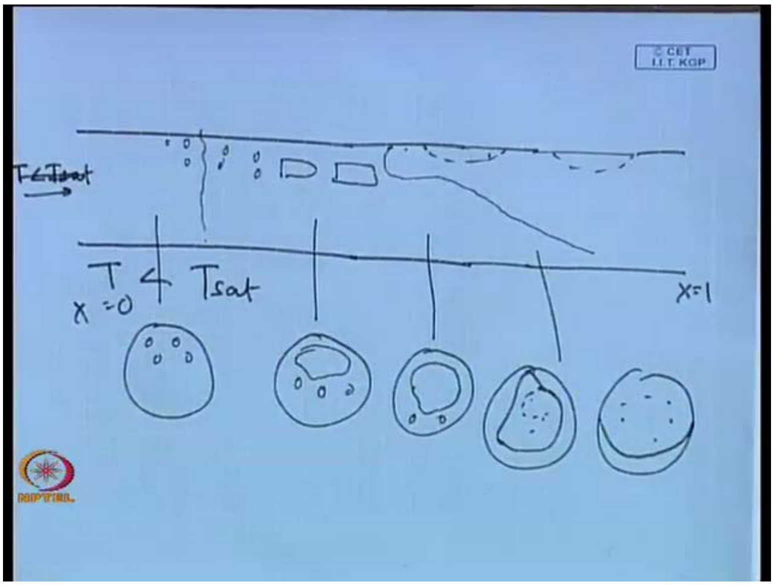

Again we start with liquid where t is less than t saturated. I will write it here, t less than t saturated, we start we have pure liquid till a particular portion and then gradually the vapor bubbles they start to come they gradually detach from the wall. And then they start flowing and then gradually they become more and more elongated just like the your slug flow sets in. And then we find a situation due to asymmetry there wll always be a tendency of the vapor phase to be on the upper portion and the liquid phase to be on the lower portion. So, what we find is we find that in the annular flow pattern there is a continuous tendency of drying out and rewetting. What happens there is a continuous tendency of liquid it gets dried out completely, but since there is a tendency of liquid to wet the wall it again rewets and again dry outs again rewets.

So, such a situation arises if we take up the cross sectional views of these cases here the cross sectional view will be something of this sought. Then gradually we keep on observing the cross sectional view, it will be something of this sought. Then again if we take a cross sectional view, the bubble will be larger and there will be smaller such bubbles. We take another cross sectional view we will find thicker liquid here and the thinner liquid here and things like that. Then we find that there will be portions when only the lower portion will be wetted and the upper portion will be dried out and this particular portion if we observe.

So therefore, this constant intermittent drying out and rewetting, this is something very unique and finally, after that of course just like the vertical heated tube. Here we have the quality equals to one here we have x equal to zero here we have only vapor flow. So, therefore, we find that in horizontal heated tube since gravity also sets in addition to the situations which we had observed in this particular case of vertical tube. We find that there is a possibility of intermittent drying and rewetting of the upper surface of the tube in wavy flow or annular flow as you call it there is. And then gradually this intermittent drying period it gradually becomes longer and longer. So, it is progressive drying out over a long tube length of upper circumference of the tube wall in annular flow.

And naturally as you keep on increasing the liquid flow rate then there is less obvious effect of gravity and therefore, the flow patterns become more and more symmetrical and more and more close to vertical flows as the liquid flow rate increases. This particular situation was for a low to moderate liquid flow rates as we go to higher and higher liquid flow rates, situation will be more similar to that which we have observed in vertical flows. Do you get it? So, in this particular way we find that when we take a tube, what are the flow patterns when same tube we just make it horizontal? What are the flow patterns same tube keeping it vertical we heated? What are the flow patterns same tube we make it horizontal? And heat it what are the flow patterns? So, these things we can understand from this particular situation.

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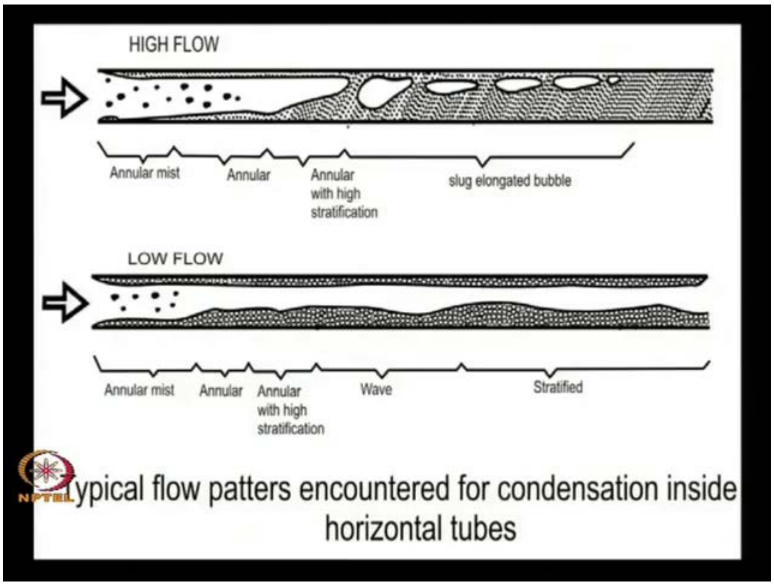

Now, let me take up once this is another situations which I have which is can be accounted for condensation. Condensation also we find naturally initially the flow pattern will be annular and then gradually just the reverse of what you have seen there. We had started with bubbly slug annular here, we start with annular means annular then some sought of stratification then slug and things like that. And remember one thing the range of existence of the different patterns how long it will be bubbly? How long it will be slug? How long it will be annular? These things they depend upon the entry condition, the hydrodynamic condition and things like that.

If a situation can be made such that the bubbles the bubble rate of generation bubble generation is very high at the walls. Then probably we will not get a bubbly flow pattern at all during evaporation. We will directly or straight away go to the slug flow pattern such a situation can also arises. So therefore, which are the flow patterns which are going to occur and what will be the range of occurrence of the different flow patterns that depends upon the inlet conditions, the other hydrodynamic condition and so on and so forth.

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Now, let us see if instead if air, we simply introduce another liquid. So, instead of air water flow we have say kerosene water flow or toluene water flow. Kerosene water flow it will be more akin to oil industries toluene water will be more akin to mass transfer operations sought of a thing. So, in this particular case what do we think what should happen do not look at the figure for the time beginning just try to understand the physics what happens. There we had one particular situation what was it that the liquid will always wet the pipe wall here both are liquids, both can wet the pipe wall is it not?. So therefore, as we had only bubbly flow here.

Here we can have oil in water dispersed flow as well as water in oil dispersed flow depending upon the flow conditions. High oil low water velocities we have oil sorry water in oil dispersed flows low oil high water we have oil in water dispersed flows. Now, this is a very interesting situation dispersed flows we need in a variety of cases and if we are dealing with liquid liquid cases be it a reactor or observer or whatever it is, we find that when we have oil in water flows. We start with a low water high oil flow rate then keeping the total mixture velocity constant we keep on increasing the water velocity decreasing the oil velocity. So, that the total mixture flow rate is constant.

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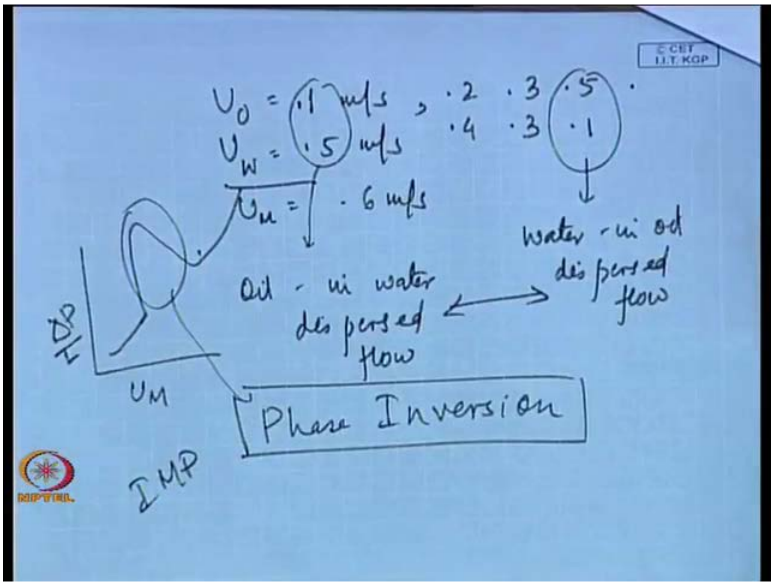

We can do it say for example, we start with say u oil of say one meters per second say just for or may be it is 0.1 meters per second and u water is say 0.5 meters per second. So that the mixture velocities point 6 meters per second then we take another flow rate where this is 0.2, this is 0.4, this is 0.3, this is 0.3. In this way we keep on going this is say 0.5 this is 0.1 and then finally, we reached to this particular flow pattern. So, under these circumstances what we have? We have an oil in water dispersed flow and gradually as we keep on changing the flow proportions of the two keeping the mixture velocity constant.

We finally, reach a condition where we have water in oil dispersed flow. And from very frequently we call one of them dispersed the other inverted dispersed some researchers. They prefer to call it oil in water, water in oil different sought of nomenclatures are there in use. And we find that the transition from oil in water dispersed flow to water in oil dispersed flow this is very very important. It is very important because the total hydrodynamics changes, the total interfacial surface area changes if water is dispersed in oil if oil is dispersed in water.

Suppose we have an organic phase and then equi phase say this particular. Any particular reaction or mass transfer, it is controlled by the organic phase part it is much any say. Suppose it is toluene acetic acid is dissolved in toluene and we have a water phase, acetic acid is more soluble in the water phase. What happens it ready shifts from the toluene phase to the water phase to the water phase. So, in this particular case we will have a better transfer a better mass transfer if the toluene is dispersed as droplets in a continuous water phase.

So therefore, we would like to ensure toluene in water dispersed phase and we would always like to see under what condition it will tend to become water in toluene dispersed phase under which conditions we do not expect a very drastic increase in mass transfer. So therefore, there are several such situations where we would like to ensure one type of dispersion or we would very much like to predict the transition from one dispersion to the other. Now remember one thing when we are having this transition what happens what is happening initially suppose we are having say kerosene or toluene dispersed in water.

Gradually as we keep on increasing one flow rate, decreasing the other flow rate what happens? Gradually we find that the toluene droplets they start becoming larger and larger water phase it is start breaking down smaller and smaller droplets. So therefore, there is a continuous creation and recreation of surfaces large amount of interfacial surfaces are being created and recreated and lot of chaos is forms under this condition. As a result of this, this particular transition which is known as the phase inversion for liquid liquid cases, this particular word is very very important you are supposed to remember.

This the phenomena of phase inversion during which one particular dispersion inverts to form another type of dispersion this is very important and this is usually characterized by the sudden increase in the pressure drop. So, suppose you take a pressure drop reading you find the pressure drop gradually increases and moment you approach the phase inversion there is a drastic reduction in the pressure drop. And again when you enter another dispersion the pressure drop decreases gradually. So, therefore, if you plot say delta p or delta p by L verses say U mixture, you find that the pressure drop gradually increases. Then when it come to phase inversion there is a stiff increase and again there is a gradual increase this particular portion this marks the phase inversion point.

So therefore, it is very important to know because under this just like point it is very important to identify this condition because it is marked by a very high increase in the pressure drop. And therefore under this particular circumstances maybe what we have observed in a laboratory studies several transfer operations are highly enhanced under this condition. So, this is something very special for liquid liquid flows you do not have it for vapor liquid or gas liquid cases. There is one other very important phenomena for liquid liquid flows which we shall be discussing in the next class.

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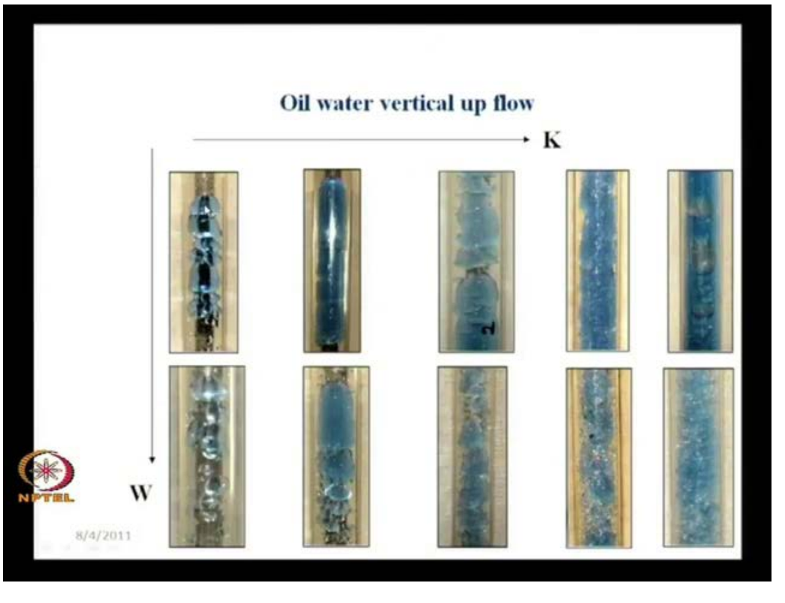

Today I will just show you some particular pictures where you can see. See in this case it is it was a kerosene water flow in a vertical pipe. You can very clearly see kerosene droplets in the water phase. If you observe this particular photograph very carefully, you will find that entire cross section is blue it is marked by a kerosene phase and some circular water droplets large water droplets are there. So, here we have brought out the phase inversion very well. Here it is kerosene dispersed in water, here it is water dispersed in kerosene such a situation which will not get for air water or vapor water cases.

Here also we are tried to do it at a higher water velocity, here we find that the kerosene droplets are smaller and in this case water is very finely dispersed in kerosene it is sought of an emulsified flow. So, this is something very special for liquid liquid cases. So, there is there are certain other interesting factors for liquid liquid cases which we will be taking up tomorrow. And then we will go to some other interesting or unique features of flow patterns for different geometries different flow conditions and So on and So forth. So, tomorrow we will be continuing this lecture and we will studying more about flow pattern tomorrow. Thank you very much.