Fluid Flow Operations
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Module – 12
Multiphase flow phenomena and its application-Part 2
Lecture – 31
Hydrodynamics in multiphase flow

Welcome to massive open online course on Fluid Flow Operations. In this lecture we discuss something about, important aspect of a Hydrodynamics in multiphase flow. So, we have discussed in our previous lecture that what is exactly that multiphase flow system and how it is different from the single phase flow. And, also where the different of this phenomena of this multiphase flow are applied in different chemical biochemical even in civil engineering processes and also what are the requirement for studying this multiphase flow systems for actually analyze the process of different chemical engineering and civil engineering phenomena.

So, in that case we have actually discussed that this phenomena will be something different from the single phase systems. Though almost of you will get the different type of phenomena, but since there are more than one phase are flowing. So, it will be something different and the pattern whatever it will be giving it will be totally different from single phase flow. We got the different pattern of the single phase flow like what is that a laminar flow, turbulent flow, even what is that boundary flow.

So, all this type of phenomena for single phase flow here in multiphase flow systems also those phenomena will come except that phenomena more flow pattern will comes in this multiphase flow systems. And so before going to that we will discuss that what is that single phase flow pattern, we got this single phase flow pattern like here; it will be laminar flow, it will be turbulent flow, even it will be transitional flow.

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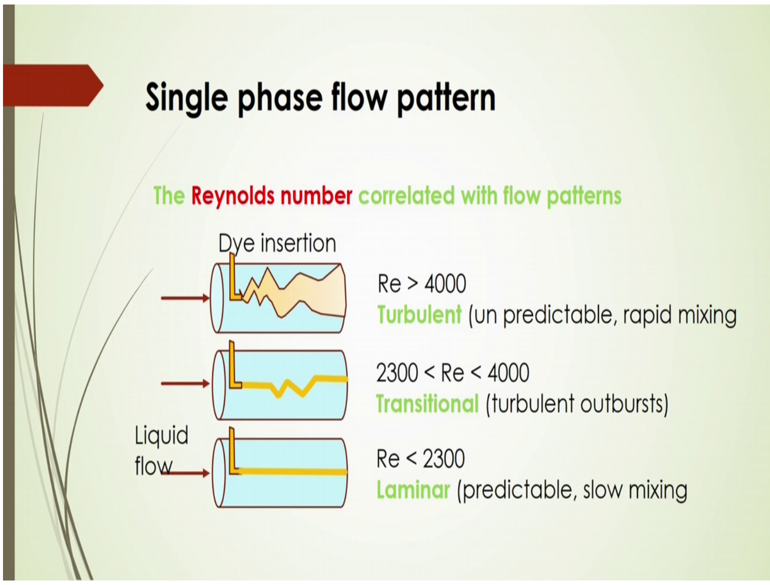

Now, that can be actually assist based on the Reynolds number, if Reynolds number is greater than 4000 then, you can say the flow will be a turbulent. When if it is less than 2300, then it will be laminar flow and in between it will be transitional flow. So, this is for single phase flow and this Reynolds number is basically defined based on the single phase flow, they are actually what is the definition of Reynolds number it is, simply rho u d by mu; that means, here physical significance is the inertia force to the viscous force.

And here in this case the Reynolds number will be based on the single phase velocity like; here velocity is u for the liquid or gas and also the density of the fluid even viscosity of the fluid will be based on the single phase flow. But in case of multiphase flow you have to consider the effective density effective viscosity even what is the actual velocity of the individual phases that you have to consider.

Then you can assist what should be the turbulent or what will be the actually condition for the turbulent flow, transition flow or laminar flow. If you consider that in that case if Reynolds number is greater than 4000 turbulent multi flow phase systems say, accordingly that if velocity density and the viscosity will come. So, this is the single phase.

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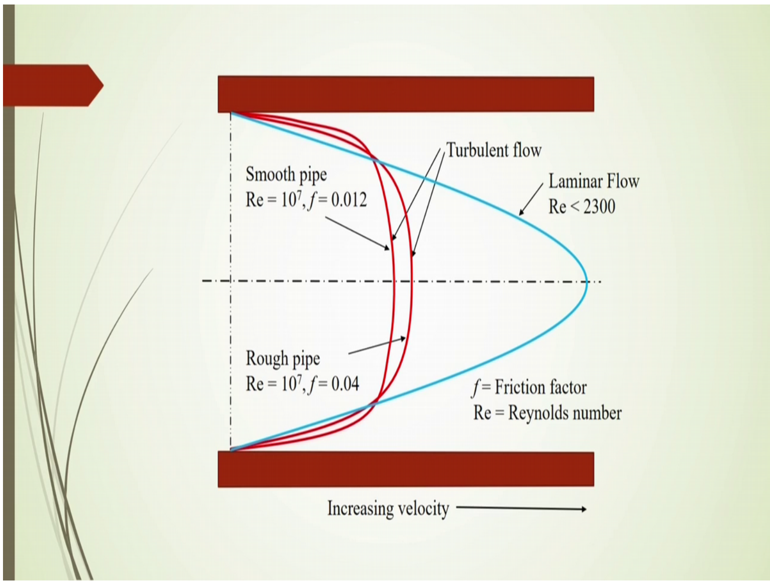

Similarly, that different pattern, like turbulent flow pattern, laminar flow pattern, even friction factor roughness of the pipe all are in a single phase phenomena. How it is behaving and what will be the profile that is shown even it is discussed in earlier lecture for the single phase flow systems. So, the beginning of this lecture there.

Now, what will be the then flow pattern different flow pattern whenever more than 1 phase will be flowing through the conduit, here not only a single liquid like water is flowing to the pipe. It will be simultaneously gas and liquid both will be flowing through the pipe or gas and even you know solid particles even you know that liquid liquid, even 2 liquids are flowing through the pipe even gas liquid solid three phase will be flowing through the pipe in that case what should be the pattern.

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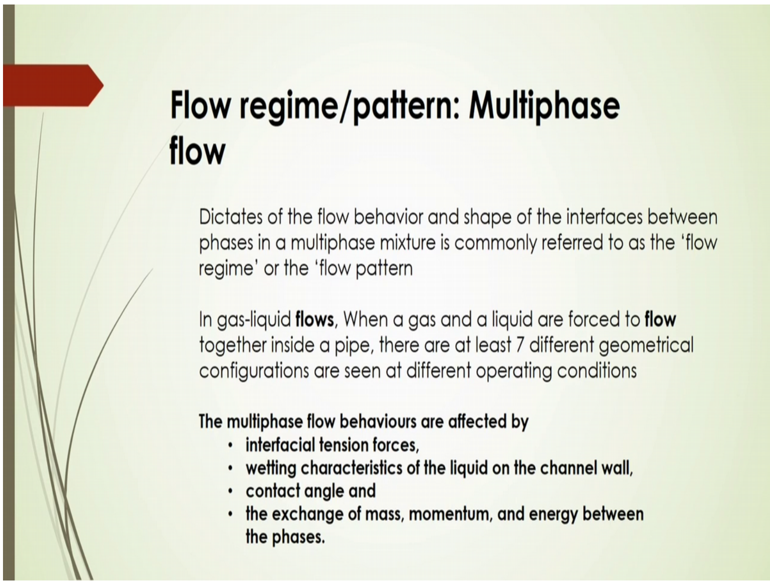

Now, let us discuss that initially two phase flow system, because most of the operations are being a happened in of chemical engineering process of bio chemical process in the two phase flow systems. So, if you know the two phase flow phenomena, then you will be analyze the, what will be that three phase flow systems also. So, what is that flow pattern in multiphase flow systems? This flow patterns sometimes it is called flow regime also. So, it will dictates the flow behavior and shape of the interfaces between phases because two phases or more than one phases whenever flowing through the pipe you will see the between the phases there will be some interface formation.

So, in that case the shape of the interface between the phases in the multiphase mixture, when it will be coming and what is the behavior of that flow based on this shape and interfaces and that will commonly referred to as the flow regime or the flow pattern. So, as a definition you can say that it flow regime or flow pattern dictates the flow behavior and the shape of the interface between the phases in multi phase mixture is commonly referred to as the flow regime or flow pattern.

Like in gas liquid flows when a gas and liquid are forced to flow together inside the pipe then there are at least 7 different geometrical configurations are seen at different operating conditions. Like here you will see different geometrical configurations there, we will discuss on the subsequent that is slides here. Now, in that case during that flow behavior that is the when two if to two phase will be flowing through the pipe. So, during the flow you will see some behavior that is affected by this inter facial tension forces wetting characteristics of the liquid on the channel wall or contact angle if in the exchange of the mass momentum and the energy between the phases.

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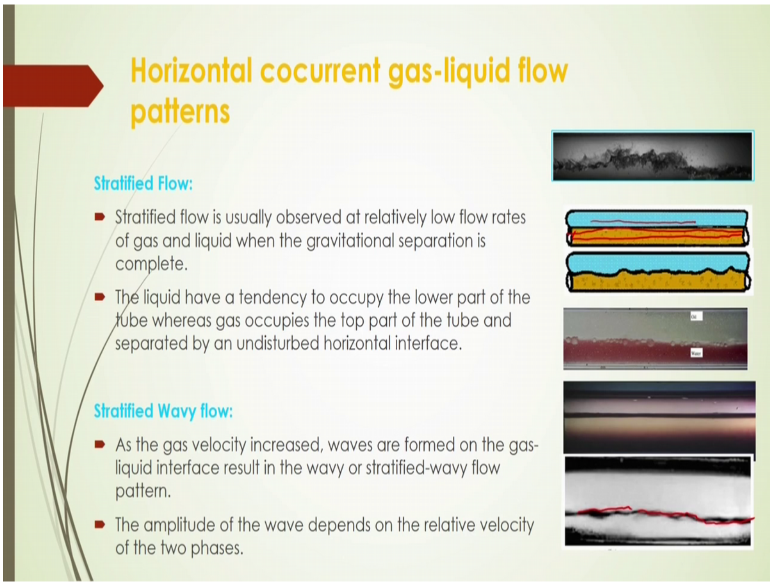

Let us see then what are the different flow patterns whenever liquid gas liquid are flowing through the pipe. And in that case you will see this type of flow patterns will have in the horizontal as well as vertical pipes also. So, when a horizontal co current gas liquid flow pattern we were considering, then you will see one type of flow pattern it is called Stratified Flow.

So, what is that is stratified you will see in the picture it is shown that is the stratified flow. In this case this you will see there will be two phase flow relatively low flow rates of gas and liquid, if you consider gas and liquid when the gravitational separation is there complete. So, what does it mean that you will see whenever gas and liquid will be flowing through the pipe here at the bottom part there will be liquid and the upper part there will be gas. So, there will be separation of these two fluid here in this case gas and liquid. And they will make it clear cut what is that surface between those two phases.

So, that is why it is called the stratified flow, there will be no intermixing of the fluid here in this case. And the liquid have a tendency to occupy the lower part of the tube whereas, the gas occupies the top part of the tube and separated by the undisturbed horizontal interfaces. So, this is called stratified flow. Whereas you will see, the during this low velocity of this gas and liquid you will see there be stratified, but if you increase the little bit of this gas and liquid you will see there will be a formation of wavy shape of interfaces between these two phases. So, those type of flow will be called as Stratified Wavy flow.

So, as the gas velocity increased then waves are formed on the gas liquid interfaces, and results are in the wavy stratified wavy flow pattern. And here you will see this the surface of this interface of these two fluid, there will be you know that this is not the straight that it would be what is that formation of the wavy shape there; so, the amplitude of the wave that depends on the relative velocity of the two phases.

So, you have to remember that what will be the exact velocity of the gas and liquid, if you will see relative velocity, if suppose gas velocity is higher than the liquid velocity. Relative velocity will be that gas velocity minus liquid velocities will be your relative velocity. So, if your what is that relative velocity little bit increases, then you will see amplitude also it will be accordingly increases. So, when this case it actually basically depends on the energy distribution between these two phases; so, the amplitude of the wave that depends on the relative velocity of the phases.

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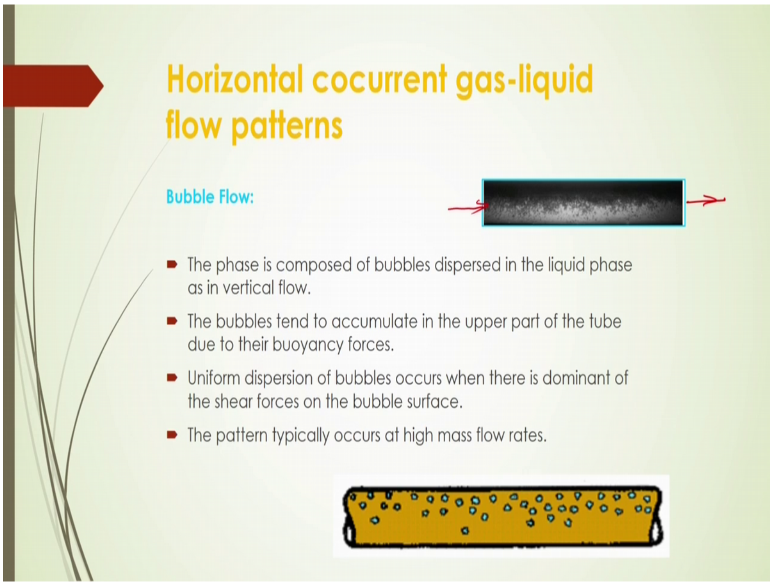

Now, another important flow pattern that is observe in gas liquid flow whenever two phases will be flowing through the pipe at certain gas and liquid velocity, it is called the Bubble Flow or Bubbly Flow. The phase is composed a bubble is passed in the liquid phase and the flow so it is not a vertical here. So, in this case what will happen? The composed of bubbles dispersed in the liquid phases, here you will see whenever liquid is flowing through this pipe here you will see the gas and liquid will be a mixing to each other, and the bubbles, the gas will be dispersed in a liquid phase as it is dispersed phase of the bubbles and it will be flowing through the pipe. And in this case bubbles try to accumulate in the upper part of the tube due to their buoyancy forces.

And also at a certain gas and liquid velocity you will see there will be uniform dispersion of the bubbles that will occur when there is no, there is a when there is a dominant of the shear forces on the bubble surface. So, if the shear forces higher the above the surface, then bubbles will be breaking up and it will be making a smaller bubbles, and it will be flowing, and the distribution of the bubble should be more uniform through the pipe. And the pattern generally occurs at high mass flow rate of this fluid. So, this is the characteristic feature of the bubble flow here.

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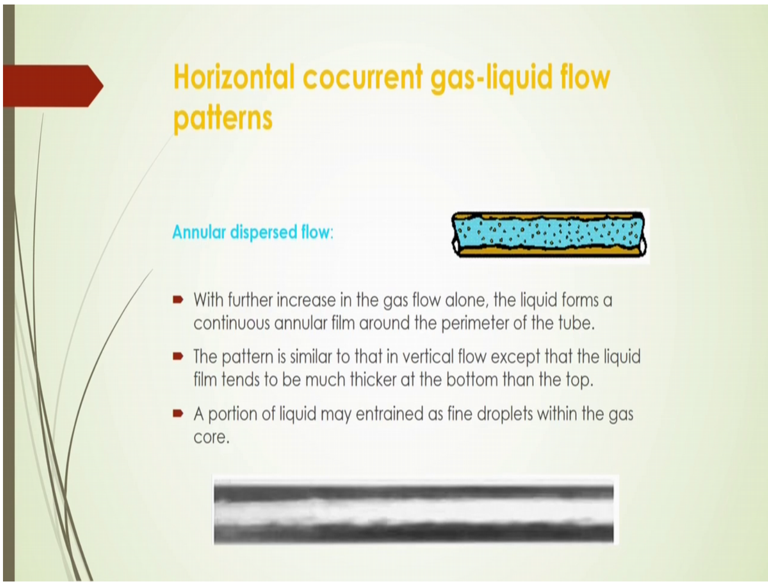

And, another important flow pattern it is called the annular flow pattern. And, it is annular dispersed flow is called you know with further increase in the gas flow alone, the liquid forms a continuous annular film around the perimeter of the tube. You will see in this yellow colour here it is the, this is the liquid and here it is the liquid and in the middle part there will be a gas.

So, there will be a what is that clear cut interfaces between liquid and gas, but in the periphery you will see there will be a occupation of the liquid. So, that is why there will be a formation of continuous annular film around the perimeter of the tube. And this happened only at a certain gas flow rate and if you are increasing the gas flow rate this film thickness may be decreases.

So, accordingly that depends on the gas flow rate. And the pattern is similar to that in the vertical except that the liquid film tends to be much thicker and bottom than the top. You will see since there will be a you know that gravity effect you will see in the bottom part there will be film thickness will be lower higher than the top one. And a portion of the liquid may entrained as a fine droplet within the gas core here.

So, through this gas you will see there will be a some liquid droplet will be flowing through the gas, because this droplet will be forming from this liquid part because of the high energy transferred and formation of some droplet and that droplet will be entertained in that gas flow rate. Here this picture you will see in this core region here see gas is flowing and this black one it is just simply liquid there. So, this from this liquid there will some portion of this liquid droplet will be our formation and it will be flowing through the gas as a droplet.

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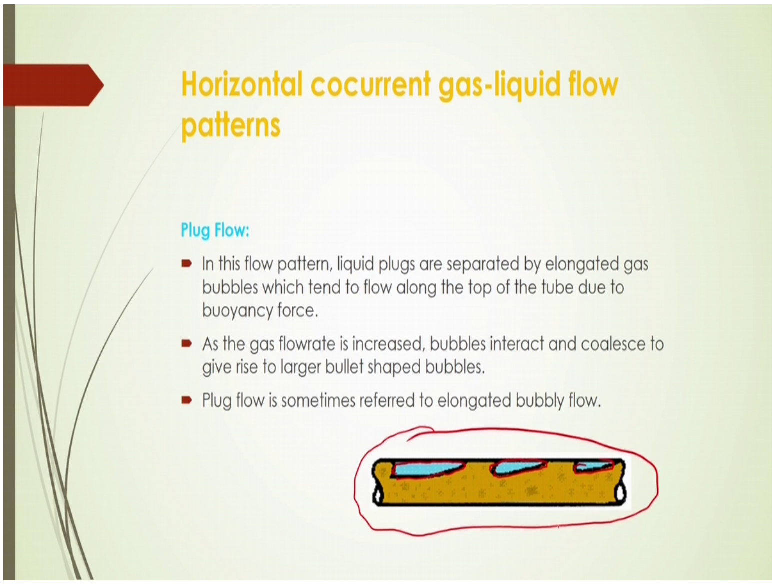

Another important pattern it is called Plug Flow. How see this picture, here in this case some portion of this you will see a gas will be flowing as a slug that is some bubbles that will be attached to the top part of the pipe and that will be a certain shape of the this bubble and it will be longer and some will be smaller, but it will not be exactly the shape of the sphere. So, there will be formation of this the non spherical part that is longitudinal a gas bubbles.

So, and it will be attached to that or it will be flowing just adjust in to the upper part of the wall. And in that case you will see non uniform shape and it will be certain shape may be due to the higher buoyancy it will be attached to the top part, and because of which there will be a flow like this and of course, the surface instant effect and inter facial phenomena will affect to form this type of flow at a certain flow velocity. Now in this case you can have the liquid plugs also instead of gas plugs.

So, in that case a liquid plugs are separated by the elongated gas bubbles and which tend to flow along the top of the tube due to the buoyancy force. So, if there are two miscible fluids there you will see instead of gas, it will be liquid plug also. So, in that case the continues liquid may be in the bottom part and the dispersive liquid part with the top part.

And in the gas liquid flow systems that the gas flow rate is increased the bubbles interact and coalesce and give rise to a longer bullet shaped bubbles. And it will form a, what is that this type of a gas plug there. And plug flow is sometimes referred to as elongated bubbly flow also.

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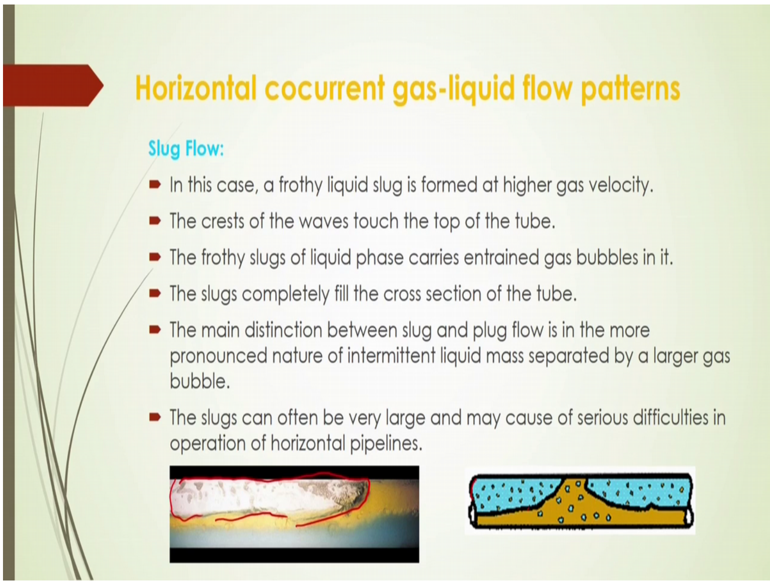

Now, slug flow here you will see again that type of things here, the in the case where the frothy liquid slug is formed at higher gas velocity you will observe that this type of slug flow here.

And then you will see there will be one formation of crests of the wave and that will touch the top of the tube. And the frothy slugs of the tube phase carries and to entrained gas bubbles in it. The slugs completely fill the cross section of the tube and the main distinction between the slug and plug flow is in the more pronounced nature of intermittent liquid mass that is separated by a large gas bubbles here. And the slugs can often be very large and may cause of serious difficulties in the operation of the horizontal pipelines. So, this type of you can have slugs in this case there may be a liquid there may be a gas slugs also there.

So, this type of we are see how the characteristics feature of this formation of this. So, whenever two phase flows are form are actually executing you will see this type of deferent flow patterns you can observe.

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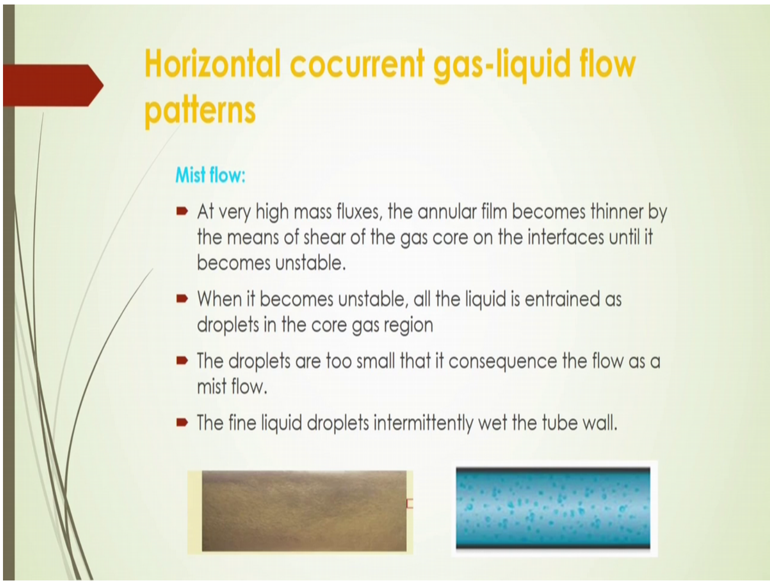

Another is mist flow; in this case at high mass fluxes the annular film becomes thinner, by the means of shear and the gas core on the interfaces until it becomes unstable. And in that case I will see the droplets are too small that it consequences the flow as a mist flow. And the fine liquid droplets intermittently wet the tube wall there. So, that is why this type of flow pattern is called the mist flow pattern.

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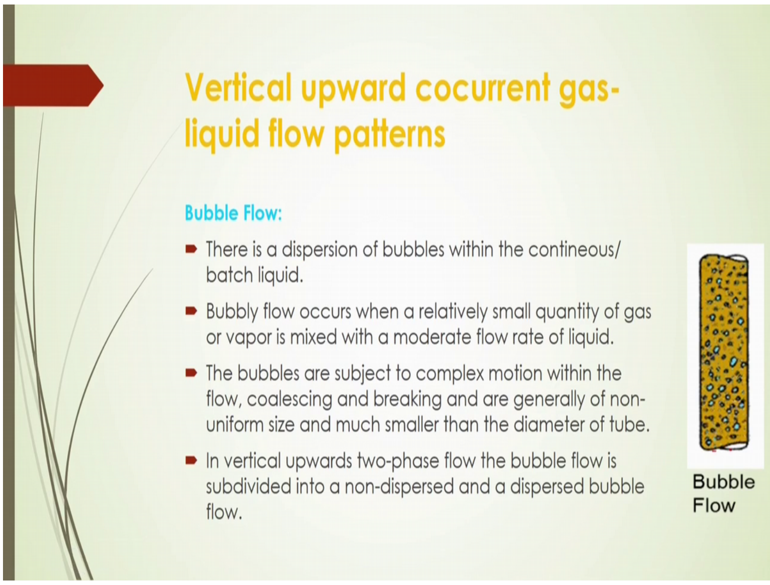

Now, let us consider the Vertical upward cocurrent gas liquid flow patterns here. So, in this case also you can give get the bubbly flow, even slug flow plug, flow annular flow all those different flow patterns that is discussed in the horizontal pipe you can get all those flow patterns in vertical pipe also. Of course, in this case that gravity effect will be there and to actually balance those gravity force you have to apply the gas or liquid velocity in such way that that will give certain flow patterns based on this flow velocity or relative velocity there.

So, there is dispersion of the bubbles in the case of bubble flow within the continuous or gas liquid here. So, if it is a column, so in this case from the bottom of the column if gas is supplied in the liquid medium in a liquid batch. So, in that case you can expect that gas is actually flowing as it is dispersed phases of bubbles. And in this case this bubbly flow occurs when a relatively small quantity of gas or vapor is mixed; with a moderate flow rate of the liquid. And the bubbles are in this case subject to complex motion with in the flow.

And sometimes this bubbles are coalescing and breaking and sometimes you will see it will form a non uniform bubble size and much smaller sometimes it will be there, based on the a flow rate and also a mechanism by which the formation of bubbles are there. And in vertical upward two phase flow the bubbles flow is sub divided in to non dispersed even dispersed bubble also. You will see not only in the vertical flow, you will see you can get this type of a flow in vertically down flow also.

In that case there will be some jet pump to be applied from the top of the column so that, the you can get the formation of the bubbles by entraining the gas in to a pool of liquid by a jet energy. So, in that case the due to the liquid momentum, down ward liquid momentum the flow of the bubbles will be opposite to its buoyancy. This type of flow pattern this called inverse bubbly flow pattern.

So, for this inverse bubbly flow patterns also you can get the uniform bubble size even non uniform bubble size that depends on the flow rate of the gas when what will be pressure inside the column that will affect the formation mechanism of the bubble there.

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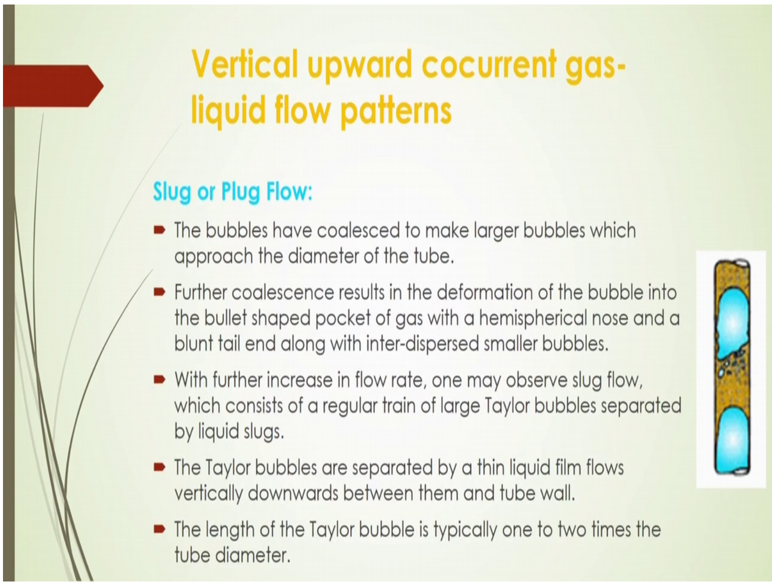

And slug and plug flow again this type of plug and slug you can expect in the vertically upward flow, whenever at a certain gas and liquid velocity you will just supply the gas and you will see there will be a formation of bigger bubbles and that size of the bubbles will be in such way that its sometimes form a bullet shape.

So, that is why it is called that bullet shaped slug flow here. So, or sometimes it is called Taylor bubble flow. And this bullet shape bubble it is called Taylor bubble flow and the bubbles are have coalescence to make larger bubbles this is small bubbles generally coalescence to each other and making larger bubbles and approaches to this diameter of the pipe and formation of this bullet shape bubble.

And also you will see this coalescence that will results in a deformation of the bubble in to a bullet shape pocket of the gas it is called with hemispherical nose in this case you will see hemispherical nose and a blunt tail and along with and inter dispersed smaller bubbles there.

So, whenever this bullet shape nose will be forming and this bubbles will be forming along with that is smaller bubbles also will be forming through the pipe. So, in this case this smaller bubbles of course, it will be coalescence to big form a larger bubbles and this larger bubbles will be enough to occupy the space of this column cross sections, and that is why it will form a this type of bullet shape of bubble.

And this you will see these two bullet shape bubbles, even more than bullet shape bubbles also will be there. If your column is too high that case you can get, I think more number of even bullet shape bubbles and in that case in between that bullet shape bubbles it is called the liquid slugs.

So, this bullet shape bubbles are separated by the liquid slugs. And in this case whenever this bullet shapes will be forming and it will be moving through the pipe, and between this bullet shape surface and pipe one there will be very thin a liquid film it will be separated this bullet shape to from this wall and it this thin liquid film will be moving downward whenever it will be this bullet shaped bubbles will be moving upward. And the length of the bubbles will typically one or two times the tube diameter will be there.

So, in case and accordingly what should be the number of bullet shape bubbles will be form can be calculated. So, it will be discussed or it is being discussed and what is that multi phase flow lecture they are in other courses. So, I am not going to details of this what will be the length what will be the size of that bullet shape, just it is the basic understanding of what are the different types of flow patterns are formed in the bubbly flow system. And this is not the scope of this course here. So, all those descriptions should be described in other separate courses, that is multiphase flow systems if it is there any courses is floated in the MOOC’s courses are not.

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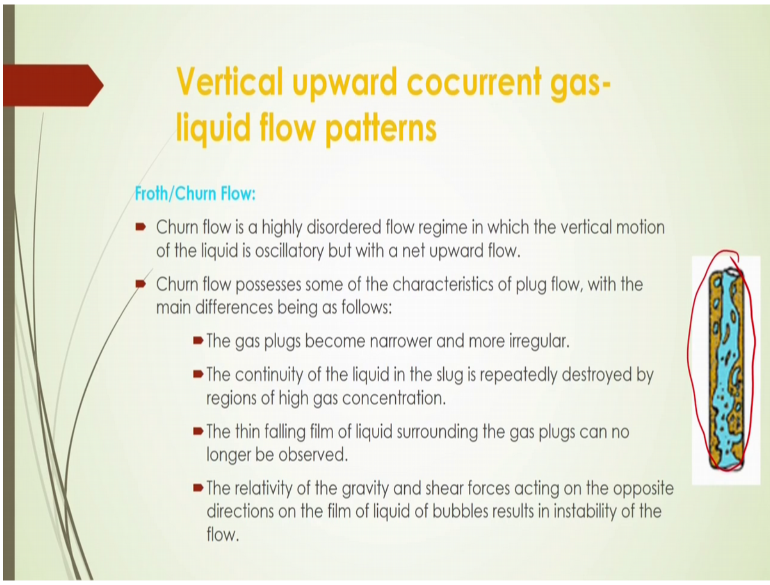

And then vertically upward cocurrent gas liquid flow pattern in this case other type of flow pattern it is called Froth or Churn flow. So, churn flow is a highly a disordered flow and in which the vertical motion of the liquid is oscillatory, but with a net upward flow it will be there. And see this picture here, how this churn of this flow pattern is formed whenever gas and liquid will be flowing through the pipe. So, churn flow possesses some of the characteristics of plug flow, with the main differences as given here. The, the gas flux become narrower and more irregular in this case.

And the continuity of the liquid in the slug is repeatedly destroyed by the regions of the high gas concentration. And the thin that is falling film of liquid surrounding the gas plugs it will not be a longer there. And the relatively of the gravity and the what is that; that means, what is that gravity force and the shear force that is acting on the opposite directions on the film and its relative that is quantity that will affect on the film of the liquid and bubbles, that will results to the instability of the flow.

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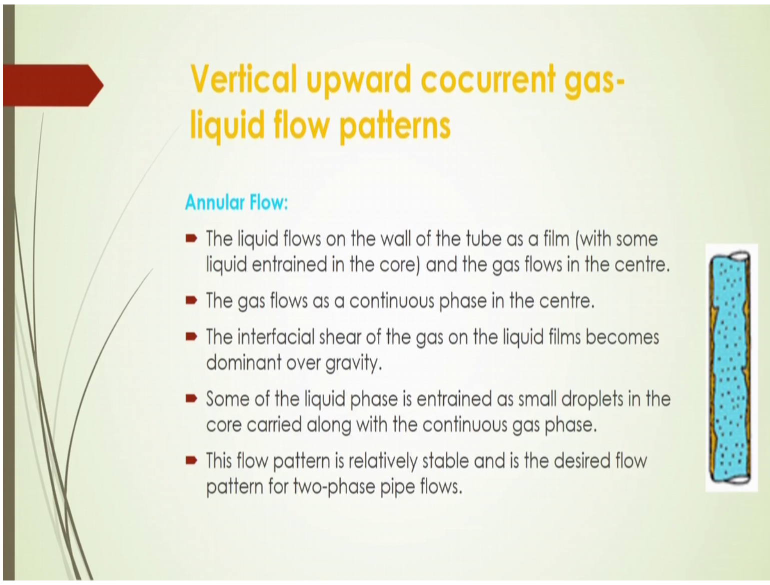

Another type it is called Annular Flow, the liquid flows on the wall of the tube as a film with some liquid entrained in the core and the gas flows in the centre. In this case the gas flows as a continuous phase in the centre, and the interfacial shear of the gas on the liquid films becomes dominant over gravity. And some of the liquid phase is entrained as a small droplet in the core carried along with the continuous gas phase and this flow pattern is relatively stable and is the desired flow pattern or two phase pipe flow system.

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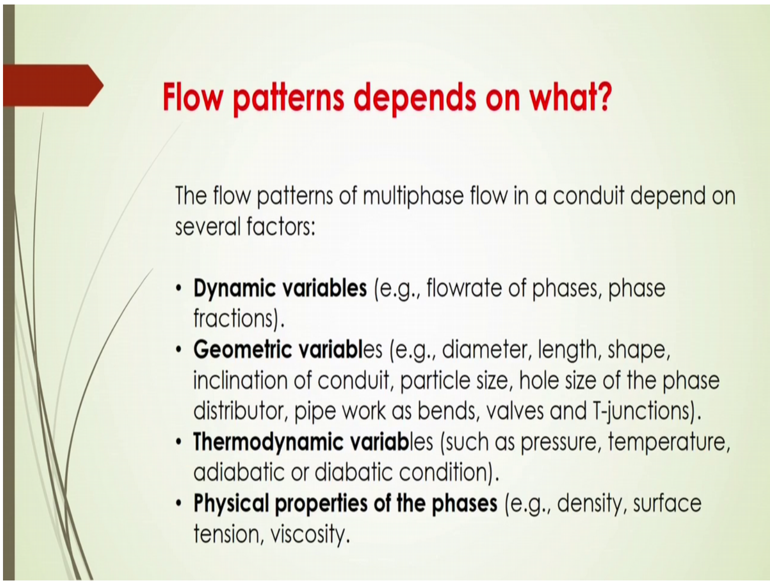

Now, question is that, these different types of flow patterns that you are obtaining whenever gas and liquid will be simultaneously flowing through the pipe, in that case what are the actually different factors that affect on this flow patterns. So, mainly you will see that the in the multi phase flow systems whenever you are just developing any flow that you need what is that you need one fluid, even one liquid, one gas one can do it whose diameter will the their length of the tube, even at a certain temperature and pressure. Even some other pressure, what are the liquid or gases are being used to that, what are the properties.

So, all those variables like; you can a segregate this or classify this is a variables as dynamic variables, geometric variables, thermodynamic variables with physical properties of the phases. So, what are those dynamic variables; dynamic variables are flow rate of the phases, phase fractions all are dynamic variables. Even geometric variables like; diameter, length, shape, integration of the conduit, particle size, even distributor size, distributor whole size and also you can see if the conduit of pipe is that bends or not. Whether any valve is or t junctions are provided there or not. So, all those factors will affect the flow patterns of the multiphase flow systems. Another is thermodynamic variables; of course, there in the pressure temperature whether it is adiabatic or nonadiabatic condition you have to see.

So, at a certain pressure and temperature this flow patterns will occur. If you change the pressure and temperature of course, this flow pattern will shift to others flow pattern and also physical properties of the system like; density, surface tension, viscosity. These 3 physical properties are very important to form these interfacial phenomena, and based on that interfacial phenomena and also with dynamic variables if you apply some inertial force, then only you see there will be a formation of interface phase.

And that interface will give you certain pattern of the flow. So, that is why you can say that this flow pattern depends on what is that; this various type of variables like an; variable, geometric variables, thermo dynamic variables, physical properties of the phases there.

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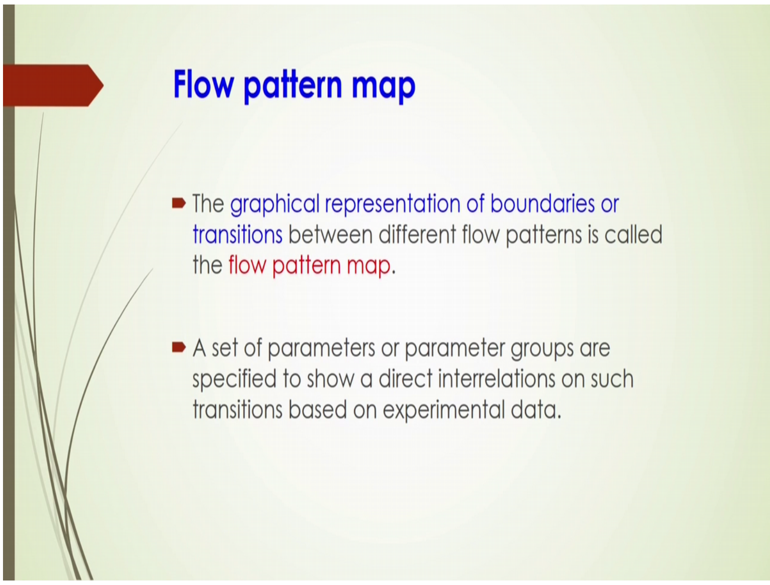

Now, another important aspects of the multiphase flow system is called flow pattern map. Now, in that case you observe I think different type of flow pattern. Now flow pattern is one important presentation of that flow patterns, that is observed in multiphase flow systems.

So, it is generally graphically represent in the different flow patterns in such a way that in the graphs or the based on the flow pattern observations you can make some what is that remarkable that is a boundary based on which you can say whether this flow pattern will occur in this particular region or not or this flow pattern will occur in this particular flow regimes or not. So, this is the flow pattern is nothing but, that the representation of the flow pattern and its transition; that is transition means what?

That transition is nothing but that one flow pattern to go to the another flow pattern; like bubbly flow pattern to the slug flow pattern. If you go from this bubbly flow pattern to the slug flow pattern, you will see there will be a change of gas flow rate of liquid flow rate. So, when you will get this bubbly flow pattern to the slug flow pattern then you have to know what is that particular gas velocity or liquid velocity and between these two actually a flow pattern it is called transition. That is bubbly to slug. So this transition, so you can have this transition point at a certain gas and liquid velocity, what is that.

So, based on that certain gas and liquid velocity at this transition by assessment of this transition point you will be able to actually do the experiment, you know which pattern you want to do. Like; if you want to do the, I will show that the graph how it will be coming, I will discuss that. So, this is that flow pattern map is nothing, but the graphical representation of the boundaries or transition between the different flow patterns. And a set of parameters or parameter groups are generally specified to show the different interactions on such transition based on the experimental data.

So, generally a very easier way to represent this flow pattern map is based on the gas velocity liquid and velocity for two phase systems. For three phase systems also you can have like; slurry velocity or gas velocity and also gas liquid solid, if there is a continuous solid is flowing. So, in that case you can have this flow pattern map. So, let us here just consider the two phase flow pattern map here. So, here in this figure it is shown that one flow pattern, it is in horizontal pipe of gas liquid two phase flow.

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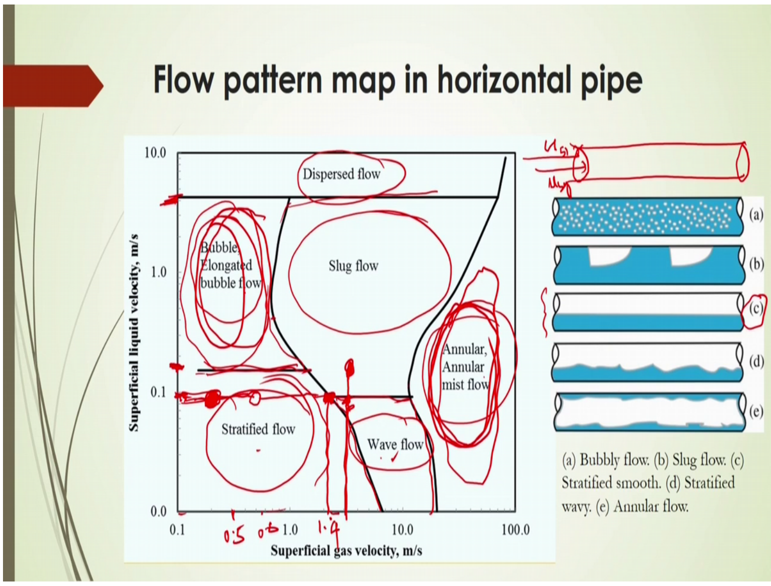

This is one graphical representation of the different flow pattern you will see; this one is here this dispersed phase flow pattern. And this is bubbly flow pattern, and this region is called slug flow pattern, and this is annular flow pattern, and here this you can get the stratified flow pattern and this wave flow pattern. Now this has been this zones are divided by a certain line here this is the by boundary.

So, these boundaries are representing the transition points of this two flow patterns like; the dispersed phase to slug flow this is your transition point here. Bubbly flow here this is your boundary; bubbly flow to slug flow. Here bubbly flow to stratified flow this is you boundary a point. And, here slug flow to the wave flow this is your boundary. Stratified flow wavy flow this is your boundary, wavy flow to annular flow this is your boundary. Even slug flow to annular flow this is your boundary. So, this boundary is the critical point at which you can get the mixture of these two phase flow and separation of these two phase flow there by this.

Now, this different flow patterns in a gas liquid flow in a horizontal pipe that can be represented this graph just by using the axis apply the superficial gas velocity and superficial liquid velocity.

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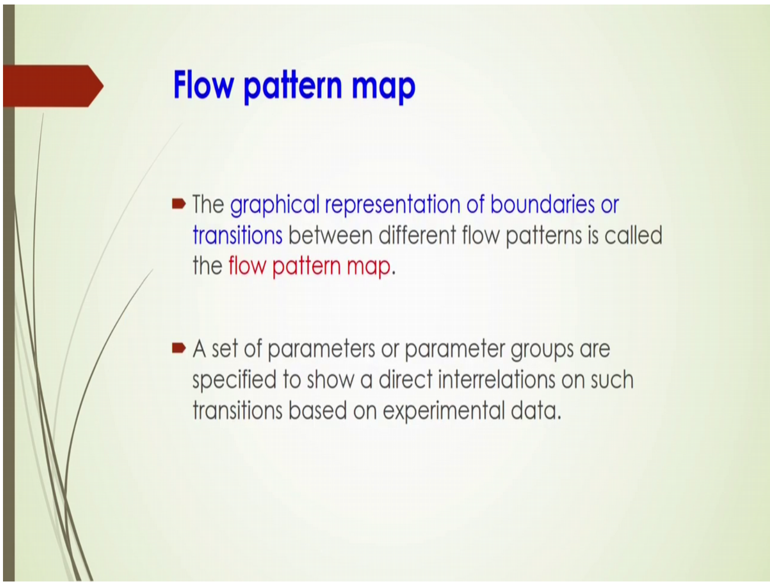

So, we told that here this the parameter that is being used to represent this transitions based on the experimental data, that may be different groups also instead of this gas and liquid velocity. So, in the x axis you can observe the superficial gas velocity and superficial liquid velocity. Now question is that how we can make these points here.

It is generally based on the experimental data, now if you do an experiment laboratory scale you will see of course, if you use only air and water. What will happen if you use air and water only suppose in this pipe there is air and liquid both are flowing simultaneously.

Now you just control the gas and liquid velocity other all properties are or variables are remain same or constant. So, in this case for a particular cross sectional area this pipe, this is a horizontal pipe and uniform cross sections both the ends. So, in this case there will be a certain velocity of what is that liquid and gas velocity, suppose liquid velocity is u sl and gas velocity u sg superficial gas and superficial liquid, we will come to the point on the superficial gas velocity.

So, there will be a certain liquid velocity certain gas velocity you are just a maintaining. Now if you observe that flow in the pipe, then you will have certain flow pattern. Now what is that flow pattern? So, that depends on only gas and liquid velocity. Very interesting that if you maintain that gas velocity is 1 meter per second. And liquid velocity is 0.1 meter per second. So, in this case what will happen, you will see you will observe there will be a stratified flow, very low velocity here the stratified flow there. What does it mean? there will be a clear cut what is that interfaces between this gas and liquid and gas will be a flowing over the liquid and both will be separately flowing that is the c here when this figure it is shown so this c.

So, at this gas velocity of 1 meter per second and liquid velocity of 0.1 meter per second, you will observe this type of flow. Now you will see if you increase the gas velocity, suppose if your gas velocity is 10 meter per second where as your liquid velocity is what is that 0.1 meter per second again, but you are just simply increasing the gas velocity at higher, that is 10 times of superficial gas velocity. Whereas liquid velocity it remains same you keep it 0.1 meter per second. So, in that case what type of flow pattern you can observe, you will see there will be a slug flow formation.

So, based on that changing of superficial gas velocity and a superficial liquid velocity you will see different type of flow pattern you will observe. Now if you are keeping 1 what is that fluid velocity constant and increasing the other fluid velocity increasing, in that case you see keep on increasing the gas velocity by keeping a constant of liquid velocity, you will see there will be a certain a gas velocity at which there will be a change of flow pattern like; stratified to wavy be or you will see that wavy to be annular flow pattern. If you are keeping the liquid velocity 0.1 meter per second constant, you will see if you are having this gas velocity what is that like 0.5 meter per second.

So, in that case where it will be there, this is the combination of this. So, here at this points that means, you will observe that this point is coming within this region. So, what is that from this map you can expect what will be the a up flow pattern. You can get this type of a stratified flow pattern. Even if you increase again the gas velocity is 0.5 to 0.6, again you can get the stratified flow pattern, there will be a change of stratified flow pattern by keeping the liquid velocity cost. Even if you increase what is that the gas velocity here at like what is that 1.4 meter per second here, you will be see there will be a flow pattern that is either stratified or what is that wave flow pattern.

So, there is a mixture of this flow pattern or you can get the slug flow. So, at this particular point you may expect the slug flow, you may expect the wavy flow, you may expect the stratified flow. Even if you increase little bit of this superficial gas velocity what will happen you will see immediately your flow pattern will be changing from the stratified flow to the wavy flow pattern or slug flow pattern. Now there will be mixing at this point, now here you will see at this point of this 0.1 meter per second, there will be observation of this slug flow and wavy flow.

Now, in this case if you decrease small amount of this superficial liquid velocity you can expect this wavy flow pattern. Or if you increase the superficial liquid velocity even 1.5 meter per second, then you can expect this slug flow pattern. So, in this way you can explain that from this graph what should be the exact flow pattern you can expect from your, what is that by experiment. So, that depends on that superficial liquid and superficial gas velocity.

Even before going to the experiment you can also have this type of flow pattern, suppose if you want to do the experiment any experiment for a certain operation. Suppose that process is very actually selective for particular what is that flow pattern like suppose; carbon dioxide, gas absorption in a sodium hydroxide solution. Now what type of flow pattern you will follow in your pipe or conduit?

So, in that case it will be more suitable, if you are having the bubbly flow pattern so, in that case, when that bubbly flow pattern will be obtained. So, you can actually access from this flow pattern map. Now, in that case you can have this bubbly flow pattern in this region; that means, here you can I think change the superficial gas velocity from this from this to this, up to what is that 1.4 meter per second or 1.5 meter per second and superficial liquid velocity from 0.1 to I think that is what is that 0.1, I think 0.15 to or to up to here 10 not 10 it is exactly may be somewhere here at this graph.

So, with in this region you have to operate the experimental a processes here and then you can expect that bubbly flow regime. Or, any other a process like you want to have the flow pattern of dispersed flow pattern then you have to increase the liquid velocity beyond that I think 8 meter per second. So, in that case you can get this type of flow pattern there. Even you can if you want to have the annular flow pattern then you have to operate the what is that you have to select the operating condition of gas and liquid velocity with in this region. So, you can easily identify which region or at which gas velocity and liquid velocity will give you which flow pattern.

So, that is why flow pattern map is very interesting and this is formed and based on the experimental data and then you can access this flow pattern or you can get the flow pattern without doing experiment that what type of flow pattern. Now if you want to do any experiment for this particular flow pattern, simply you just select which flow rate you have to maintain or which gas flow rate, which liquid flow rate you have to maintain that things and there will be a certain correlations of this flow pattern transition that is not given in here, it will be discussed somewhere in this multiphase flow lectures there are these correlations are there.

So, this is the basic idea how to actually obtain the, or select the superficial gas and liquid velocity to get the particular flow pattern.

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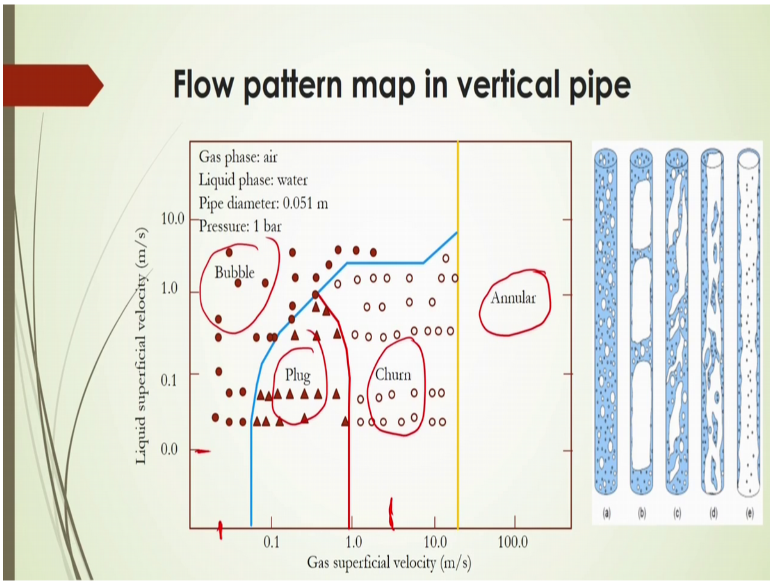

Similarly, for the vertical flow also you can expect this type of map and for air water system and if your pipe diameter is 0.051 point meter at a atmospheric pressure then you can get this flow pattern like; bubbly flow, and then plug flow, churn flow there. So, again based on this superficial gas velocity and superficial liquid velocity this different type of flow patterns annular, churn, plug and bubbly flow you can get just you know that get this superficial gas and liquid velocity at that particular flow pattern.

Now, if you want do the experiment in vertical column is there, like that I told that if it is suppose carbon dioxide gas is absorption sodium hydroxide solution, what we have to do. Then you have to follow the bubbly flow pattern, then you have to actually select the gas flow rate that will be less than 0.1 meter per second. Even liquid velocity just arbitrary you can follow or keep it constant that is 0 also you can say. So, in that case you can get the bubbly flow pattern and then you can do that absorption processes that is physical chemical engineering process.

So, this type of flow pattern, even in churn turbulent flow also there it is when you can get the churn turbulent. You can if you select the gas velocity of 1.5 meter per second or more than 1 meter per second. And liquid superficial velocity up to I think 0.1 or 5 meter per second, then you can get this churn turbulent flow there. So, you can calculate or you can obtain the superficial gas or liquid velocity from this flow pattern map for your particular experiment.

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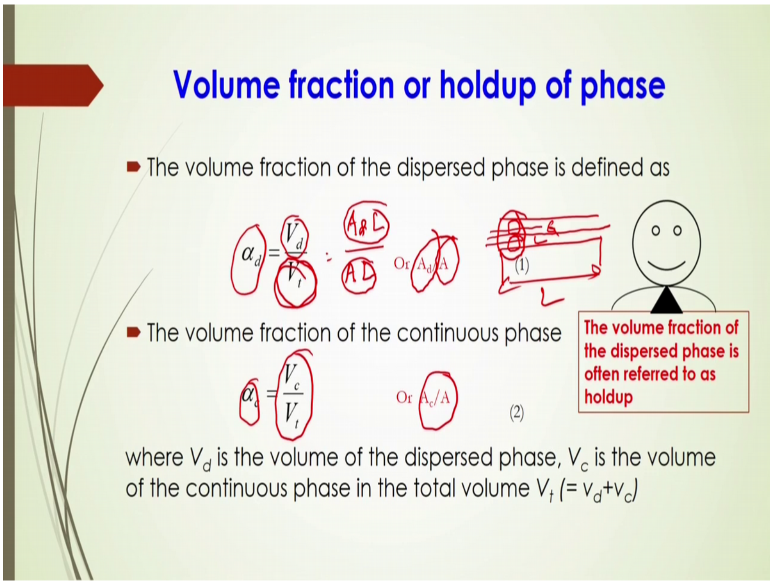

Now, some other important hydrodynamic characteristics of a two phase flow there or even you say that multiphase flow this is volume fraction or hold up of the phases. So, it is a very important hydrodynamic characteristics or hydrodynamic parameter for assessment of any chemical engineering processes, there for two phase flow or multiphase flow systems you can say, even three phase flow also it is there. So, in that case volume fraction of the dispersed phase is defined as what is the dispersed phase suppose gas and liquid flow.

What is the dispersed phase? Gas is dispersed and liquid it is continuous. So, in that case d is for dispersed and t is for total phase here. And alpha d is denoted for gas holdup it is defined as the volume fraction of the gas or dispersed phase to this total volume of the gas liquid mixture.

So, in that case V d by V t. V d is what V d is called volume of dispersed phase, and V t is the total volume of dispersed and continuous phase. Or it is defined as what will be the cross sectional of the dispersed phase, that is occupied in that particular column or pipe and what will be the total cross sectional area of the column ok. So, here suppose this is a pipe and in this pipes, gas and liquid both are flowing let it be stratified flow here it is liquid and it is gas.

So, gas is occupying only this much cross sectional area and liquid is occupying this much cross sectional area, total cross sectional area is this. So, upon that gas holdup will be based on this phase if length is like this L, then you can say it will be here A d by A d into L. A d A d into L divided by what is the total cross sectional area into L.

So, this will be your what is that this is your total volume of the dispersed phase and this is your total volume of the gas liquid mixtures. So, L will be cancel, so it will be simply A d by A. So, in this case this gas holdup will be is equal to which is denoted by alpha d that will be V d by V t. And volume fraction or that is yeah pulled up or the continuous phase, it is denoted by that alpha c that is generally it is defined as similarly that V c by V t. c for continuous phase. So, it will be coming as A c by A. So, where V d is the volume of the dispersed phase, V c is the volume of the continuous phase in the total volume V t, V d plus V c.

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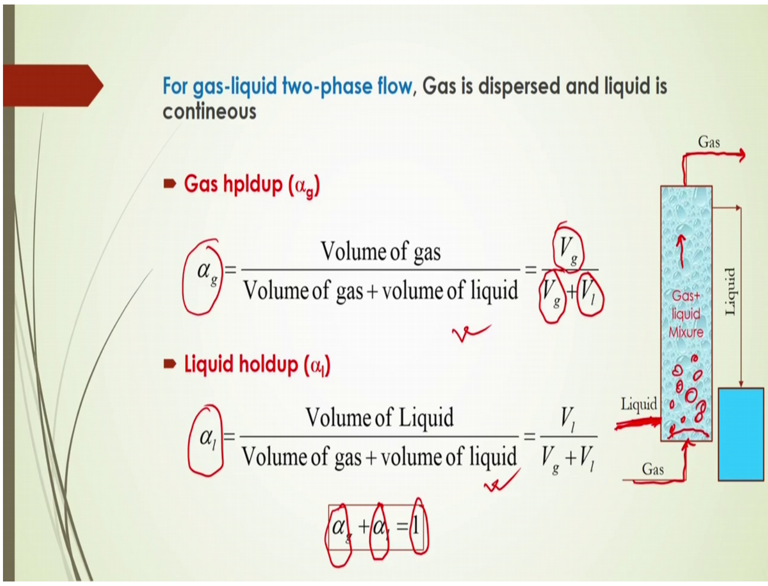

Now if you consider that only gas and liquid two phase flow. So, in this case gas is dispersed and liquid is continuous phase. So, gas holdup will be is equal to alpha g, that will be is equal to volume of gas divided by volume of gas plus volume of liquid. So, it will be volume of gas that is V g divided by V g plus V l.

So, here see in this column from the bottom there is a gas is supplied through a distributor and it will be dispersing as it dispersed phase of bubbles in that column. And it will be moving up due to their buoyancy and it will be separating from the outlet and liquid will be, if it is continuous liquid is supplying then liquid will be supplied at a certain flow rate. And, gas is at a certain flow rate. So, here liquid will be there.

So, what this particular column at a particular time, then what should be the volume of liquid and volume of the gas? So, once you know that volume of gas and volume of liquid out of this total gas liquid volume then you will be able to calculate what will be the gas holdup. So, gas holdup is defined by this equation and liquid holdup similarly by this way. Now this alpha g and alpha l this is fractions actually, the summation of these two fractions will be of course, equals to 1 if only two phase will be there of gas liquid system.

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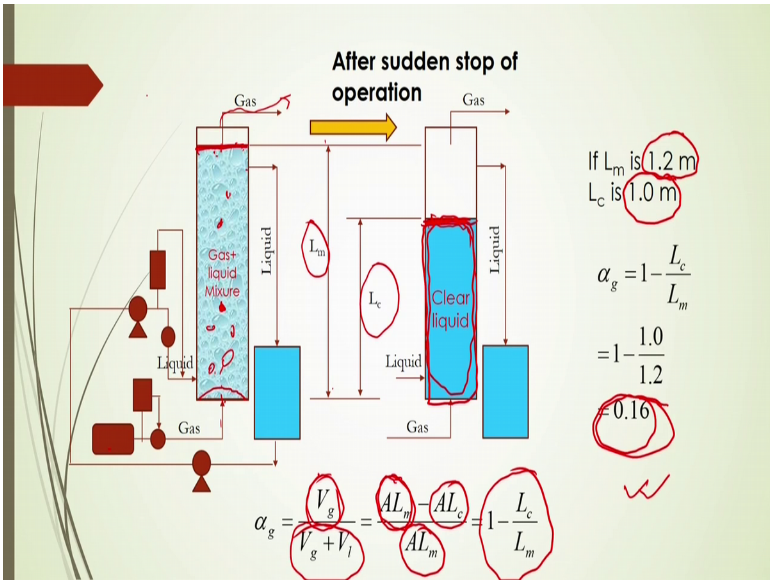

And here see important that how experimentally this hold up of the gas can be obtained. Now let us do this experiment here in the column from the bottom through the compressor, through a rotameter at a certain flow meter we have discussed that rotameter that will give you the flow rate of the fluid. So, rotameter through rotameter and it will be coming through a valve and then to be passing through the column as it is first phase of bubbles through air distributor.

Distributor is the gas distributor, there will be a certain hole and through the hole gas will be coming out as a bubble. So, when it will be moving up and at the same time liquid also will be supplying at a certain flow rate, should be measured by this rotameter and it will be supplied through a pump and then you see there will be a certain gas liquid flow rate. And, at that particular certain flow rate gas liquid flow rate, you will see gas liquid mixture will be in the column and it will be up to a certain height of the column.

And, there we will see after certain stop suddenly stop of this operation of gas and liquid what will happen you will see the gas which is actually coming out from this a compressor, and through the distributor, and that gas whatever in the column it will be disengaging or you can say that collapsing at the top, and it will be separating and it will be coming out at the top. And, from this top, when all the gases will be separated out, why it will be separated because all the gas which is coming to distributed to the distributed will be form a bubble and due to the buoyancy (Refer Time: 48:34) all the bubble should go to the top, a level.

And it will be collapsed here and then simple a gas it will be coming out. And, then after a certain time you will see all the gases gas bubbles will be collapsed and all the gas bubbles will be released and from the top and then you will see there will be a clear liquid height in the column. So, in this case in this clear liquid you will see there will be no a gas here in this case.

So, it will get after suddenly stopping this operation and if you allow sometime then after a certain time you can get this clearly liquid height in the column. Now, initially when there will be operation of gas liquid at a certain flow rate that a gas liquid mixture height in the column was look like this; if it is supposed L m it is denoted by L m that is mixture height. L m this is L m and after disengaging or after dissolving all the gases and it will be coming out from the and it is s coming out from the column and you will get this clear liquid height.

And this clear liquid height if it is denoted by L c, from this liquid height clear liquid height and the mixture height we will be able to calculate what will be the gas holdup. How? Now gas holdup what is the definition that is the volume of gas by mixture of gas and liquid. So, in this case what will be the volume of gas, how to calculate? So initial what will be the total gas liquid volume that will be calculated by A into L m. A is the cross sectional area of the column, and then L m is the total gas liquid height. So, then you can get what will be the total volume of gas liquid mixture that will be A into L m.

Now, if you subtract this total a liquid volume; that is clear liquid volume here after separation of the gas, then it will be calculated as A into L c that will give you the clear liquid volume inside the column. Now, subtract in this clear liquid volume from this gas liquid mixture volume then you will be able to calculate, what should be the, what is that volume of the gas.

Very simple, what would be the amount of gases that is coming out from that? So, now, divided by total gas liquid mixture is nothing, but A into L m. Now it will be as a 1 minus L c by L m. So, here you can say that; if L m is suppose 1.2 meter, and L c is 1.0 meter then what should the alpha g. That is gas holder that is 1 minus L c by 1m then it will be 1 minus 1 divided by 1.2 it will be coming as 0.16.

So, this is your gas holder. So, in this way you can calculate what would be the gas holdup. This is your over on gas holdup that is not that at the particular individual section what is in this particular section what will be the gas holdup. This is not that. So, it is actually over all has holdup it is measured.

So, in this way you can measure what will be the overall gas holdup. Even it is called phase isolation technique the method by which this gas holdup is measured it is called phase isolation technique. Even volume expansion technique also it is called why? because initially if you pore some liquid at this liquid height; clear liquid height and if you note down the this as L c and after supplying the gas you will see there will be increase of this gas liquid volume up to a certain height.

So, from that total gas liquid height to the clear liquid height if you subtract and divided by total gas liquid height, then you will be obtained in this over all gas holdup there. So, in this way you can measure the gas holdup.

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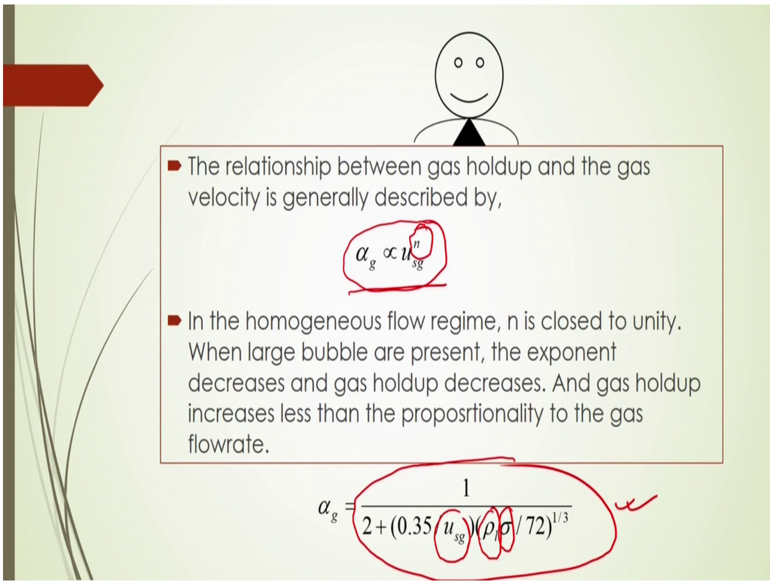

Now, in this case what you have to remember that the relationship between the gas holdup and the gas velocity, in generally described by this because, if you increase the gas velocity, of course, you will get the more gas holdup there. So, in the homogeneous flow regimes, here in this case n should be unit; that means, n is close to unity when there will be a homogeneous mixture of gas there inside the bed at; that means, here all the bubbles whatever forms are uniform in size and it will be distributed throughout the cross section of the column everywhere the density of the bubbles a number of bubbles will be same there almost same.

So, that is why in this case this you can expect this gas holdup should be is equal to u n g to the power n, n is here one for homogeneous, but what heterogeneous system you will see where that heterogeneous system should be there in that case all bubbles will not be same in size, and some bubble should be performing as a longest bubble, someone bubble will be forming very smaller some bubble will be forming elliptical shapes some bubbles will be there. So, all the gas will not be distributed throughout the cross section uniformly. So, in that case it is called heterogeneous systems that heterogeneous system should give you heterogeneous sections that this n should be greater than 1.

So, in that case of this exponent will decrease a gas hold up then will decrease and in this case what the homogeneous system this n should be in such a way that in that case gas holdup increase less than the proposrtionality of the gas flow rate in that case of a homogeneous flow. Whereas in heterogeneous flow, that may be is greater than 1 in that is you may expect more a gas holdup, but other physical properties also important there maybe surface tension. If you change the surface tension how this gas hold up will be changing even if you change the viscosity of the fluid.

And, how this gas holdup would be changing there are several co relations are there to calculate the gas hold up. One important correlations that is given by Haggmark 1947 that he actually given this correlations to calculate the gas holdup or predict the gas hold up in this case if you know the superficial gas velocity density of the liquid and surface tension of the liquid you will be able to calculate what should be the gas holdup there.

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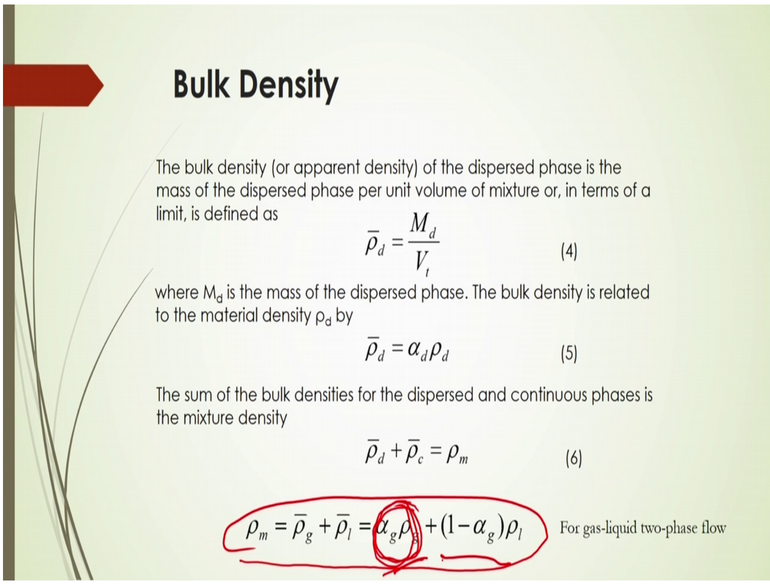

Another importance Bulk Density of the mixture if you know this gas holdup then bulk density of the mixture will be simply calculated by this equation here. Rho m; rho m is what is the mixture density and alpha g rho g is called this is bulk density of the gas. And this is where or it is called effective density of the gas and this effective density of the gas can be calculated just by multiplying the gas holdup with this material density of the gas.

So, this is your, what is that alpha g rho g similarly 1 minus alpha g into rho l that will be your bulk density. So, mixture density you can calculate simply once you know that gas hold up then what should be the mixture density or bulk density.

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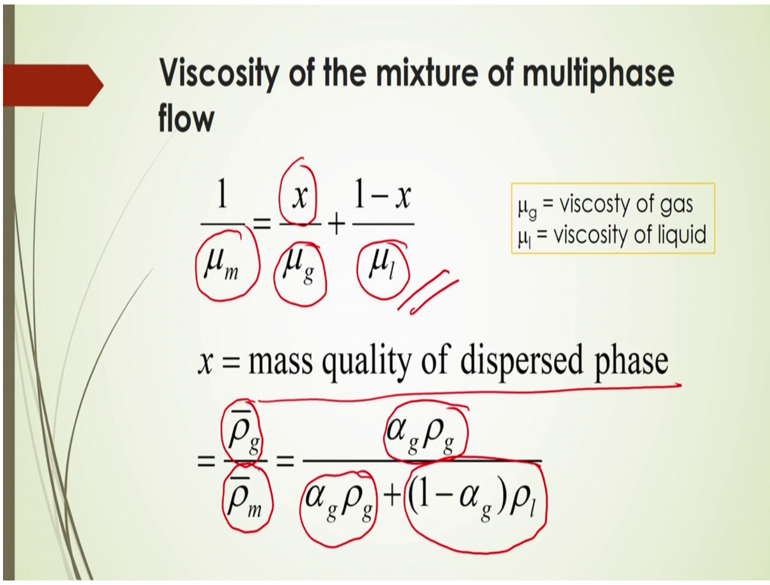

Similarly, viscosity of the mixture also you can calculate based on this equation here mu m is the mixture viscosity, and this is viscosity of the gas, this is viscosity of the liquid; x is called mass quality of the dispersed phase here. So, mass quantity of the dispersed phase it is defined as; what is the bulk density of the gas and what will be the bulk density of the mixture. The ratio of these two of density is called the mass quality of the dispersed phase.

So, this is simply alpha g rho g divided by alpha g rho g plus 1 minus alpha g into rho l. So, by this equation you will be able to calculate what should be the mixture viscosity.

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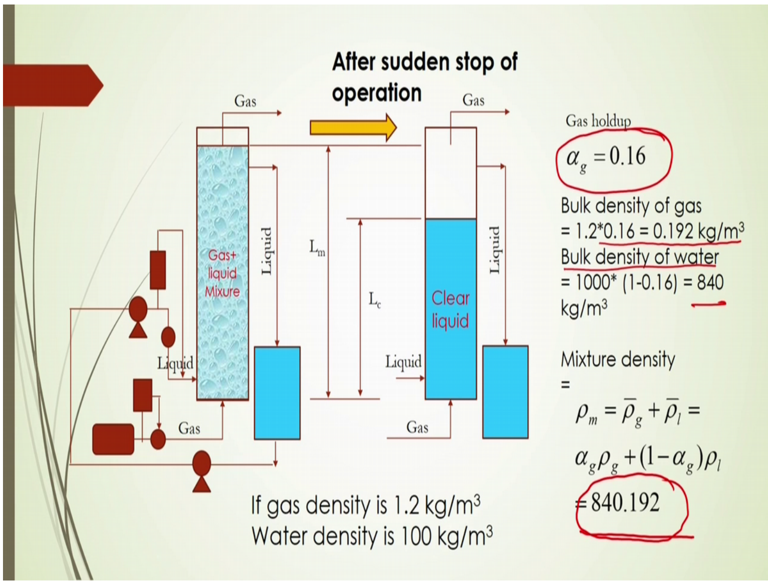

Similarly, if we give an example for this, what should be the mixture a density here? So, you can calculate easily by knowing the gas holdup. Gas holdup is 0.16 then mixture density will be is equal to for air water system or air the density is 1.2. So, this bulk density of the gas and bulk density of the water is like this. So, effective density it will be coming as 840.192. Whereas the material density of the liquid is 1000 kg per meter cube, where as mixture density is coming here, 840.192.

So, in the multiphase flow systems the density of course, will be changing when viscosity of course, will be changing. So, accordingly you have to consider for the process analysis.

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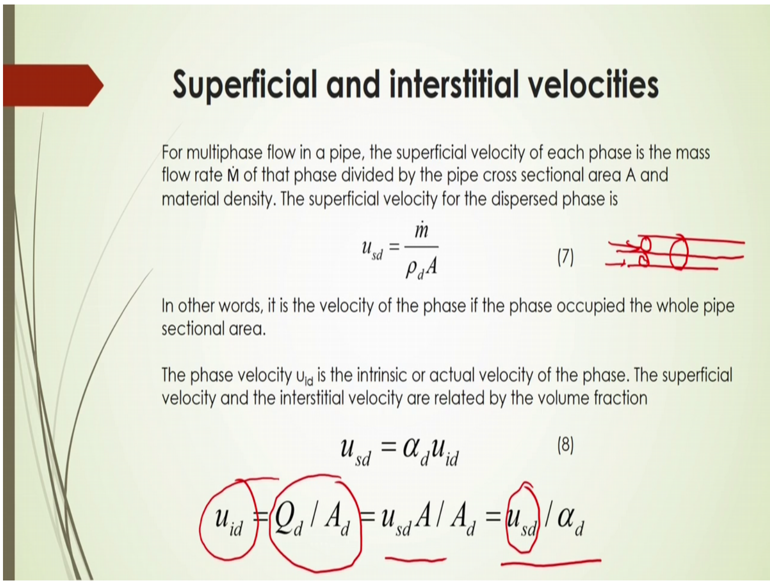

Another important is the velocity we will see whenever gas and liquid both will be flowing through the pipe; you will see that it will not be the superficial velocity of the individual phases there will be actual velocity. So, actual velocity will be changing because when both the phases will be a flowing through the pipe, in that case the cross sectional area effective cross sectional area of the each phases then it will be changing. So, it will change because you will see if there is a suppose two phase flowing through the pipe and here in this bottom pipe liquid and upper part is gas.

So, here cross sectional area this is cross sectional area and total cross sectional area is this. So, in this case you will see if you consider that the velocity is superficial velocity, then only you have to consider whole cross sectional area and the flow rate of that particular gas will be through the whole cross sectional area where as the simultaneous flow of gas and liquid that individual phase may not occupy the whole cross sectional area there will be smaller cross sectional will follow.

So, in that case smaller cross sectional area of that total flow rate, it will give you the higher gas velocity that will be your actual velocity. So, that is why an actual velocity or it is called interstitial velocity. So, interstitial velocity or actual velocity will be obtained based on the shear interstitial velocity u id is equal to Q d by A d. So, here in this case u sd in to A d that is u sd by alpha d; that means, u sd is what superficial velocity. What is the superficial gas velocity? That is if the phase occupied the whole pipe cross sectional area and then if you divide this volumetric flow rate by this whole cross sectional area then you get the superficial velocity. Whereas, this interstitial velocity was actual flow velocity will be actual cross section based on the actual cross section rate of the phases.

So, that is why this interstitial velocity will be greater than the superficial gas velocity. So, actual velocity of the individual phases will be greater than the superficial gas velocity. So, you have to remember this.

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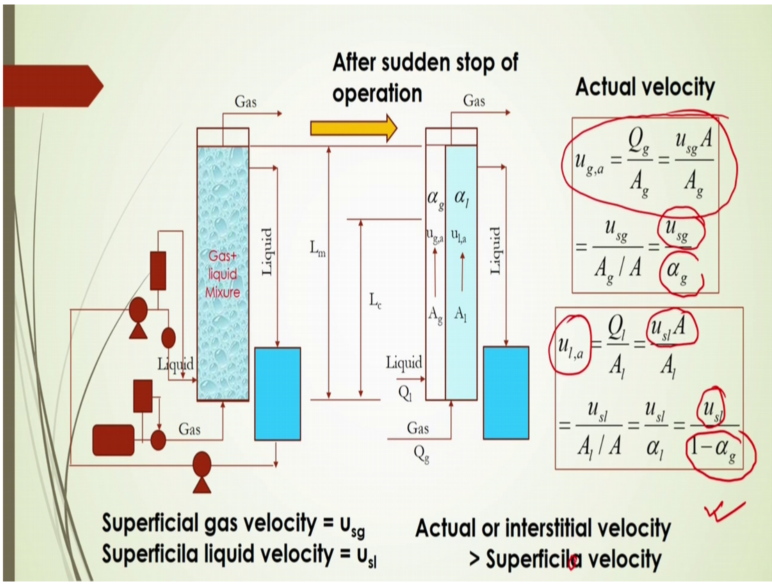

Now, here in this case you will see that how this actual velocity is coming then this actual velocity will be is equal to superficial gas velocity divided by its hold up. Similarly, actual velocity of the liquid that is it will be superficial liquid velocity divided by the holdup of the liquid that will be 1 minus f epsilon g. So, based on this equation you can obtain the actual velocity of the gas and liquid if both the gas and liquid flowing through the pipe though actual or interstitial velocity should be greater than superficial gas velocity. So, you have to remember this.

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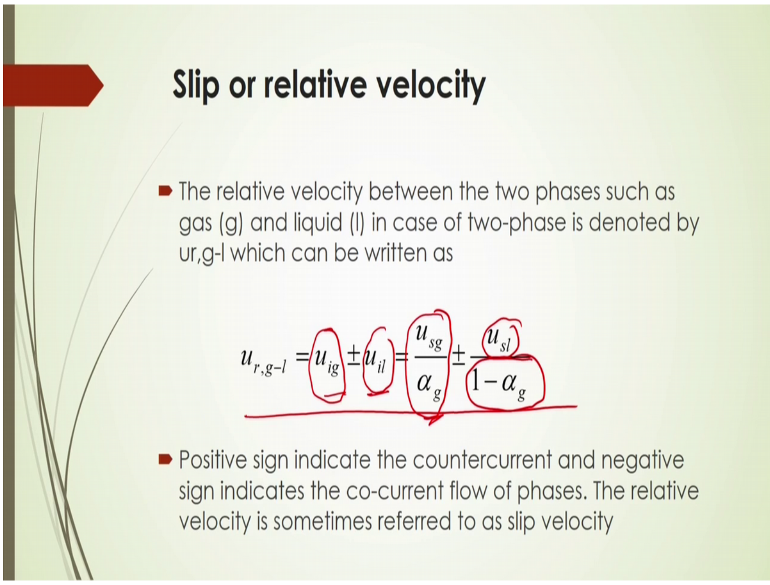

Another important velocity it is called slip or relative velocity; so, the relative velocity between the two phases such as; a gas and liquid. In case of two phase is denoted by u r or g l, that is here which be written as a u rgl that u ig minus u il, u ig gas velocity and u il is the interstitial liquid velocity. This is simply interstitial that is u sg superficial gas velocity by alpha g. This is plus minus u sl by 1 minus epsilon g plus minus a positive sign here it decade the counter current and the negative sign indicates the concurrent flow phases. The relative velocity sometimes referred to as slip velocity here.

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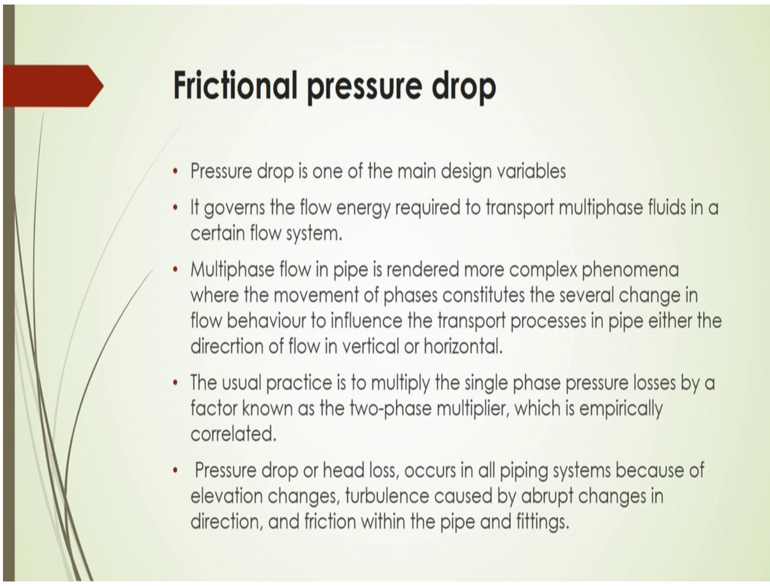

Now, another important aspects of the multiphase flow system it is called Frictional pressure drop, frictional pressure loss. So, in this case the pressure drop is one of the main design variables. Pressure drop or head loss occurs in all piping systems because of the elevation changes turbulence caused by abrupt changes in the direction and friction with in the pipe and fitting and usual practice is to multiply the single phase of pressure losses by a factor that is known as two phase multiplier which is empirically correlated.

So, fictional pressure loss you can obtained from the two phases for the two phase system based on the single phase frictional pressure drop.

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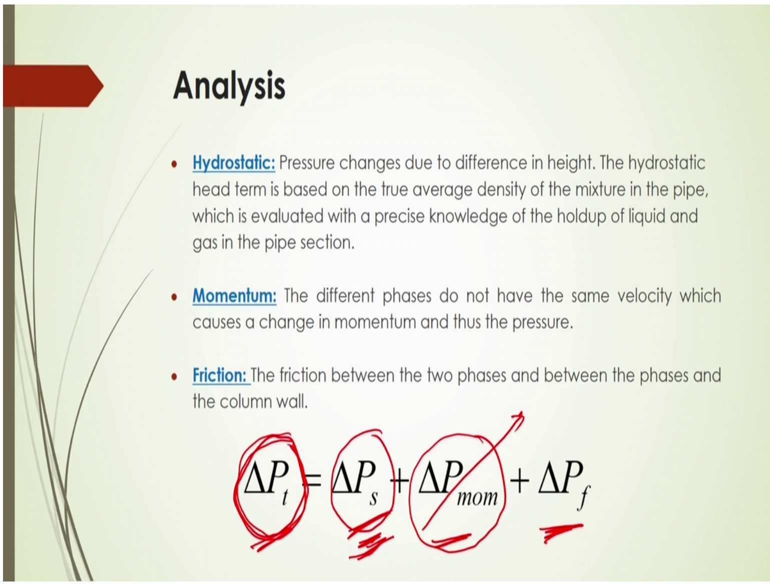

It maybe some factor multiply of that the single phase friction of pressure drop. Now, generally for two phase systems the total a fictional pressure drop total pressure drop you can expect from the summation of the static pressure drop pressure drop due to momentum exchange and pressure drop due to the friction.

So, there will be hydrostatic pressure momentum pressure and frictional pressure. So, once this is total pressure drop that can be obtained by measurement and if you know the static pressure; obviously, some measurement and this is momentum pressure it may be sometimes useful may not be sometimes useful. In this case it is important term when there is a pipe cross section is changing from point to point and there will be a what is that dominant effect of momentum because of that flow then you have to consider this momentum. If there is a uniform cross section throughout the ends of this pipe, then you can neglect this momentum in sense. Because there will be no of velocity changes at that particular location and in that case there will be a negligible effect of this momentum.

So, ultimate these two friction pressure drop will be there two pressure drop will be there; one is total pressure drop will be summation of hydro static pressure drop, frictional pressure drop. And, from this you can calculate what would be the frictional pressure drop from this total pressure drop just you have to subtract the static pressure drop and then you can get the frictional pressure drop.

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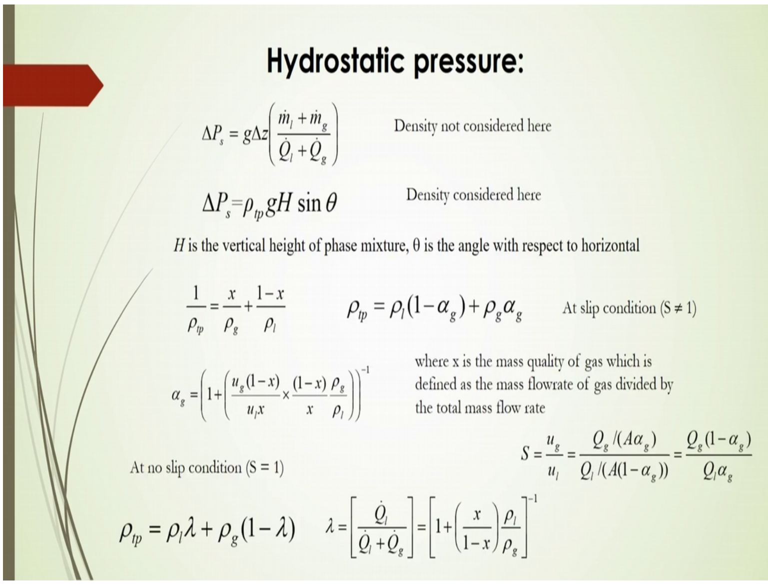

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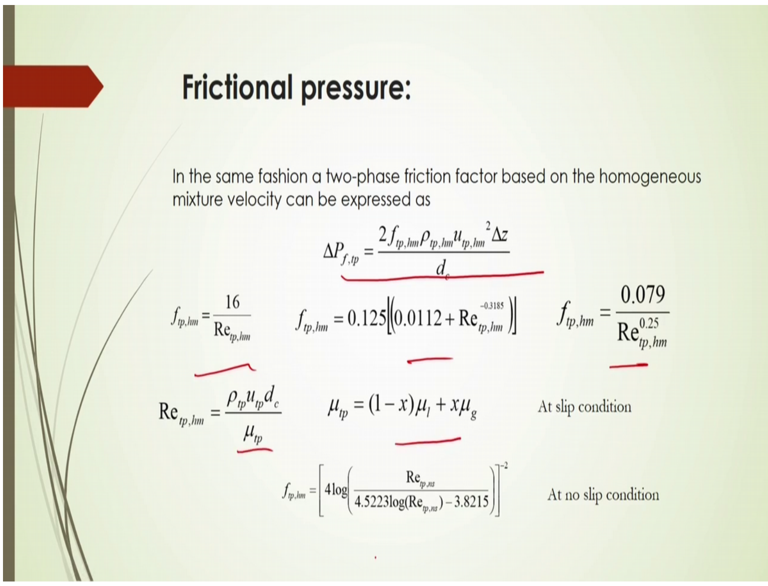

Once you know the frictional pressure drop, you can obtain this frictional pressure drop just by considering this equation. And, what will be the parameter for that you can calculate here.

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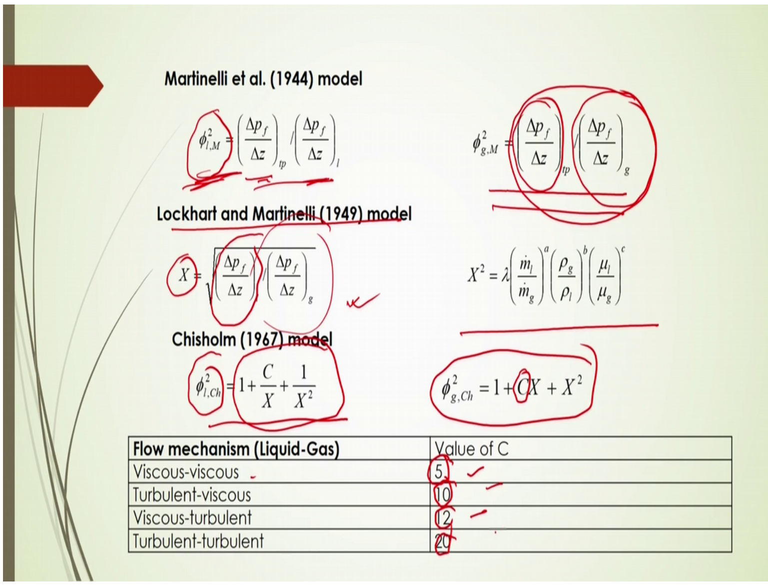

And then what is that, once you know that frictional pressure drop per unit length for the multiphase flow system and single phase flow system. If you divide it then you will get some value it is called Martinelli two phase multiplier and it is called Martinelli parameter. And for gas flow system if you divided these two phase flow frictional pressure drop by single phase gas frictional pressure drop then you can get this Martinelli parameter. Now also Lockhart Martinelli parameter is defined as that frictional pressure drop of this liquid to gas, it will be called as Lockhart Martinelli parameter.

And this will be obtained by this physical properties and Chisholm has developed this relationship of this Martinelli; Lockhart Martinelli parameter with this multiplier Martinelli here two phase multiplier. So, two phase multiplier as per Chisholm it will be is equal to 1 plus C by X plus 1 by X square and or you can say that phi g square Ch that is Chisholm parameter, or multiplier it will be is equal to what is that? This 1 plus C X plus X square; so, ultimately this C is called constant, this C can be obtained by the experimental results. And then this C will be is equal to 5, 10, 12 based on this flow pattern flow mechanism. Here for viscous systems will be 5 turbulent viscous it will be 10 and viscous turbulent 12 and turbulent turbulent like this 20.

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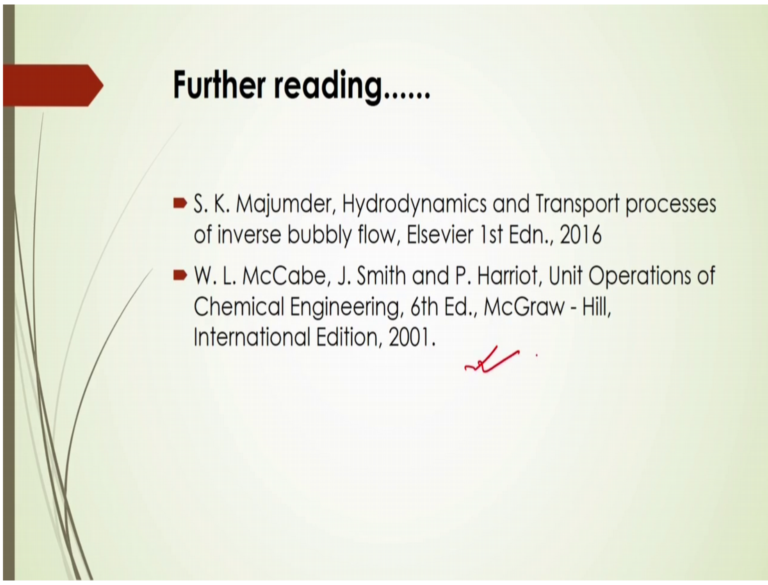

So, these are the basic fundamental of hydrodynamics of these multiphase flow systems. So, I would suggest you to go further for more details if the more information's you can get from these books here. So, I think you have got some idea of that two phase systems of, how this two phase system are basically different from that single phase systems.

So, thank you for this lecture today and next class onward I will discuss something what is the some applications of these multiphase systems there. And, more details of this multiphase systems you can get from other courses that is plotted and here just introduction of this multiphase flow systems.

Thank you for this lecture.