Multiphase Flows
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Lecture – 4
Flow Regime Map for Gas-Liquid System

So, welcome back what we were discussing in last class is about the basic terminology we used to define the multi-phase flow. And we have defined several terms definition volume fraction impaction stop number stokes number dilute flow regime dense flow regime and everything. Now we will start with the basic course and the course is now what we are going to discuss first is about the flow pattern.

Now, in multi-phase flow or any flow the flow patterns s very important. And it actually what it does the flow pattern is derive or it tells you about the overall behaviour of the system. So, like in single phase flow we have 2 type of flow and one is laminar flow and turbulent flow and in between there is a transition. So, you can say 3, so what it does? If I know the flow is laminar then we know we can think about the profile that it is going to be velocity profile is going to be parabolic. And if we say that the flow is turbulent we are going to say that it is going to follow u by u max is by 7th law or so; so that you will have more flatter profile at the centre and it will be kind of changing or linear at the wall. So, the flow pattern for engineering purpose is very important and very critical to overall visualize the flow.

So, what we do we also try because the notion of understanding of the mechanics or fluid mechanics say is again coming from the flow pattern and we know that we have different set of equations; available depending upon that what kind of flow you have. So, if you have laminar flow you have a different set of equations, if you have turbulent flow you have different set of equation you have different equation for the friction. And all and what is the basic motive to do that is to calculate the delta p. So, if I am designing any pipeline system if I am designing any flow system I should understand what is going to be my delta p.

And we all know from our single-phase experience that the delta p is going to be the function of the flow pattern. So, what we are going to classify in also that like in we did it in single phase flow, we are also going to see that what kind of a flow pattern is feasible in multi-phase flow reactors or multi-phase flow vessels or multi-phase flow contactors.

Now, here the flow is not very simple it is more complicated compared to the single-phase flow and it is complicated because you have a second flow secondary flow; also, it means second feeds is also available. Now so we go beyond thinking about the laminar and turbulent or transition. Now we are we have different flow regimes and this flow regimes which we call is actually depends and will discuss that is that how these 2 phases are interacting with each other. So, again the interaction is going to be very critical and will see the equation of interactions later on, in this course, but right now before writing the equations or the interactions I would like to tell that what are the regimes you encounter. If you interact or if the 2 phases or is flowing together. Now these 2 phases can be gas liquid, can be gas solid, can be liquid solid or in more complicated cases it can be all the 3 phase where the gas liquid solid is coming into the contact and flowing together.

Now, because these phases are different their flow regimes is also different there is no universal flow regime which we can say that laminar or turbulent does not matter, what fluid you have if the fluid Reynold number is beyond a certain number, say for a closed conduct if a Reynold number is more than 4200 the flow is going to be turbulent, if Reynold number is less than 2000 the flow is going to be laminar. So, this kind of a universal definition is not available in multi-phase flow; and that make the field very challenging and interesting because will see that the flow regimes what we will discuss will change very swiftly if you change any of the parameter. So, what we are going to do today is we are going to discuss about the flow map flow pattern map and will try to cover the gas liquid flow pattern and then will also cover liquid solid and gas solid, but today we will try to cover basically on the gas liquid flow pattern. And if time permits we will also try to see the liquid solid.

So, let us start with the flow pattern with this background that this is something which is very critical to analyze the flow and that that understanding we already have from our basic undergraduate fluid mechanics course.

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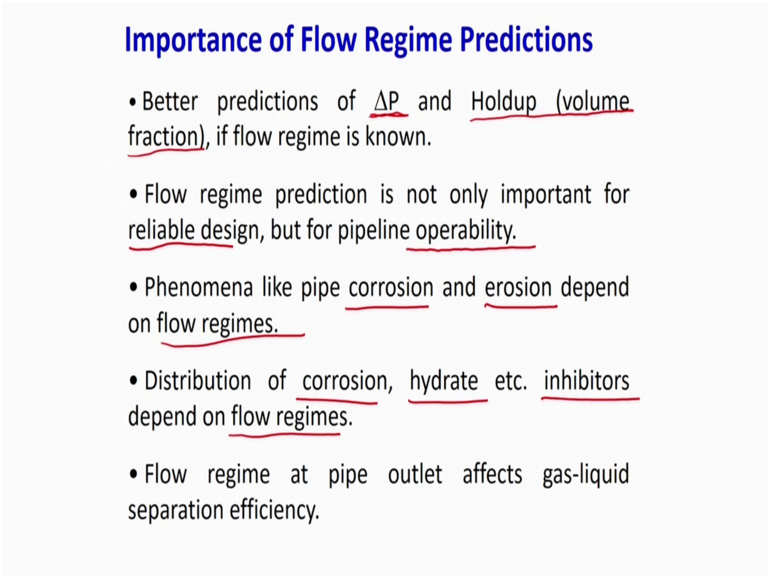

So, the first question will be asked and I have discussed some of this already; that why on the earth I should understand the flow regimes, what is the need to predict the flow regimes and the flow regime prediction if you want to understand any multi-phase flow vessels or I will say vessels because it can act as a reactor it can act as a contactor, it can as just to flow the systems.

So, for me right now I will refer it as a vessel. So, why on the earth I should understand the flow regimes. So, the flow regimes to analyze any multi-phase flow system if you have. So, either it is a gas liquid, liquid solid, gas solid any multi-phase flow system. The first job I will do to understand the system is, what is the different flow regimes involved in the multi-phase flow of these 2 phases or 3 phases which here we are contacting, and how this flow regime is going to change right changing any of the parameter.

Now that parameter can be velocity, can be fraction of the one of the phase velocity of one or 2 both of the phases, can be column dimensions also and will discuss that that why the column dimensions is also very critical in predicting the flow regime map. So, what why we need the first question is that why we need. So, the first answer or kind of most important answer is that it gives us the better prediction of delta p and holdup.

So, we will see the holdup volume fraction, we have already defined, but the first thing which is very critical is that it is going to tell me the exact prediction of better prediction of delta p. And that is very critical for any flow to happen, as we know that the flow the gradient for the flow is the pressure drop. So, if we know the pressure drop, then only we can understand whether the flow will take place or it will not take place and what will be the pattern of the flow. So, the flow regime map help us to calculate the delta p and how it help us we will see later on, but the if you do not know the flow regime map that is very difficult to calculate the delta p itself.

Then it also tells about the holdup of volume fraction of one or both the phases and most of the flow regime curve we will also define in terms of the volume fraction that how much volume fraction you have. So, it gives 2 things and that is very critical for in analyzing any multi-phase flow particularly if there is a flow; so that is delta p and holdup ok. Then it is also important for the reliable design ok. So, we will see that why it is being reliable design is necessary or kind of why, how the flow regime map is going to change your reliable design and pipeline operate ability. So, it helps us in both in prediction of desirable design.

And it also says that where what is the operate ability of this kind of a system, how we should operate ok. So, those things are there and why the operate ability is going to be a so because we know that operate ability depends on delta p and we already said that delta p is going to depend on the flow regime map. So, that is also a very critical thing and that is why we need the flow regime, then they are certain phenomenon. Now this is a multi-phase flow so because of that and one particle in discrete form. So, depending on the nature of the fluid the corrosion as well as erosion both can happen ok. And that depends the either the corrosion or erosion depends on the flow regimes.

So, we will see the different flow regimes and well also try to see that if this kind of regimes will be there the erosion will be very high. So, the erosion and corrosion both depends on the flow regimes and therefore, if you are designing the system depending upon what is the flow regime you are operating what is the system you are operating your design parameters will change; and that is why again it is being correlated to the reliable design so you want to have a reliable design you have to have know that whether this regimes whatever I am operating is going to have more corrosive or more erosion will take place and you then you have to give the extra safety factor.

So, that is the one thing then second thing not only the corrosion and erosion, but even the distribution of the corrosion and if there is some hydrate formation that also depends on the flow regimes. So, depending upon what is the flow regime, your corrosion distribution or hydrate formation if something is taking place particular in the petroleum pipeline design that will also depend the flow regimes. And if you want to have inhibitors what kind of inhibitors you want to use to say reduce the drag or something then also a wax formation that; how much you have to use how to distribute that all depends on the flow regime. So, that is something is again very, very critical that inhibitor performance.

And it also affect and that is very critical for any petroleum industries that how the flow regimes is there, if you want to have a separation it will also affect your separation. So, your separation will also get affected based on the flow regime. So, suppose in a pipeline of petroleum, where the petroleum is being transported petroleum products say in a crude oil is being transported where some gas product is also there, there is liquid and gas both are involved. Whether they will automatically get separated or they will not get separated at all suppose if the gas is disposed in a very fine bubbles or liquid is dispersed in a very fine droplet form the separation will be very difficult. If they are having a separated flow it means liquid is flowing at the bottom of the column and a pipeline and gas is flowing on the top the separation may be easier. So, their separation efficiency and at the end we want to separate them so their separation efficiency also depends on the flow regime.

So, even you post processing so if I think about a petroleum industry and why I am talking about the petroleum industry because it is one of the most critical industry for the chemical engineers per say or even for profitability this is one of the most critical industries. So, if suppose I have a petroleum industry and we have to find that what is the flow regime, I am operating my pipeline to transport the fluid crude from the oil well to the companies or to the refineries.

So, depending on the that flow regimes our gas separation efficiency can also be changed and the process required for that thing can also be modified. So, these are the important point where why the flow regime predictions are very critical, and why if someone is thinking about any multi-phase flow system, the first job he should do is to prepare a flow regime map. And that flow regime map helps you a lot to understand about the system. So, what I am first going to do? I am going to discuss a typical flow regime map for the gas liquid and we will see that that regime map is going to change though the variables will remain the same the kind of the parameters or these things is going to be remain same.

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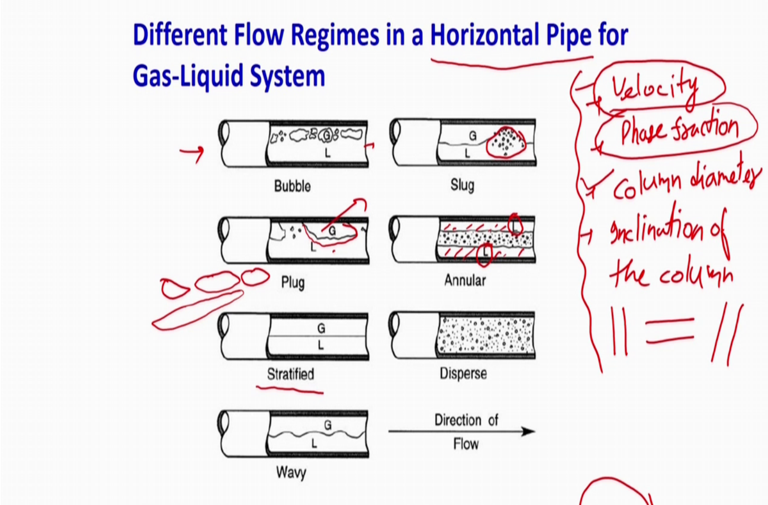

Sketches of flow regimes for flow of air/water mixtures in a horizontal, 5.1 cm diameter pipe. Adapted from Weisman (1983).

So, the most important or you can say the challenging part of the multi-phase flow is that; the flow regime actually changes with the changing the velocity of each phases ok. Any of the phase of both the phases if you are changing the velocity it will change. So, it will change with the velocity; and because you are changing the velocity definitely the phase fraction is also going to change as we have already discussed that. So, the phase fraction that is also, it is going to change it also changes with the column diameter and that is very, very critical.

And it is not true with a single-phase flow. So, we know that in single phase flow also the flow regime changes with the velocity, you keep on increasing the velocity your flow will transform from laminar to transition and transition to turbulence. So, that is nothing surprising, because it is multi-phase flow phase fraction also plays a role and we have already discussed the correlation between the phase fraction and the velocity inside whatever we are going to achieve, but which is very critical and more challenging is that; in multi-phase flow the flow regime also changes with the column diameter. So, your regime may change. So, if you are studying a regime say for a small curve diameter column and if you are changing the diameter of the column your flow regime may change.

And that we have already discussed in beginning classes of multi-phase flow, where I said that if you are going for the scalar particularly in multi-phase flow, what you are going to see is that; your flow physics is going to change once you change from laboratory scale equipment to pilot plant scale equipment, from pilot plant a scale equipment to industrial scale equipments.

So, your regimes your flow physics is going to change and why the flow stage exchanges because with changing the dimensions of the systems, overall your flow regime it may change. And that makes the problem very interesting as well as very challenging. So, you have to understand the flow regime and you have to also understand the flow regime as a function of all these variables, even it also changes with the inclination of the column.

So, it means what? If I have a column which is vertical and if I have a column which is horizontal or inclined at a certain degree, the flow regime for even if I keep the velocity same if I keep the column diameter same, even if then the flow regime will be different. And that we even the things more challenging because it means; you have to understand everything you have to understand the effect of the inclination whether the flow is horizontal, whether the flow is vertical, what is the velocity at which you are operating, what is your column geometry you are operating, what kind of a fluid you are operating that is also very critical.

So, the regime is going to be different for the gas liquid gas solid liquid solid gas liquid solid. So, you are going to have a different regimes in that. So, all these things depend and it changes the flow regime map changes with all these parameter and because of that the studying the flow regime is the first job one do once we have to analyze a multi-phase flow system. So, that I should understand that which flow regime I am working. And that is the first question is being asked that if you are operating any multi-phase flow system will just first question is being asked that which regime you are operating. And why it is very critically we try to understand.

So, suppose I have a pipeline system gas liquid system is being transported in the pipeline it is very critical again I am telling for the petroleum industries where we have to transport the crude oil which have some fraction of the gas and some fraction of the liquid, and they are flowing together ah. So, how the transportation will take place how it affects. It is going to change and so the system is mostly horizontal there is some inclination also, but most of the time it is horizontal. So, we discussed that what will be the flow regime you will encounter.

So, if we increase go from left to right what we are doing, we are actually increasing the this is the direction of the flow is from the left to right and if you are going from the top to bottom actually we are increasing the velocity. So, what this system whatever the sketch has been taken this is the Weisman 1983 paper I have taken from that. So, this is adopted from this paper journal paper one can refer that paper. And this is for a air water system so this is not for the crude oil particularly not for natural gas and the crude oil composition. It is for the air water system much simplified system, and the column dimensions I have mentioned because as I said that if you change the column dimensions your flow regime map also changed.

So, this is for a column of 5.1-centimetre diameter. So, around roughly 2-inch column this plot has been made. And it says that initially what will happen if you have a liquid and gas linked together if your liquid gas velocity is very small then what will happen you will see the bubbly flow it means; your bubble some bubble formation will take place. So, the moment you will aspire the gas inside a liquid the gas will form a bubble and it will be start flowing with the liquid. So, that you will see the bubble and the bubble can be a very irregular shape depending on the velocity of the gas injection.

So, if your velocity is low you will see the bubbly flow, then if you further increase the velocity of the gas and again I am just increasing the velocity of the gas I am not talking about the liquid. So, if you increase the velocity of the gas then what will happen? slowly just bubble because now the velocity of the gas is higher they will start agglomerating or they will have a coalescence. Now because they are coalescence they will form a bigger bubble and you will see a plug kind of a structure. So, you will see the continuous liquid and glasses is in form of the plug so this is the gas plug. So, you see the plug of the gases and that is called the plug flow.

So, you will now see the bigger bubbles and the bubbles will be in form of the plug. Now if you further increase the velocity beyond a certain point then, what will happen? The gases will get a continuous structure why? Because again these 2 plugs will start getting agglomeration or coalescence they will be coalescence take place between these 2 bubbles. So, say it is a small bubble here and the bigger bubble is here then there is one more bigger bubble. If you keep on increasing the velocity then all you will see is a continuous layer of the bubble a big bubbles and that is called the stratified flows.

So, what will happen you will see that a structure will be formed where the gas will be flowing on the top of the pipeline and liquid will be showing on the bottom of the pipeline; and that is called a stratified flow as what I was discussing that if I have to see the separation the separation efficiency may be better.

So, that is the way it has been achieved if you operate the gas at a little bit high velocity, but getting they stratified flow it is very unstable flow so, getting it is very difficult. So, what will happen if you change the velocity further what will happen this is stratified which you are seeing a strong a straight line will get disturbed and you will see a wavy like a structure like on a river you see ah. So, you will see a wavy like a structure and that wavy like the structure is called wavy flow ok. So, that is structure will get disturbed because of the higher gas velocities.

Now, if you further increase the gas velocity, what you will happen? You will see that they this structure will further get disturbed. And what you will going to see is this small droplet of the bubble which is actually now penetrating inside the liquid. So, this will be the bubbles which will be penetrating inside the liquid. So, a liquid will gas will be there on the top and some bubbles will be start penetrating inside. Now if you further increase the velocity and you make the velocity even higher what you will see you will see the reverse, the bubbles will come at the center and the liquid will be on the wall.

So, this will be the liquid fill and a continuous bubble layer you will see and that is called annular flow. So, I have the very high velocity the gases all the gases will now come at the center of the column because of the pressure drop and liquid will pull at the wall or thrown at the wall and you will see annular flow profile. So, this is a liquid there is a liquid here those places and the gas is actually flowing in form of the bubble at the center of the column that is called were annular flow.

Now, if you again increase the velocity very high of the gas then what will happen? The gases will be uniformly distributed across the flow and that is called dispersed flow. So, we will see complete dispersion of the gas bubbles small gas bubbles which is flowing inside. So, that is the way different flow regimes is operated once you chief on changing the velocity of the phrases, but please remember this is for only horizontal pipe, this is only for the horizontal pipe for a column diameter of 5.1, if you increase the column diameter your regimes may change.

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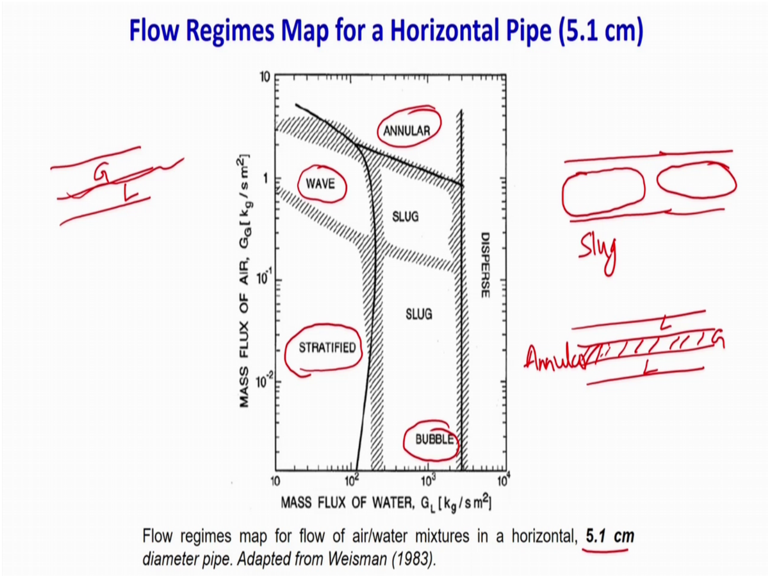

So, what people have done that Weisman has tried to plot he did some experiments, and all these experiments he tried to analyse. And what he did he make a plot which is called the flow regime plot and this y axis and x axis is keep on changing depending upon which author paper you are following at which group paper you are following. So, he plotted it with mass flux of air to the mass flux of water.

Now, one can also plot it in terms of the velocity, so many some of the graphs you will see that velocity of the water and velocity of the air ok. So, if the area is going to be the same you are going to have the row of the water is going to be same. So, you can convert the same plot very easily in terms of the velocity. So, for 5.1 again horizontal column he had plotted the mass flux of water and mass flux of air. And if you see that if you have a very small mass flux of water, as well as very small mass flux of air then what we are going to get is that a stratified regimes.

So, you will see the 2 flows liquid will be on the bottom; gas will be on the top you will see the stratified flow. Now if you keep the mass flow rate of water constant and you keep on increasing the gas velocity what will happen? The enhanced gas velocity it will go to wavy. So, that will you will get the wave kind of a structure or wavy flow. If you further increase the gas velocity what you will get the gases will come at the center of the column and you will see the annular. So, you will see the annular kind of a flow ok. So, that is the way this is going to change.

Now, what I am going to do I am going to change actually both gas and liquid flow here previous slide, we have just discussed that I am changing the gas flow here we are changing the gas and liquid both the flows. Now if I further increase the gas liquid velocity then even at a lower gas velocity instead of the bubbly flow, what you are going to get? Sorry stratified flow what you are going to get is the bubbly flow.

So, if your liquid velocity is relatively higher and if you are putting the gas at a lower velocity what you are going to get is the bubbly flow, but in the same case if your liquid velocity is low same diameter everything same if you are just inducing the bubble air then it will go to stratified flow. So, depending on the liquid velocity that flow regimes may change that is what; we have discussed the velocity of both the phases not only one phases.

So, previous graph we have discussed liquid velocity same and then we were discussing about the regimes, now we are changing both. So, bubbly flow you will get only if your liquid velocity is higher than a certain values which is around say 110 LPM or 120, this of mass flux kg per meter square per second, then only you will get the bubbly flow neither you will directly go to stratified flow.

Now, if you keep on the same range of the liquid velocity if I keep on increasing the air velocity then what will happen? You will get a slug flow, now what is slug flow? It is very close to the plug flow, but the where the bubble size is very, very big. So, the slugging means; the air will form the bubble will be of a diameter which is approximately equivalent to the diameter of the column. So, that is called slug and that definition this is slug. So, what will happen you will see a big bubbles because now kind of coalescence will take place you are keeping the increase in the velocity. So, as I said the plug if you further increase the velocity we will get the slug where the diameter of the bubble will be too big and it will be as big as the diameter of the column.

So, that is called the slug flow some people also call the Taylor regime, Taylor bubble regimes we will discuss it in the later on once we are going for the micro channel discussion, but right now we call it as a slug. So, the diameter of the bubble is very big as big as the column diameter and liquid will be thrown at the outside, but this is not the continuous please remember this you will see the several slug ok. So, it is not continuous. So, do not get confused with the annular you will see the continuous line this will be the annular. So, this is liquid, this is liquid and this is the gas then it is called annular.

So, the slug flow occurs and will see a very big bubbles ok. Now because of that big bubbles, if you think about the pressure drop or the flow it will be fluctuating because sometimes we will get only liquid, sometimes we will get only gas or mixture of the gas and liquid, but it will be a pulsating kind of a flow at the outlet. So, the separation again what I was talking about if I am talking about horizontal flow the separation is going to be different will discuss anyway about the separation. So, the slug regime occurs even if you increase keep on increasing the gas you will again get the slug regime. And after a certain velocity of the gas when the gas velocity is very high you will get the annular. So, this will be the annular.

And the disperse says if your liquid velocity is too high ok, then for all the gas velocities you will get the dispersed phase. So, say they said that in a column of 5.1 centimeter of diameter at around roughly 3000 kg per meter square per second of water flux mass flux, you will always get whatever the air velocity does not matter you will always get a dispersed stage. So, this is the flow regime map they have plotted in 1983 for a horizontal pipeline of a column diameter 5.1 and they have suggested that this kind of a regimes you will get. So, what we have seen that; in this regime curve that the regime is going to be it is strongly depend on the velocity of the both the phases. So, if you change the velocity of one phase or both the phases your whole regimes may change. So, that is the way the flow regime map is going to occur and they have plotted it.

Now, if you come back to our separation principle. So, suppose if I have to do the separation in the petroleum industries pipeline, if the flow is stratified definitely we know that the separation will be much easier. if the flow is slug kind of behavior the separation will be much tough because it is going to be the pulsation. And annular flow again because the gases has to evolve at the end of the day on the top of the system it will actually bubble. So, the separation efficiency for each of the cases will be very, very different and for dispersed phase say.

So, very fine bubbles or then it was kind of going to very difficult to separate. So, kind of they can even form emulsion completely in the dispersal regime. So, the separation efficiency are the post process also going to depend strongly on that what flow regimes you want to operate. So, that is the way and if you change the diameter of the column like, the same paper Weisman has shown the diameter now they have reduced it for the half so 2.5 centimeter.

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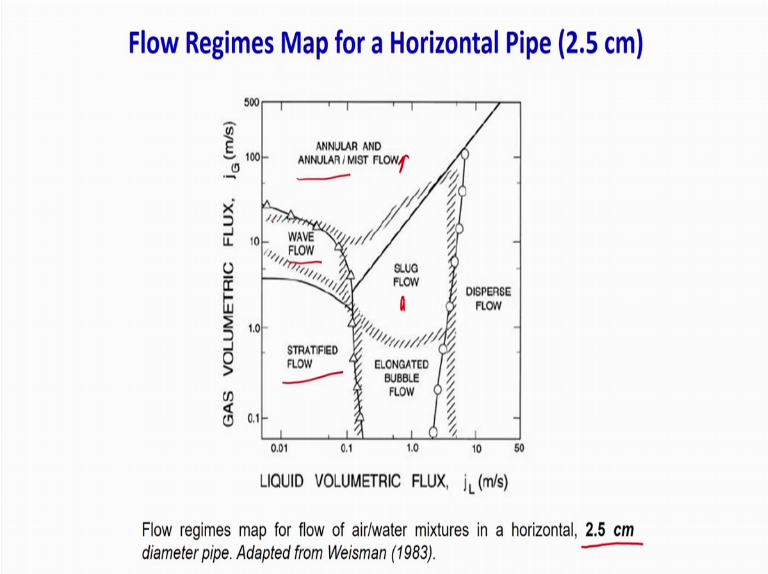

Flow regimes map for flow of air/water mixtures in a horizontal, **2.5 cm** *diameter pipe. Adapted from Weisman (1983).*

Now, once they have reduced the diameter by half all these numbers is actually modified. And now they have shown it in terms of the volumetric flux and in the unit will be in terms of meter per second. So now, you see that you are having now different the whole dimensions has been changed. So, though the regimes remains same, but you are changing the diameter the evolution of that regime is now taking place at a different location altogether. And that is what we were discussing that if you change the flow regime, if you change the dimensions of the system your flow regime get modified. So, maybe were earlier you were getting the wavy you start getting the annular flow regime ok.

So, in that way the overall pattern remains same that if you have a smaller liquid velocity or mass flow rate, then you are going to an a smaller gas velocity or you are going to have a stratified flow. If you keep the liquid flow range changed if you increase the velocity we get the wavy flow if you go further you will get the annular flow. And if you have a velocity which is a little bit higher you will get the bubbly flow or elongated bubble flow it means the plug kind of a flow, then you will move to the slug and then again you will move to the annular. And if your liquid velocity is very high you will always get the dispersed regime. So, that is the way the overall regime get changes, but all these boundaries is now shifted.

And it means now at the same velocity whatever you are getting say a bubbly flow in case of bigger column, you may get dispersed phase or dispersion dispersed flow in case of the smaller diameter column. So, that physics or the flow regime may change and that is what we were discussing earlier that why the scale up in the multi-phase flow reactors is. So, critical and one need to understand the whole hydrodynamics whole flow regime before going for the scale up issues.

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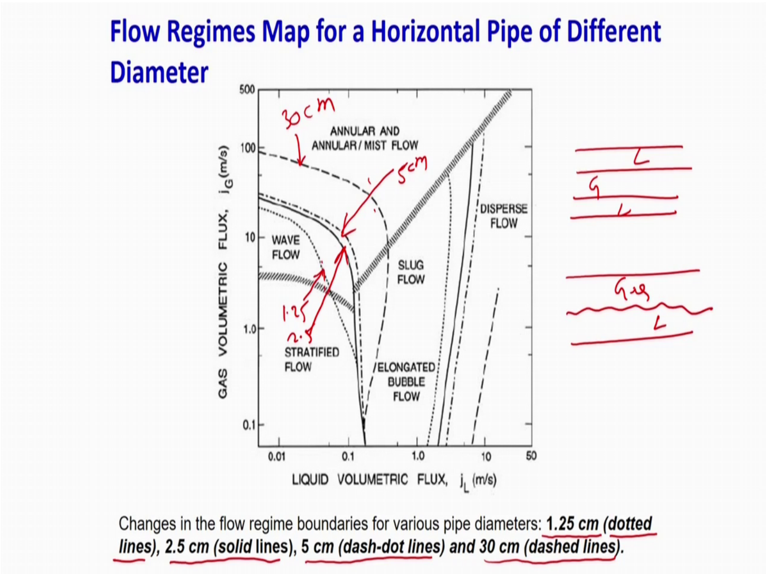

So, this again the column diameter where the different dimensions how the flow regime changes with this you get idea or feel, how the flow regime changes for different diameter of the system. The system remains same it is the air water system horizontal pipe, but these are the boundaries if you are seeing here for the different diameter system. So, please note it down that 1.5 centimetres there is 3 column, 1.5-centimetre diameter, 2.5-centimetre diameter and 5-centimetre diameter. So, if you will see that 1.25 the dotted line shows that 1.25 system solid line shows 2.5 system and dash dot line shows you the 5-centimetre system and bigger evenly go with the bigger 30 centimetre the dashed line is showing the 30 centimetre.

So, the 4 diameter column we have tried to compare to so that; how the regimes will change, if you change the dimensions. And you will see that even a small change in the diameter is changing the regimes the location of the regimes may change and if you change the diameter very high then your location of the regime even can be shifted very big.

So, if you see here this is the regime for if I just say that this is for 1.25 this is for say 1.25 now if you increase it this has been shifted this is 2.5. If you further increase it this has been shifted this is 5 centimetre and this is 30 centimetre. See the variation if I see the variation this is the log cross. So, that is why maybe you are not able to see the difference, but ideally the difference is very big if in terms of the liquid velocity. If I see, gas velocity if I see then the wavy. So, the stratified wavy regime which will say is being transferred from a velocity in the range of say 20 centimetre for the smaller pipe to 100 centimetre per second for the bigger pipe for the volumetric flux ok.

So, that that is the safe so 10 times increase in the volumetric flux you will have to take before you go to the annular regime if you change the diameter from 1.525 centimetre to 30 centimetre. So, the flow regime that the jump is very high, actually, it is not very small jump, ok. Similarly, the liquid volume fraction which will be safe we see in the range and if I take average of this somewhere at this line here then earlier it was say around 0.09 upon 0.08 now it is moving to a factor of around 0.5, if I take somewhere here ok. So, there is a big jump in both liquid velocity or liquid volumetric flux and gas volumetric flux before the regime get change.

So, it means if you are doing the scale up and why the flow regime map is so critical, that if you are going to scale up you should understand how your flow regime map is going to change with the diameter of that column or with the dimensions of the column. And if you are not very sure about it and if you do not know about that what will happen you will do a design which is not going to work. So, suppose if I design something for the angular flow regime with the change in the diameter that will come to the wavy flow regime. And now if you see the annular flow regime the flow is like this, this is liquid, this is liquid this is gas and in the wavy regime this is the liquid and this is the gas, we know that the contact area is going to be change drastically.

Now, if the contact area is going to change differently your heat transfer your mass transfer reaction if the anything is taking place it is going to change drastically. So, you will see a different result all together and that is what we were explaining that; how why it is very difficult to scale up the multi-phase flow reactors and to do the proper scale up you should understand that what is the flow regime map whatever we are doing, what is my flow regime map, how this flow regime map is going to change with the dimensions of the system. So similarly, all the dimensions, if you see has been shifted towards the right side. So, the regime transition for the lower diameter was taking place at a much lower volumetric flow conditions whether it is gas or liquid. now it is shifting towards the right side. So, same regime change will take at a much higher gas flux or liquid flux conditions ok.

Now, one can argue that this may be because of the area that is why we are not plotted in terms of the velocity per say we are plotting in terms of the flux so it is the per unit area is already being there. So, that is the way it has been there. So, you have to shift right side and that is why the scale up is a critical and one should understand the flow regime map and that is why the flow regime map is so important so that; you can understand how your flow is going to take place and you can do a reliable design.

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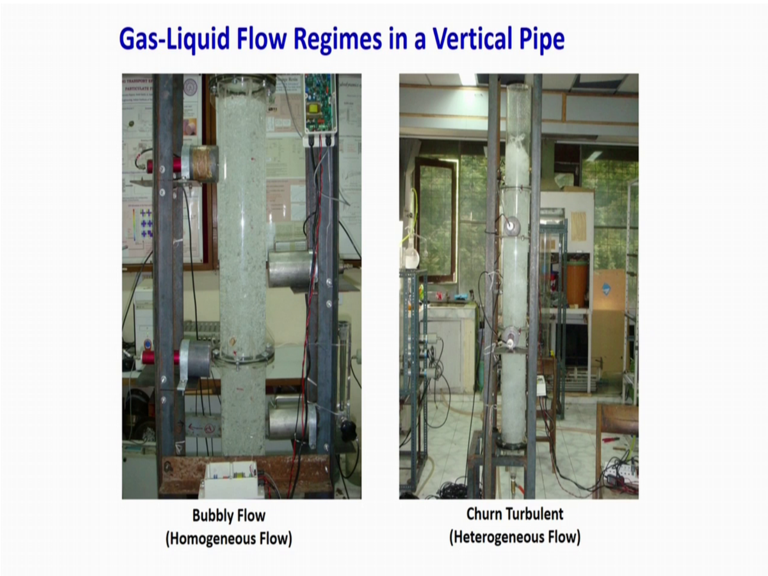

So, this is whatever we have discussed till now is a horizontal column this is the 2 photographs taken in our lab for vertical columns and if you see the vertical column this is the bubbly flow in which you can see a small bubbles maybe the picture is not very clear, but if I would like to zoom it. Then you can see that there is a bubbles here small bubbles which are flowing inside and the bubbles are pretty much individuals though it looks very high fraction the fraction is not very high because the camera is refracting the lights it is looking like a very high fraction. So, this is the small bubbles which is flowing inside and this is a churn turbulent regime a very high gas velocity how you will see. So, this you see that is very violent system from the top you can make it out and this system is very calm and cool because the velocity is very low.

So now whatever we have discussed earlier was for the horizontal pipe now whatever we are going to discuss is for the vertical pipe and the vertical pipe all the things will be again different and this is just 2 typical photograph I have just tried to show.

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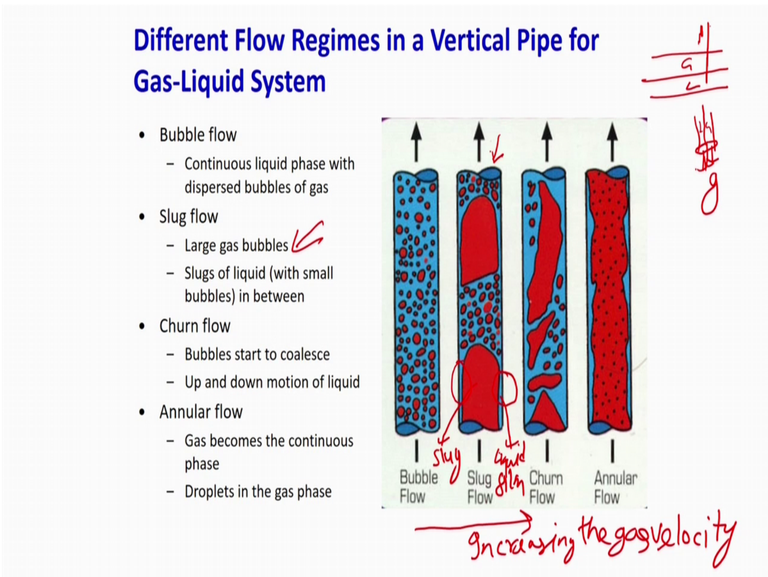

So, if your system is vertical then what happened the flow regimes will be different. And as I said that the flow regime in multi-phase flow is going to be the function of the inclination of the system also some of the regimes even now we will never get like the stratified regime.

Now, the stratified regimes where the gas and liquid was flowing will separated say this is the liquid this is the gas this mainly because they are separated because of the buoyancy effect or their density difference. Now that density difference we are able to feel because there is a gravity which was acting here. Now if you make the column vertical the gravity will act uniformly across whole the column dimension or whole the column diameter here. So, what will happen you will never see so this a whole curve diameter you will see the gravity. So, there is no way that the buoyancy can get affected and the liquid gets separated in these 2 parts. So, the gas is flowing like this liquid is flowing like this it is almost impossible it is not possible at all.

So now, that flow regime is stratified flow regime, wavy flow regime all those things will go out plug flow regime that is also going to be out because you are not going to get those regime there was you are getting because the gravity was playing a role and it was different once you are going there and the buoyancy can play a role and then liquid and could have get separated, but now this is no scope of liquid to get separated the column is vertical gravity across the diameter is going to be the same. So, because of that now your flow regime will be different and we get mainly 4 type of the regimes, and one is the bubbly flow and if you go from the left to right again what I am going to do we are actually increasing the gas velocity, increasing the gas velocity or you can say gas mass flux or volumetric flux.

So, what will happen initially if the velocity of the gas is very small then, what will happen? There is small bubbles you will see and that bubbles will actually uniform will moving from bottom to the top and the coalescence will be very, very small and you will see a pretty much distributed bubble dispersed bubble across the column and size of the bubble can differ, but there will be a particular range through which the size of the bubble will change that actually range depends on the surface tension and other parameters which we really discuss once we discuss the bubble column, but what will happen once you put the velocity very small velocity of the gas once you sparse in the liquid. Then what will happen you will see a small bubbles ok. And these bubbles will be well distributed the coalescence will be relatively less. So, the bubble size distribution will also be not very uniform, but yes distribution will not be very wide. And you will see a dispersed kind of a bubble phase ok.

So, that is kind of a graph you will see. Now if you keep on increasing the velocity what will happen the coalescence will start and you will see the bigger bubble ok. Now depending upon the column diameter again I am telling you that depending upon the column diameter you can see the slug flow regime or you cannot see the slug flow regime at all because how we have defined the slug flow where the bubble diameter is approximately similar to the diameter of the column. So, like these are the slug so this is the slug ok.

Now, think about the system which is say 30 centimetre in diameter. Now getting a bubble stable bubble of a diameter of around 30 centimetre, it is very, very tough. So, if you have a column or if you have pipeline or you have a reactor or contactor which is very big in the diameter then the bubble slug flow regime goes out of the question. So, you have changed the dimensions your regime will go out. So now, you will never get a slug flow regime and you directly shifted to the churn flow regime.

Now what is the churn flow regime? There what happens you will see the bigger bubble, but the diameter of the bubble is not equal to the diameter of the column, but the length of the bubbles is very high you will get a very elongated bubbles length. And you will see a wide distribution of the bubble length and the velocity that is why it is called churn turbulent flow because the velocity is very, very high. So, bubble velocity will be very high it will be randomly moving. And if you further increase the velocity of the gas then what will happen you may see annular condition. So, may be the gases are flowing at the center of the column and liquid is thrown out of the near the wall. So, these are the 4 regimes actually you can get and as I said that for the slug the large gas bubble you will see, but and you will see the small liquid fill here that is the liquid fill across the bubble and the wall. So, that is the slug the liquid film is very, very small this is the liquid film that is the typical classification of the slug flow ok.

In the churn turbulent bubble, the bubble get coalescence it bit mean even bigger elongated bubble this moves up and down the liquids and kind of the bubble size distribution is very high. If you further increase the velocity the bubble gases can come at the center of the column and they form a annular flow. So, these are the flow regimes 4 flow regimes you will get in a vertical pipe compared to the flow regimes whatever we have discuss in the horizontal at least 3 flow regime you will get rid off and that will be the stratified wavy flow and plug flow so this 3 will go out.

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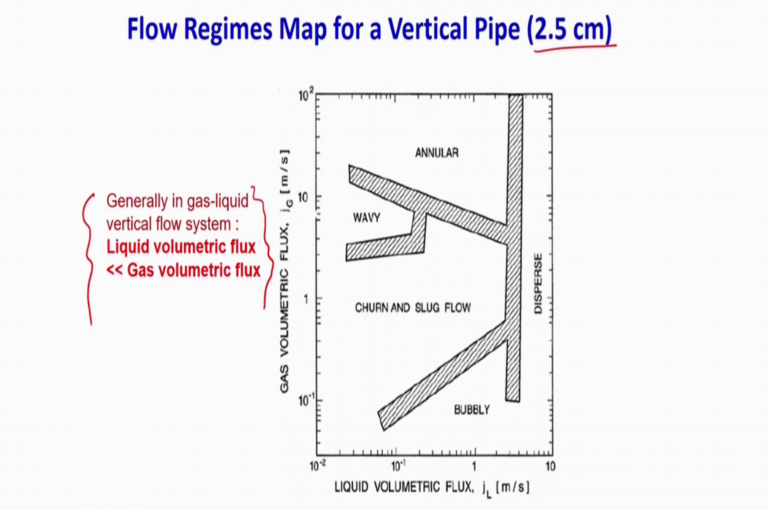

A flow regime map for the flow of an air/water mixture in a vertical, **2.5 cm** diameter pipe showing the experimentally observed transition regions hatched;

Now, again if I try to plot this gas flow, this regime curve then again this is the for a column diameter of 2.5 centimetres we have already discussed that. If your column dimensions are bigger some of the flow regimes you will not see and with the change in the diameter of the column you are going to see the change in the flow regime. So, this is the typical again the column has been made for the air water system and mixture of a column diameter of 2.5 centimetre. And these are the hs line because the sharp transition is very difficult to observe in the vertical pipe line. So, this are the hs area is actually showing the transition regions where the transition tank take place.

So, the sharp line will disappear in case of the vertical column. And you will see a region where the transition time take place even for the same particle column diameter of 2.5 ok. Now this I have mentioned just for the information that most of the gas liquid vertical flow system the liquid volumetric flux is much, much lower than the gas volumetric flux which was not the case for the horizontal pipe ok. If you see that that can be may be equally same, but here the what will happen the liquid volumetric flux will be much, much lower compared to the gas volumetric flux, you can see the order of magnitude difference here this is maximum 10 and here it is going to 100.

So, that is the vertical column limitations or you can say that the way the vertical column has been operated. And again, if you see that for all the liquid flux unlike to the horizontal flow if you start bubbling the gas you will see directly the bubbly flow regime. So, you will see the bubbly flow regime or it will directly move to the slug flow or churn flow regime for a very small dimension of this. So, you will see a bubbly flow regime if the gas velocity is very, very small for all the liquid velocities.

Now, if you keep on increasing the liquid gas velocity and if see that now it is pretty much independent actually till a very high velocity, it is pretty much independent of the liquid velocity. So, if you see that this other than this only it is actually changing that the change in the liquid velocity is going through the dispersed low neither it is only the gas velocity with which it is moving. So, this is bubbly flow if you increase the gas velocity you will get the slug flow or churn turbulent flow.

Again I said that depending on the column dimensions if you column dimensions are very small you will get first the slug then the churn turbulent some people also say that you get the wavy flow, wavy flow is nothing but is the churn turbulent kind of a flow, where you see the wave kind of a structure and if you further increase the gas velocity you will get the annular at a very high liquid velocity you may get a dispersed flow too, that where the things will be get dispersed because. So, gases will get uniformly dispersed inside this inside the liquid if the liquid velocity is very, very high. So, that is the flow regime map you see for a column diameter of the 2.5 and it is merely going to depend on the gas velocity till you are not making the liquid velocity very high.

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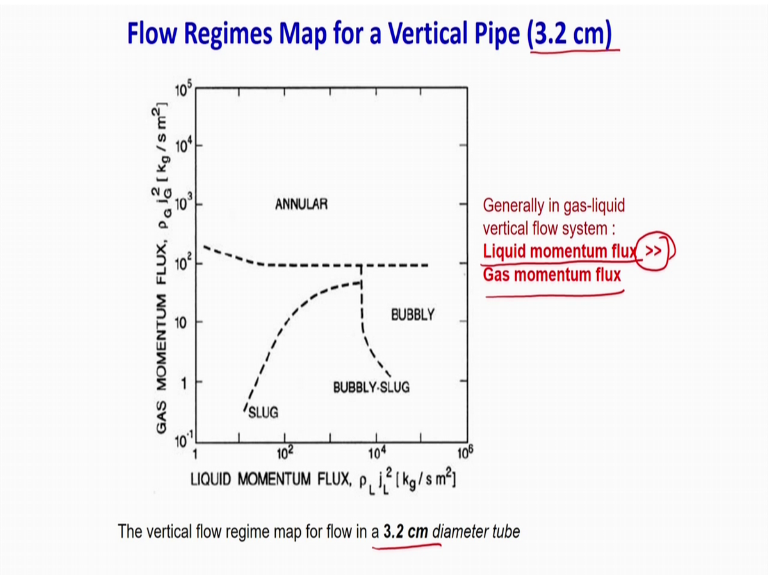

So, similarly this is the dimensions we have again changed it and the diameter of the column has increased to 3.2 and again the gas momentum flux it means nothing but rho g square j g square. We have plotted or this has been plotted for the liquid. And the gas and if you see again this things are now changing for this the different gas velocity you will get on different gas flux you will get the regime transitions. So, the regime transition will again change because you have changed the dimensions of the column and this is the way so what will happen the things changes.

Now, if you are plotting please remember this is and we are plotting in terms of the momentum flux. So, in case of the vertical pipe earlier I said that the volumetric flux liquid volumetric flux will be much lower compared to the gas volumetric flux, but once I am talking about the momentum flux liquid volumetric momentum flux or liquid momentum flux will be much higher compared to the gas momentum flux as the liquid density is roughly 3 order of magnitude higher than the gas density.

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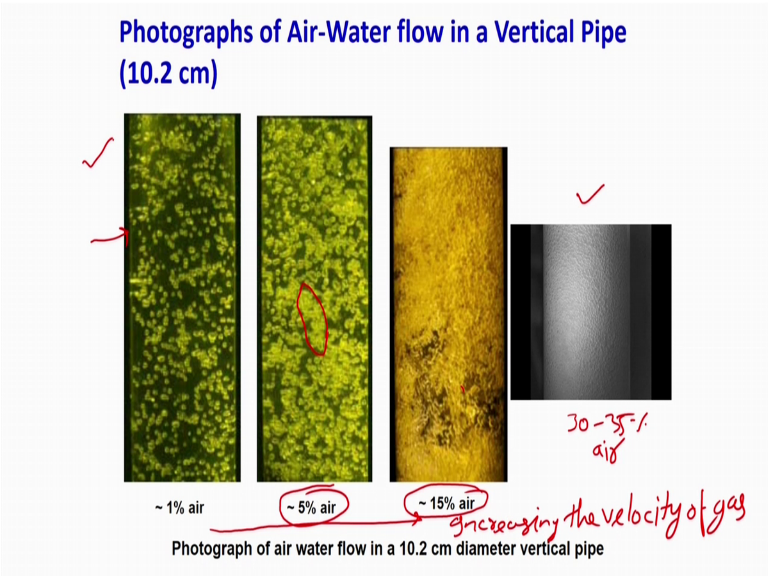

So, these are the photographs which has been taken from the literature different literatures for a pipe diameter of 10.2 centimetre for different type of flow that how the flow looks like, if you keep on increasing the velocity. So, left to right actually you are increasing the velocity of gas.

So, what will happen if you sparse in a vertical column very small velocity when you see a very uniform bubbles which are moving up they are very low coalescence. And so this is a typical photograph for that and you are seeing a volume fraction in the range of 1 percentage of the air. So, it is a air water system where air is being a sparse uniformly through the bottom. And you see that pretty much uniform tiny bubbles are being formed which are moving upward at approximately constant velocity and the bubble size distribution is there, but it is not very wide and the coalescence is very, very small.

Now, if you keep on increasing the velocity what will happen this is approximately 5 percent system. Now you see that they are more bubbles now because the bubbles are being packed more what will happen they will start having the coalescence because there are more bubbles available. Now the coalescence will start the moment the coalescence will start you will see the wide bubble size distribution. Here the bubble coalescence is started, but still it is less. So, you can see some of the bubbles which are now trying to coalesce which is forming the pebble clusters of the bubbles, but if you further increase the velocity what you will see, we will see now the coalescence will start and you will see the continuous loop of the bubble. So, this is completely packed and this is at around say 15 percent of the air and this shifted to the churn turbulent regime, where you see very big bubbles are being formed and you will see the patches of the kind of a liquid. And if you operate increase further this is around say 30 to 35 percent of the air fraction. You looks like a solid wall you not able to see anything inside because everything is refracted back from the wall. So, you will see this kind of a structure which will be completely filled with the bubbles and it will be very difficult to see inside. So, that is a vertical floor regimes and again because it is difficult to see inside the measurements is making more and more difficult, analyzing the systems will be more difficult for this kind of a system where the fraction is very high compared to the system where the fraction is very low.

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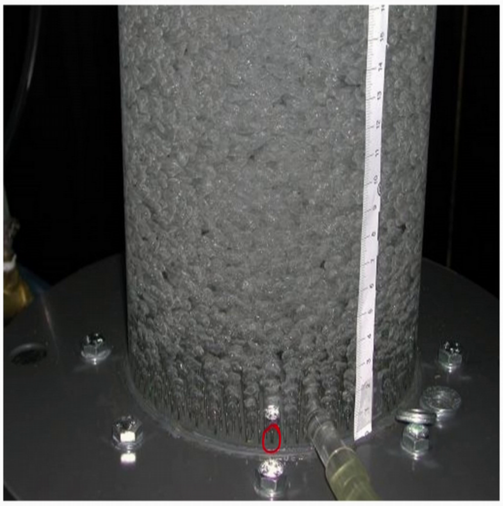

So, how this is look like then if you see that this are the is vertical bubble column, where air is being injected with tiny nozzles which is being placed. So, that the bubble size distribution can kept uniform. And you see that this is completely filled with the bubbles and you are not able to see what is happening inside. So, this is a typical bubble column which is being operated and we can measure the bubble volume fraction and all that is the separate story, but this is one type of regime.

So, you see this kind of a regime and definitely this is the regime one case and second case is this if we compare these 2 cases in this case and this case or this case and this case if you are doing a reaction then the surface area is going to be different around of single bubble. So now, mass transfer is also going to be different, velocity is different again the mass transfer is going to be different and you need to decide that which system you have to use depending on the applications.

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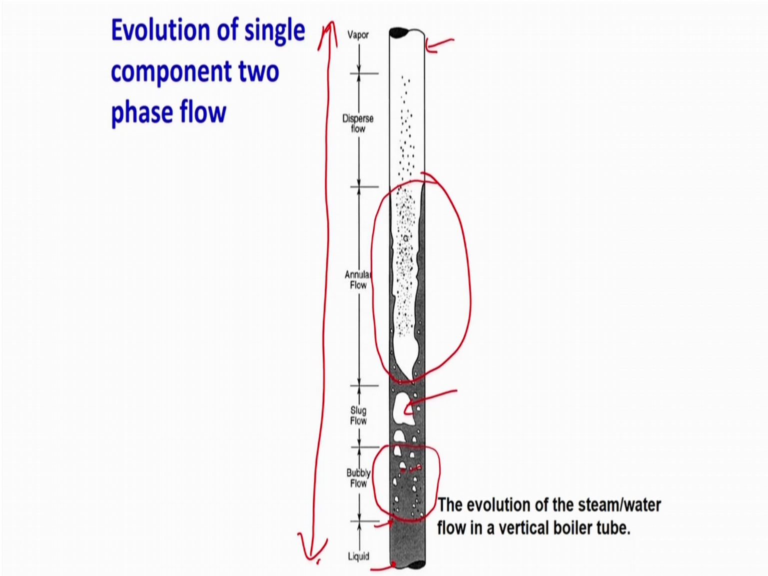

So, that is about the 2-phase flow regime particularly where the phases are being separated or injected individually. Now there are certain cases in chemical engineering or in industry particularly any industry where the evolution of the 2 phase flow take place, it means; initially there is a single phase and slowly with the reaction or with the time the second phase is evolving now one of the typical example for this kind of a flow is boiler, where we take initially the water which is single phase and then we slowly we pass the boiler in there some vertical tubes are there.

Where we keep on rotating the liquid and slowly we get that temperature which from the flue gasses and what happened the temperature increases and the water start vaporizing. Now the moment the water start vaporizing you will see the different kind of a phases different flow regimes. And that is why the boiler design is one of the challenging thing particularly the pipelining of the boiler. And if you go to industry they keep on saying that the pipeline got busted why it is happening the pipeline is the most critical phenomena is because there is a evolution of the 2-phase flow which is taking place.

Now, if you think about this vertical tube boiler tube what is happening and I'm simplified this sometimes is also in inclined. So, that things becomes even complicated let us think about a boiler tube which is vertical in nature. And what is happening suppose the liquid is being passed through the bottom and then we know that there is a tank which is on the top where the vapour get collected and then you keep on re-circulating the liquid in the rised part, it goes up in the downer part it comes down and in over end tank whatever the vapor comes it goes on the top and we can take the vapor or gas there is steam as per the desire.

So, this is the typical system so I am assuming that at the bottom part once the liquid is entered, it will be definitely pure liquid and there will be no secondary phase. Now slowly you are heating the system along the length what will happen? You will see that the liquid temperature will increase and you will see the tiny bubbles now some vapor will form and it will form a tiny bubbles. So, this is called a bubbly flow regime where the bubble size will be very small, there will be no coalescence the bubble size is just increased because there is more vaporization taking place.

Now, most of the boiler troops are very small in diameter. So, slug flow is obvious that there can be slug flow. So, if you further go up what will happen the more vaporization will take place more gas will or more steam will evolve or more vapor will evolve. And you will see that this now bubbles is start having coalescence and they will form a bigger bubble and this is called the slug regime. So, after a certain pipe we will get a slug flow regime. Now what will happen you keep on heating it then what will happen that your liquid will further get vaporized?

And you will see more of the vapours and the moment you will see more of the vapours you will see a annular flow regime. So, what will happen the liquid will be pushed towards the bottom and the gases will start flowing because the velocity is very high they will first come to the center of the column and to avoid the friction, and the gases will be moving at the center of the column and that you will see the annular flow regime.

If you further increase go up what will happen you will see, only the gas teeny drop this liquid actually is being now suspended in the vapor. So, some of the moisture form you the liquid gets suspended into the vapor that is also called disperse regime. And you will see the dispersed flow where the liquid will be in this very small droplet it will be carried away with the vapor in form of the entrainment. If you go further up you will see the complete vapor. So, what happened we have transformed from the complete liquid to the complete vapor and that is called the evolution of the 2-phase flow, and that is why the boiler is so critical to operate because you see all the possible regime in a vertical pipe during the flow transition all the transition take place in a one pipeline itself from the bottom once you inject the liquid to the top before it get vaporised.

So, that is why the boiler becomes very, very critical and designing the boiler pipeline system is even more challenging because you are evolving the 2-phase flow. So, you have to understand that what will be the gradient of the heat you have to provide throughout the length of the pipe because your heat transfer is going to change with the vapor fraction inside.

So, that is a typical phenomena which happens it can also happen with a reactive system, where the gas liquid to gas phenomena is taking place or gas to liquid phenomenon is taking place, you will see the evolution of the flow regime and that is why designing this kind of a reactor is very critical. So, suppose if I have to design gas to liquid, what will happen? You will see the reverse of it initially there will be lot of gas and then you will see the liquid. So, the phenomenon will be different. So, the evolutionary where the evolution of the flow pattern take place of phase changes during the reaction take place it is even critical to analyze that. So, that is what I just tried to show that you will see messy all the regime.

So, if you are designing such a system you have to see that how my regime change will take place along the length or with the time inside the reactor. So, designing a batch reactor it will be with the time. So, designing a continuous reactor it is going to with the length. So, that you have to keep in the mind for the better design.

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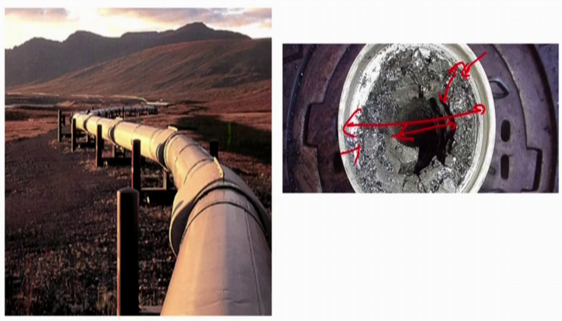

So, this is a typical diagram what I am just trying to show that; why this kind of a flow regime map is so critical. So, this is the diagram of a u s point s point pipeline there the transportation has been taking place for the crude oil. And it is a very long pipeline and you can see that there is all bends curvature inclination everything is there and if you do not operate it properly what will happen you will see the deposition will take place near the pipeline, and if such kind of a wax deposition take place which becomes rock hard if your flow regime is not maintained properly then what will happen the wax will slowly go on the wall it will be deposited on the wall only. And it will becomes rock hard if you are not cleaving at the proper time and it will reduce your flow area drastically.

So, you see that half of your flow area is being reduced earlier, this was the inner diameter now the inner diameter for the flow is ref this. So, your area has been reduced we know that your pressure drop is going to be drastically improved ok. So, you will require more pumping cost. So, that is why the flow regime identification is so critical for the pipeline transportation or the transportation of the fluid, if you are not doing it your pumping cost will increase your pipe will get damaged and finally, what we have to do this, this is wax, it becomes rock hard. You cannot do anything with it, you have to actually throw it out, whether, it is the hydrate or wax you have to actually throw the whole pipeline out.

Now, repairing the pipeline which is over the ground is very easy, but suppose if this is the same pipeline which is passing from the sea, then you have to change the whole pipeline and the pipeline cost system is a change in that cost is very, very high, so high that it may be very difficult for the company to afford that. So, you need to understand that what flow regime systems, we have to do you need to develop the cleaning methodology, we will discuss some of that in the during course, that we need to periodically clean the system clean this and that you can predict the cleaning time based on that what is the flow regime map you are operating.

So, with this I will wind up today and that is for a gas liquid flow regimes why it is critical to understand that flow regimes. If you not do it critically what kind of a problem you can face and this is one typical example we can even discuss more there are lot of typical examples are there, lot of literature is available. I will request you that please go and see some of the literatures and you can write me back if you have any issues so.

Thank you.