Fluidization Engineering
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Lecture – 07
Flow regime and its map:
Liquid-solid & Gas-liquid-solid Fluidization

Welcome to a massive open online course from fluidization engineering, today's lecture part will be on flow regime and it is map basically on liquid solid and gas liquid solid fluidization system.

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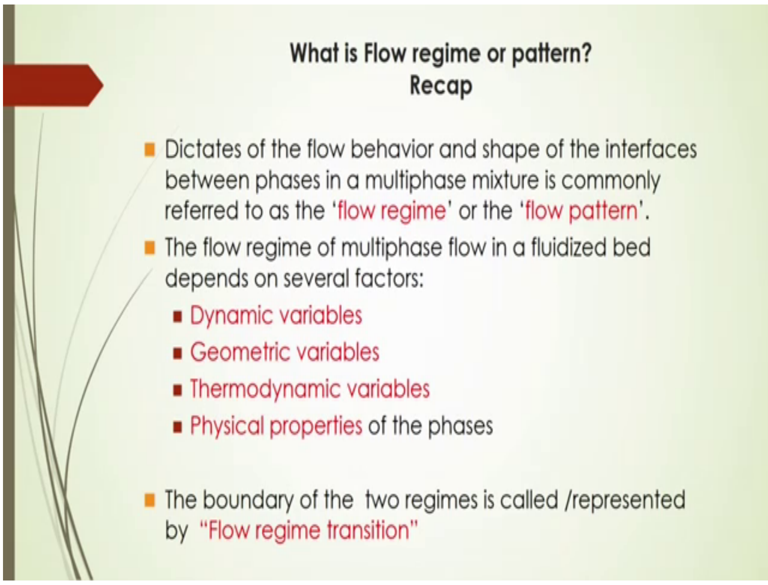

Now already we have discussed about what is the definition of flow regime or pattern the steel we are looking back a little bit for that. So, this flow regime or pattern means this is the flow behavior and shape of the inter phases between phases in a multiphase mixture, which is commonly referred to as the flow regime or flow pattern.

The flow regime of multiphase flow in a fluidization bed that we have discussed, that depends on several factors like dynamic variables, geometric variables, thermodynamic variables and physical properties of the features dynamic variables like flow rate of the gas liquid or even if solid is in continuous mode, then what will be the solid velocity and then geometric variables means column diameter or bed diameter bed cross sectional area volume of the bed, even what would be the particle diameter and the geometry of the particle like, what should be the shape of the particles?

What is the sphere city? all those variables are coming under geometry variables and thermodynamic variables are like pressure temperature; how this pressure and temperature will affect the fluidization behavior in a fluidized bed and mostly the physical properties of the phases that is density of the fluid, viscosity of the fluid and if gas liquid solid system, what should be the surface tension of the liquid that we will affect the fluidization behavior inside the bed.

If you change the density of course, the behavioral change viscosity highly viscous fluid, it is very difficult to flow are getting different flow regime inside the bed; even if you are changing the particle diameter that is coarser diameter, we will not get the specific flow regimes for particular operation, then you have to change are that accordingly the flow regime we will change and application will be different and also pressure affect there will be a at high pressure, if it is operated at high pressure is the minimum fluidization velocity will be more in that case.

Now, if we have different flow regimes of course, we have discussed in earlier classes or earlier lectures that what are the different flow regimes in gas solid system and what should be the flow regime transition it is actually nothing but the boundary of the 2 regimes, but then what should be the than flow regime made for map for liquid solid or gas liquid solid fluidization system.

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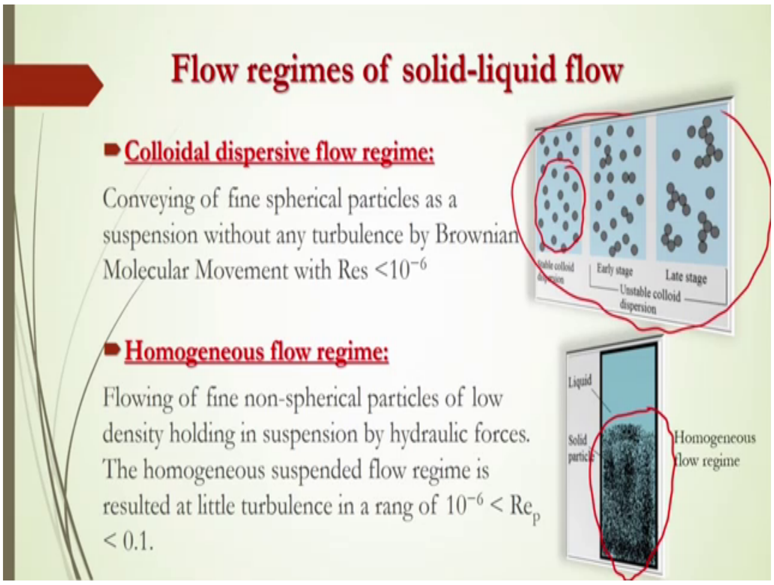

Now, liquid solid flow in that case flow regime for this operation you will get generally 2 types of flow regimes, one is colloidal dispersive flow regime and another is homogenous flow regime; this colloidal dispersive flow regimes in this case conveying of find spherical particles as a suspension without any turbulence, by Brownian molecular movement with Reynolds number of the solid particle should be less than 10 to the power minus 6.

So, in that case the colloidal dispersive flow regimes will be occurred and this type of flow regimes you will get only for the flow velocity, that you can say the velocity of the fluid inside the bed it is very low that is even over than the strokes flow regimes; homogenous flow regime you will get that flowing of find non spherical particles of low density, that hold suspension by hydraulic posters and in this homogenous suspended flow regime, actually is resulted at a little turbulence in a range of Reynolds number 10 to the power minus 620.1. So, in this case everywhere inside the bed the concentration of the solids will be almost similar or you can say the same throughout the column and in this case the liquid velocity, of course will be a little bit higher than the setting velocity of the a solid particle.

We are see in this diagram are given or this picture or given of first one is for a colloidal dispersive flow regime, in this case the particles are moving with the Brownian motion, whereas there is no turbulence in this case; but sometimes we will see some particles are making a colloid with like unstable colloid there making and coagulation to each other and then it will be moving as a Brownian motion. Whereas, a stable colloidal dispersion in that case there will be no oh actually coagulation where no actually agglomeration will be forming between the particles and homogenous flow regimes they are we will see there may be a some to cog may coagulations; since the homogenous nesar though, but depends on what should be the velocity inside the bed.

For higher velocity the breaking of this coagulate action or in consider agglomeration will be little bit lower tendency related to the other velocity. So, these are the things that homogenous flow regimes, how it will be there inside in the picture it is shown here.

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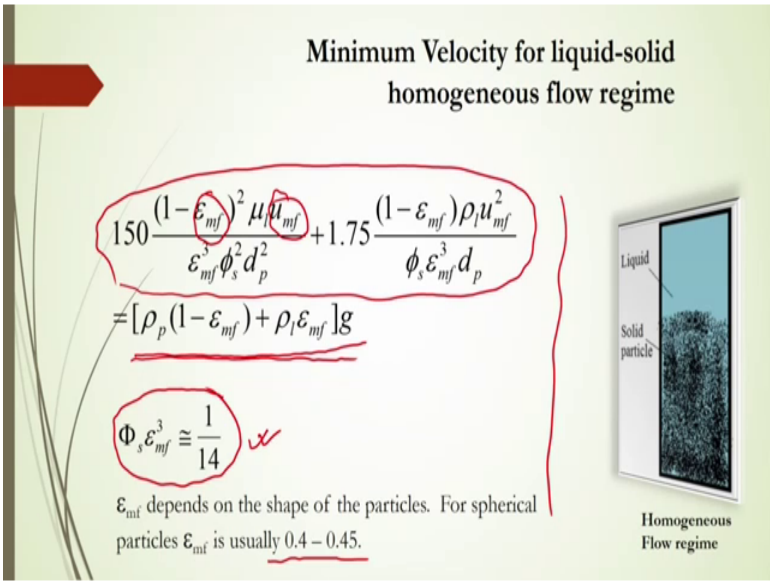

Now, of course it has been discussed, what should be the minimum velocity for gas solid fluidization system in particulate bed that we have already obtained from the balance of frictional pressure drop to the bed. So, in the same way here also we can get the minimum velocity for liquid solid or homogenous flow regimes for this liquid solid system.

In this case also you have to find out what should be the frictional pressure drop from the organ equation; organ equation here is the this is the part for organ equation by which you can calculate to the fictional pressure drop, whereas this rho p into 1 minus epsilon f plus rho l epsilon m f in to z this part is called weight of the bed or apparent weight of the bed; so this to be balanced so that at the minimum velocity for liquid solid homogenous flow you can get the minimum velocity as a umf here. Whereas, this epsilon mf is nothing but the minimum fluidization velocity, this minimum fluidization velocity again you can get from this when m and u relationship that phi s into epsilon mfq that almost will be equals to 1 by 14.

So, from the equation you can get what should be the minimum porosity or minimum void age inside the bed for this liquid and solid system and this epsilon m f minimum fluidization void age depends on the shape of the particles, for a spherical particles it will be the range in 0.4 to 0.45, so those things we have already we have discussed earlier. So, this is the way to find out or estimate the minimum fluidization velocity for liquid solid homogenous flow regime. Now flow regimes of solid liquid flow you can say another flow regimes is very important, it is called Pseudo homogenous flow regime.

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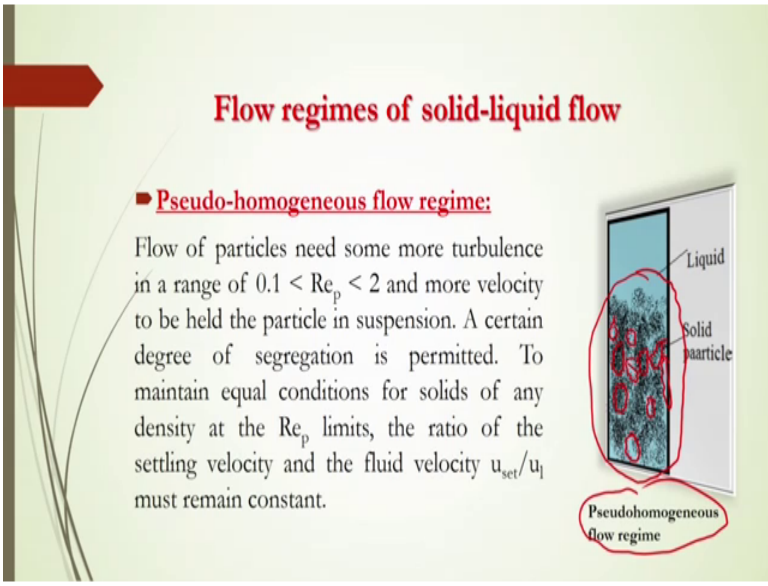

In this case flow of particles need some more turbulence, so that the particles will be suspending with very low velocity, but with the little turbulence and the Reynolds number range for this will be 0.1 to 2 and of course forgetting this turbulence you have to apply more velocity compared to the minimum and also what is the homogenous flow regime system.

And of course, for this more velocity are the particles in this Pseudo homogenous flow regimes are getting suspended and to keep suspended you have to maintain that velocity, of course greater than the homogenous flow regime velocity; a certain degree if segregation in this case also can be permitted to get this you know homogenous flow regime and to maintain equal conditions for solids of any density at the his at this Reynolds number range of 0.1 to 2, the ratio of the settling velocity of the particle and the fluid velocity must remain constant in this case. So, if you are maintaining the ratio of settling velocity and this liquid velocity in this way, you can expect this there will be a uniform suspension of the particle inside the bed, with this range of Reynolds number.

So, here this is the Pseudo solid liquid flow scene, in this picture that here there will be no actually uniform concentration inside the bed because, there will be some void age. So, that will be distributed inside the column that is not uniform throughout the column also and also particles are particles may be agglomerated inside the bed, but this agglomeration also may be in such way that, so that little bit nearer to the value of this uniformity of the solid particles are compared to the homogenous flow regimes and other them that is called heterogeneous flow regime.

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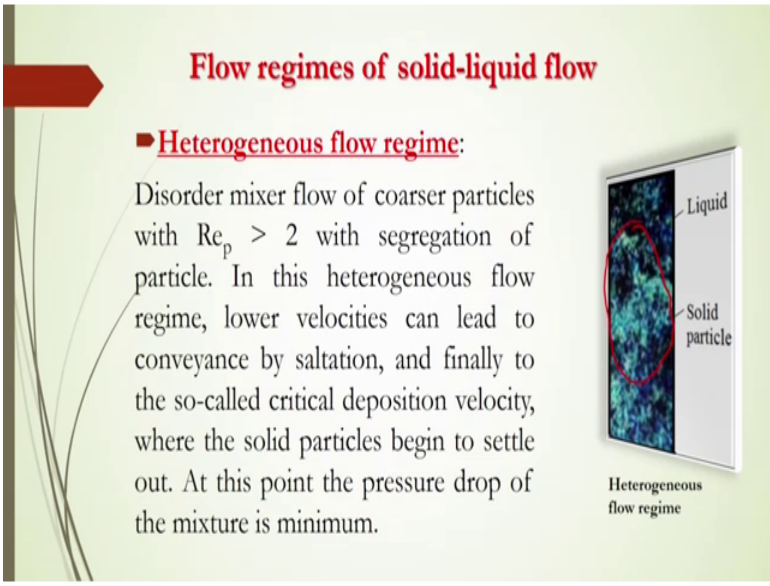

In this case of course you will see the disorder mixer flow of the particles inside the bed, in this case the velocity should be little bit higher than this Pseudo homogenous flow; in this case the Reynolds number should be greater than 2 and segregation of the particle of course will be seen by this flow regime and in this heterogeneous flow regimes.

Lower velocities can, low can sometimes result to convince by siltation and finally to the so called critical deposition velocity inside the bed; in this case the solid particles begin to settle out and at this point the pressure drop of the mixture will be minimum. So, heterogeneous flow regimes you can get it from Reynolds number is greater than 2, with little bit higher turbulence here.

So, see this picture here so this is the turbulent, you cannot observe here what should be the exactly uniformity or uniformity pattern inside the bed, there will be a internal fluid circulation inside the bed the solid particles and since the Reynolds number is greater than 2 there will be a more turbulence inside the bed and the ship of the particles may not be the same inside the bed or you can operate this heterogeneous flow regimes, we poster particles with high more than higher liquid velocity also.

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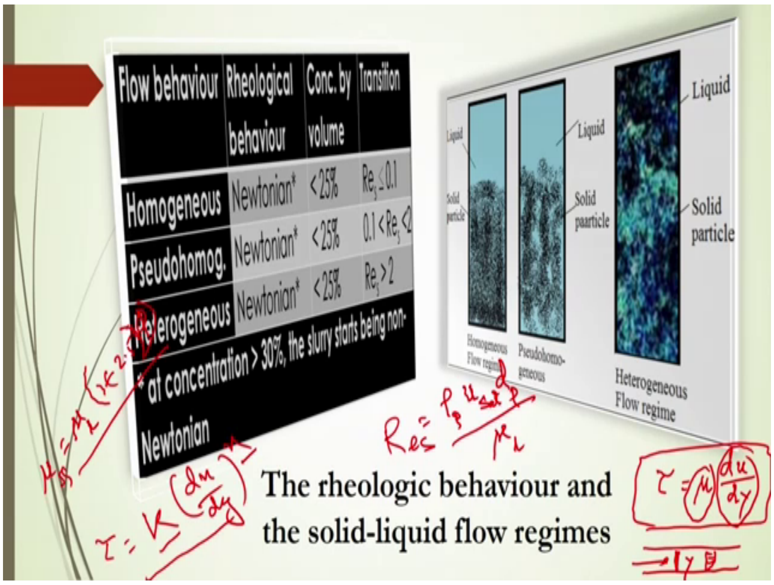

And now see rheological behavior and the solid liquid flow regimes inside the bed, here see in the table into seen that homogenous flow regime you can get for the Newtonian fluid if it is concentration; that means, concentration of the solid particle inside the bed is less than 25 percent by volume and you can get the transition from homogenous to Pseudo homogenous flow, if the Reynolds number of the particle is greater than 0.1. Whereas, Pseudo homogenous also for this Newtonian flow you have; that means, viscosity will be linear with respect to liquid and gas in this case there is no gas, so only liquid. So, Newtonian fluid if is less than 25 percent by volume, you can get the Pseudo homogenous flow, but here the Reynolds number will be is greater than 0.1 and less than 2.

Whereas heterogeneous flow behavior in this case Newtonian flow behavior also you can get if the concentration is less than 25 percent volume, but Reynolds number should be greater than 2; this Reynolds number is defined based on the terminal velocity of the solid like here rho p into up this is here Res you can say r e s will be is equal to rho p or rho s into u settling velocity into d p particle diameter divided by viscosity of the liquid, so this is Res. So, based on these Res you can just divide what should be the flow behavior with the concentration less than 25 percent. Now at certain concentration which is greater than 30 percent the slurry starts begin as a non Newtonian fluid, what is that Newtonian and non Newtonian fluid Newtonian and non Newtonian fluid actually you know that whenever stress liquid, stress is directly proportional to the shear rate then you can get it is a Newtonian fluid.

Whereas this shear stress if it is not directly related to the shear rate, then it may be non Newtonian fluid; we have also learnt in different fluid mechanics books also you can get also you just go through more fluid mechanics books they are the how Newtonian and non Newtonian fluids are classified and differentiated. So, based on this shear stress and shear rate relationship you can classify, you can say if suppose shear stress is really denoted by tau, then tau should be directly related to the directly related to the shear rate like du by dy; here du is nothing but the change of velocity with respect to the length.

Suppose if there is a flow is flowing like this in a pipe, then what should be the y that is here in r you can say here. In this y direction or you can say in the r direction, here then the velocity what should be the change of velocity in this direction, then the gradient of this velocity this radial or you can say the axial direction this will be represented by du by dy and this is called shear rate and this shear stress is directly related to this share rate and this proportionality constant is called mu this mu is called the viscosity of the fluid.

Now this if it is directly related that means, it is Newtonian this type of relationship is actually obtain for the like water so this called Newtonian fluid. If it is not directly related to this shear rate then, that means here tau if it is related like this k in to du by dy to the power n; that is non-linear relationship then this k and n we will give you the what is the tendency of what should be the behavior of the fluid.

Now, if k and n are changing it is not k is not mu; that means, here then n is not 1 then you can see it will be totally non Newtonian; that means, n maybe is less than 1 or greater than 1. So, it depends on the type of fluid, so those fluids will be called as non Newtonian fluid. So, whenever liquid and solids will be flowing in a fly for in a column of course, it will behave like a non Newtonian fluid also if the concentration of the solid inside the bed is greater than 25 percent. So, this case the viscosity of course, we will change viscosity it will be highly viscous and that viscosity will be related to the viscosity of that is Newtonian fluid.

So, that effective viscosity maybe as per Einstein's theory that you can say that viscosity of the non Newtonian fluid for slurry system that will be is equal to mu l; that means, not without slurry you can 70 pure liquid then into 1 plus here 2.5 into 5 means volume percentage of the solid inside the bed and 2.5 here this will be your effective slurry viscosity inside the bed. So, in this way you can calculate what should be the flow behavior inside the bed, now if you use run the fluidization with the higher concentrated solid particles then have to calculate the slurry viscosity not yet there Newtonian and not as a Newtonian it will be non Newtonian to it flow and the viscosity will be something different.

Now, solid particles can be conveyed upward if the transport condition is well satisfied that means, when fluid velocity extends the terminal or settling velocity of the solids here.

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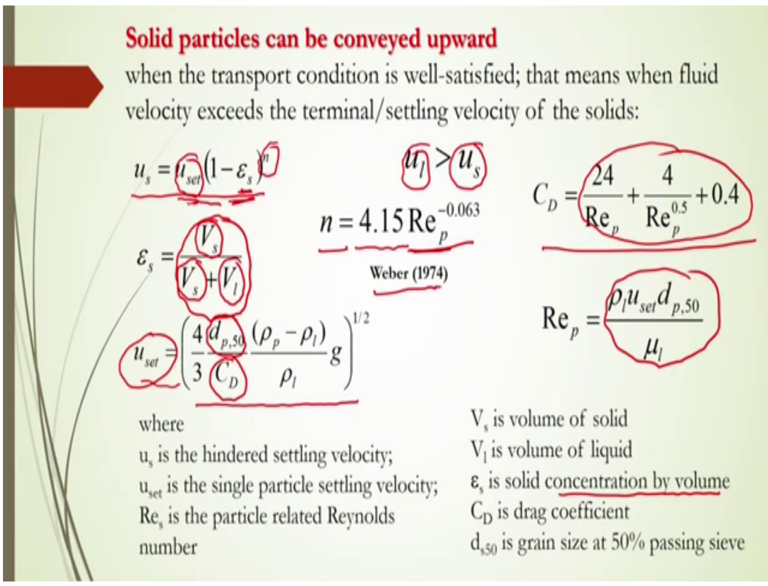

See if settling velocity as hindered settling, this course hindered settling velocity in this case this hindered settling will be is equal to settling velocity into 1 minus epsilon s to the power n, here this epsilon s is nothing, but the solid concentration by volume. So, this hindered settling you can calculate that means, here if a particle concentration; that means, is slurry concentration you can say that the bed is the higher than this individual settling velocity of the particles, may be reduced by the interaction of the other particles in that case effective hindered settling velocity, will be is equal to this settling you set a particular; that means, single particle settling velocity into 1 minus epsilon to the power n.

Where this epsilon s you can obtain what should be the ratio of solid volume to the total volume inside the bed. So, vs is nothing, but the solid volume inside the bed and this v s plus vl are nothing but the total volume inside the bed of solid and liquid respectively. So, from this ratio that is called this is nothing, but a fraction this fraction this is by volume you can calculate what should be the solid concentration by volume inside the bed and here settling velocity for individual particle or you can say that single particle settling velocity that can be of course obtained from the that is the balancing by the buoyant force and weight of the solid and it is drag whenever it is flowing under this settling velocity. So, from this condition you can calculate this settling velocity for the single particle by this here.

So, you set will be is equal to 4 by 3 d p 50 by c d into rho p minus rho l by rho l into z to the power 1 by 2, now in this case you see c d c d is called drag coefficient already we have discussed in earlier lectures that how to calculate the drag coefficient and here this d p 0.50 is nothing, but the particle diameter at 50 percent. What does it mean that is grain size or particle size at 50 percent passing sieve, what are the size of the particles are those particles which are coming down to the sieve will be considered as d 50 here and that d 50 will be considered for this settling velocity of this particle and here this n is coefficient, this coefficient depends on the Reynolds number of the particle that is the given by Weber 1974 and this will be is equal to 4.15 into Rep to the power minus 0.063. So, if you know the Reynolds number by this equation here Reynolds number is equal to rho l u set d p 50 by mu l.

Once you know this Reynolds number what should be the coefficient for n that can be calculated from this equation and once you know this n and you settling and this epsilon is easily you can calculate what should be the hindered settling inside the bed. Now to get these solid particles conveyed in upward you have to maintain this liquid velocity inside the bed, would be must greater than this hindered settling velocity. So, that is why ul should be is greater than u s there and to calculate this u settling velocity of course, another important equation for drag coefficient will be calculated based on this Reynolds number here this relationship is given.

So, from this equation what should be the criteria for getting the solid particles in the liquid medium to be conveyed upward? So, in this way you can calculate this hindered settling and then criteria for liquid velocity.

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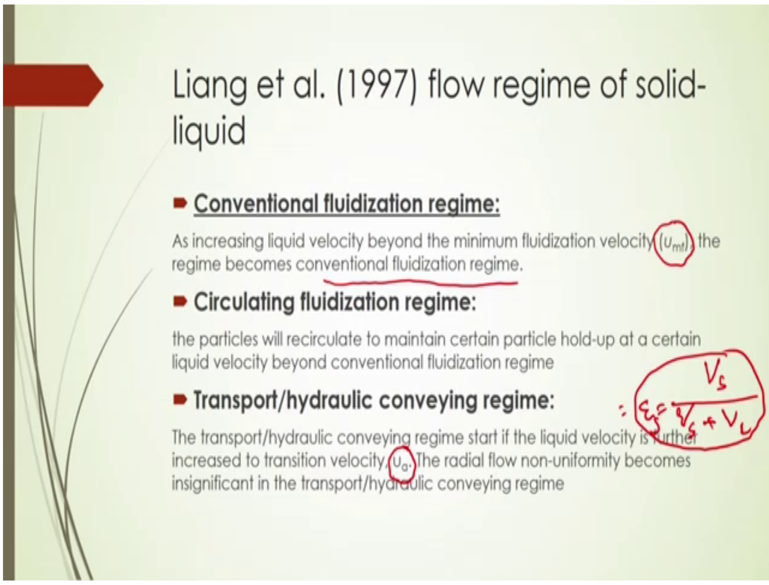

Now, Liang 1997 they have observed different types of flow regimes of solid liquid system, say according to Liang et al they have actually observed that there should be some conventional fluidization regime in the liquid solid system; whereas, other than conventional fluidization regime like circulating fluidization regime even transport or hydraulic conveying regimes also are observed, in this case as they told that if liquid velocity beyond the minimum fluidization velocity; that means, Umn that you can calculate that has been shown earlier the regime becomes conventional fluidization regimes.

It is also for the solid liquid system not commonly gas solid system. So, gas solid system also Umn, but liquid solid system Umn if you are considering; but it will be calculated in different just considering the liquid properties instead of gas properties. Now circulating fluidization regime in this case particles will recirculate to maintain certain particular hold up at a certain liquid velocity, beyond the conventional fluidization regime. So, in this case circulating fluidization in the main important point is that, you have to that to that this is calculation will be they are at a certain particle hold up inside the bed, that particle hold up means nothing but this volumetric concentration of the particle inside the bed.

That can be calculated again by this, what should be the volume of solid particles out of the total volume of solid and liquid inside the bed. So, this will be your particle hold up here inside the bed. Now this from this of course, you have to maintain constant this particle concentration or particle hold up at a certain liquid velocity inside the bed; then only other circulating fluidization regime can be obtained and transport or hydraulic conveying regime in this case this flow regime we will start if the liquid velocity is further increased to transition velocity to get this transporting or conveying mechanism in the fluidized bed.

The radial flow in this case will be non uniformity and which will become the in significant in the transport or hydraulic conveying regime. So, this is very important that you have to increase the velocity in such way in a certain manner. So, that it will be beyond the transition velocity from the circulating fluidization regime. So, for that may be the non uniform that is the instability manner instability behavior of the fluidization bed will be observed inside the bed.

Now, Liang et al also they have given 1 flow regime map for this liquid solid fluidization system, where they have represented this flow regime map as for that (Refer Time: 30:25) model based on this new star and dp star definition.

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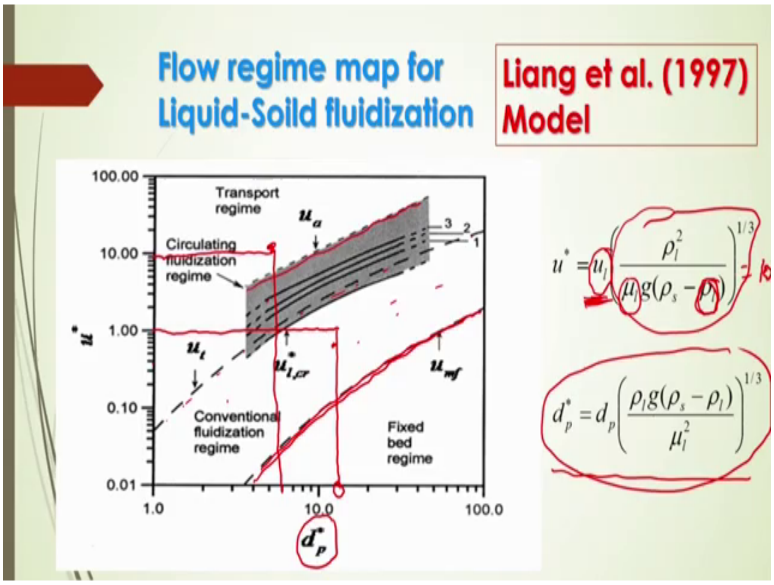

So, here dp star they have mentioned in an x axis again, it is defined as the dp into rho l g into rho s minus rho l by mu l square to the power 1 by 3 and in y axis they have defined this u star as ul into rho l square divided by mu l into z into rho s minus rho l to the power 1 by 3.

It is very interesting that here there are liquid velocities instead of cash velocity and also this density of the liquid it is considered instead of gas velocity for gas solid fluidization velocity. So, in this case since it is liquid solids the density and viscosity of the liquid will be considered. So, if you see this graph here for flow regime map for liquid solid fluidization, you are just observing here that this profile this locus; this dotted line this locus is represented for minimum fluidization velocity in this liquid solid system, that minimum fluidization velocity is being calculated based on that the balance of the frictional pressure drop, which is being calculated by organ equation or by experimental data with the apparent weight of the liquid solid bed here.

So, this equation you can get, so this here may is a function of this dp star and this line this dotted line is represented for the terminal velocity or shifting velocity of the particle inside the bed in a liquid solid system. Now this below this below this terminal velocity you will get this conventional fluidization resigned and with this dp star. So, this is your conventional fluidization system for this liquid solid fluidization; whereas, beyond this terminal velocity there will be a certain velocity and beyond that velocity also you will get different type of flow regimes, sometimes up to this region will give you the circulating fluidization regime; you can beyond this critical velocity that is represented by ua. Beyond this critical velocity you can get the transport regime by which the solid particle should be transported upward, by this high liquid velocity beyond this ua.

Now, this important point is that here you can get different flow regime just simple from this map, by calculating what should be that? Now if you want to have certain flow regime condition now what should be the used are based on the fixed dp value. Suppose here 1 point is there, now question is that you have this dp star is fixed like what is that dp particle diameter and what is that liquid density and gravitational oscillation of (Refer Slide Time: 34:01) is fixed particle concentration is also fixed and the density of the particle is there certain and density of the liquid is there viscosity of the liquid, you know then you can calculate what should be the dp star.

Now, once you know this dp star as this like here, suppose this point what should be the d p star here some value and corresponding to this value u star it is almost 1000 you know sorry it is 10; then this ten from this ten that means, this u star will be is equal to 10 it u square is equal to 10, then from this what should be the u l just divide if this portion of this then u star divided by this; that means, 10 by this value then you will get a what should be the value of ul, then how to operate the fluidized bed with this liquid velocity; so that you can get this transport regime. Now suppose if you want to get the conventional fluidization regime here and with a certain liquid velocity, then what should be the particle diameter to be taken here, so that you can get the conventional fluidization regime.

Now, if you are liquid velocity is only 1; that means, here sorry u star is 1 then corresponding what should be the u star here and then u l if it is known to you then, what should be the particle diameter you can calculate from this value. So, from this flow regime you can get the idea what should be the particle size to be taken to get this particular fluidization regime or if you are particle size is fixed, then what should be the fluid velocity inside the bed to be maintained to get this particular fluidized regime. So, you can calculate from this fluidization map. Now of course you have to know what should be the transition of this different fluidization regimes at the bed, now minimum to conventional fluidization regime of course, you have to you have to maintain the liquid velocity in such a way that you are just going to change the minimum fluidization to it is convention of fluidization with this liquid solid system.

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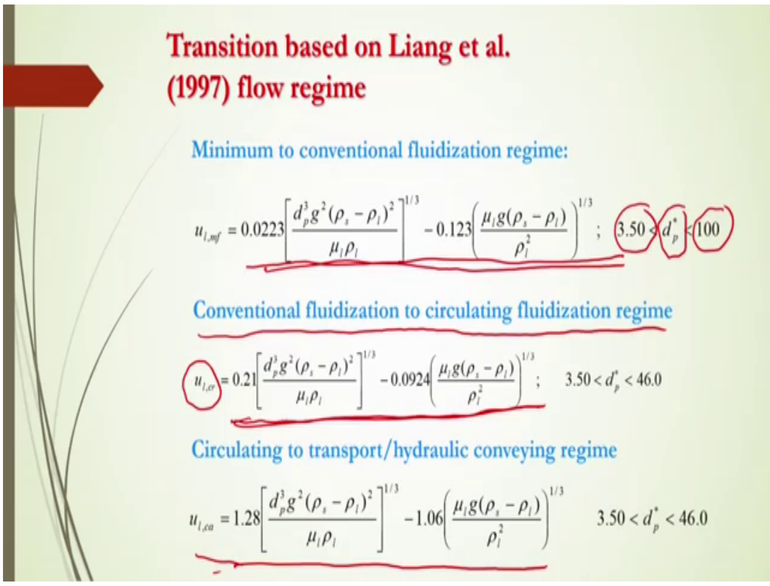

Now you have to calculate the u minimum velocity; that means, minimum velocity if your dp start within the range of 3.50 to 100, then what should be the minimum fluidization velocity.

Now, to get the conventional fluidization velocity you have to take the or you have to consider the velocity of the liquid just greater than this minimum fluidization velocity. So, from this correlation you can calculate or you can get the idea what should be the velocity for liquid for this convention of fluidization, another transition for conventional fluidization to circulating fluidization regime. Suppose if you want to work with circulating fluidization regime with this liquid solid system, then we have what should be the or you have an idea what should be the velocity of the liquid to be maintained inside the bed, so that I can get the circulating fluidization regime.

So, for that you have to calculate critical velocity or transition velocity by this correlation and this correlation will give you what should be the critical velocity for liquid; now you just to increase the velocity or you have to take the velocity of the liquid just beyond this critical velocity, so that you can get circulating fluidization regime and then how to get the transport fluidization regime or transport or hydraulic conveying regimes what this liquid solids slurry system in the fluidized bed. Here also 1 correlation is developed and it is given by Liang et al 1997, so that now you can get the hydraulic conveying regime just by this criteria. In this case also you have to calculate the velocity from this correlation like by knowing the viscosity of the liquid particle diameter even solid density and calculating by this equation, what should be the value if this value is if you are liquid velocity is greater than this value, then you can say your fluidization will be operating with the hydraulic conveying regime.

Now, coming to the point here the flow regime in the 3 phase fluidized base system, you will see the flow regime whatever regimes we got from liquid solid or gas solid system; the flow regime for 3 phase system of course, will be something different then this earlier 1. Now in this case 3 phase system you are gas liquid solid 3 phase will be interacting to each other and it will change the flow regime map and also flow regime transition because of that simultaneous interaction of the gas liquid solids inside the bed.

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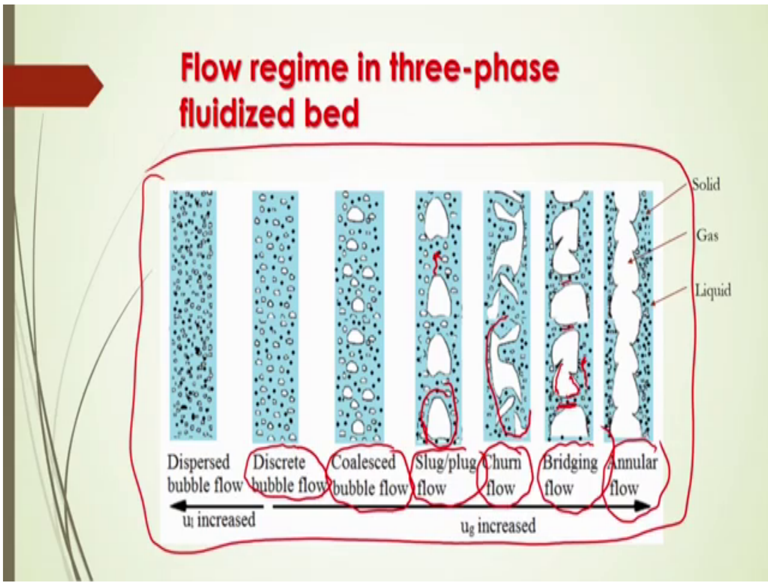

Now you see diagram here shown this regime map, in this case there are several flow regimes are shown here dispersed bubble flow, discrete bubble flow, coalesced bubble flow, slug plug flow regime, churn flow, bridging flow and annular flow. So, all this 1 2 3 4 5 6 7 flow regimes are generally observed in gas liquid solid fluidized bed just by changing the liquid velocity and gas velocity inside the bed.

Now if you if you keep the gas velocity constant and if you increase the or decrease the liquid velocity you will get this dispersed bubbly flow regimes here; that means, for low gas velocity and low liquid velocity there is possibility to get this dispersed bubble flow. In this case bubbles are dispersing in an uniform fashion and all the bubbles are almost uniform in size throughout the bed and gas should be dispersed, as a dispersed phase of these uniform bubbles with this solid particles also and then if you increase the liquid velocity for this low gas velocity you will get another dispersed bubble flow it is called discrete bubble flow; in this case the concentration of the bubbles will be lower than the earlier 1, so dispersed bubble flow.

In this case the coalescence of the bubbles maybe not possible, but they are separately moving up to the top of the column. So, all the bubbles indivisible bubbles will be moved up there will be no interaction, but they were very that is less interaction will be there, but there may be a chance of interaction of solid particles and cash particles and liquid particles, but bubble interaction will be little bit lower; whereas, in coalescence bubbles in this case interaction between bubbles and the solid particles will be higher. So, in this case whenever the interaction of the gas bubbles will be there may be a chance of coalescing of the bubble.

Coalescence means what 2 bubbles or 3 bubbles will come together and make it is bigger bubbles. So, they will come to each other and they will conjugate and to will become bigger 1. So, in this case the formation of the bubbles will be totally a non uniform; that means, here some bubbles will be more bigger some bubbles will be more finer and there will be a continuous actually coalescence of the bubbles will be there, those bubbles will be coalescence they will go very fast due to their buoyancy effect and those are not coalescence they are moving slowly to the up and whereas, the solid particle sometimes will take part to the interaction that may be hinder the coalescence part. Sometimes the in between 2 bubbles if there is a solid particles then coalescence may not be possible.

So, they may clock to the solid particles and go off, but whereas if there is no particles in between 2 bubbles there immediately coalescing and go up. So, this type of phenomena is called coalescence bubble flow. Whereas, if you increase little bit this gas velocity by keeping this liquid velocity at fixed, then you can get this another type of flow regime it is called slug or flag flow; in this case you will see big bubbles will move just as the send was to the top and send was to the top along with some smaller bubbles and with the solid particles. So, in this case the bubbles will be non uniform in shape not will be spherical, it may sometimes form this bullet shape bubbles. So, this type of is called slug flow.

But this let us say if sometimes if this bullet is just the bullet cross section, the lower part of the bullet cross section will be occupying total cross section of the or almost equal the cross section of the bed, when you will see it will the flat slug and also flat slag with the bullet nose, so this type of bubbles will be moving up as per this so here this is called this slug flow. Whereas, if bubbles are bigger but it will be not exactly the cross sectional area or the diameter it is diameter is not the same as diameter of the bed and but it is ledger and it is the shape is like that 1 slug then it maybe it is called as the plug flow. Whereas, if you are increased more velocity then what will happen you will get the churning phenomena inside the bed that is called churn flow.

In this case the bubbles should not give you the special form of round shape or what it is but may be it will be elongated and this gas will be spreading inside the bed like this shown in a figure like this here. So, this is called churn flow in this case high turbulence will be there more interactional be there, here the continuous coalescence and break up will be there inside the bed. So, this is called churn turbulent flow and bridging flow in this case you will see bubbles are moving upward, but they are some formation of the breeze type breeze like bubbles and that is why it is called this breezing flow here; in between 2 bubbles there will be a u density of the solid particles will be more higher inside the bed.

Whereas this annular flow if you increase the gas velocity again, at a certain liquid velocity you will get the annular flow in this case to the centre of the bed, you will see gas will be flowing continuously without breaking of that surface; that means, here continuous gas flow will be there, but surface between solid and liquid or surface between gas and liquid will be in such a way that there will be no uniform surface formation, there will be a some zig zag surface formation inside the bed, so it is called annular. That means, a central core region of the bed the gas should be moving up whereas, in adjacent to the wall the liquid solid slurry will be flowing. So, this type of phenomena is called annular flow.

So, in 3 phase fluidized system we can give this7 type off low regime inside the bed, the based on the gas velocity and liquid velocity changing. Now let us discussed the behavior of this different flow regime; now what is that now discrete bubble flow what is that this discrete bubble flow pattern actually predominates at low gas and liquid velocities.

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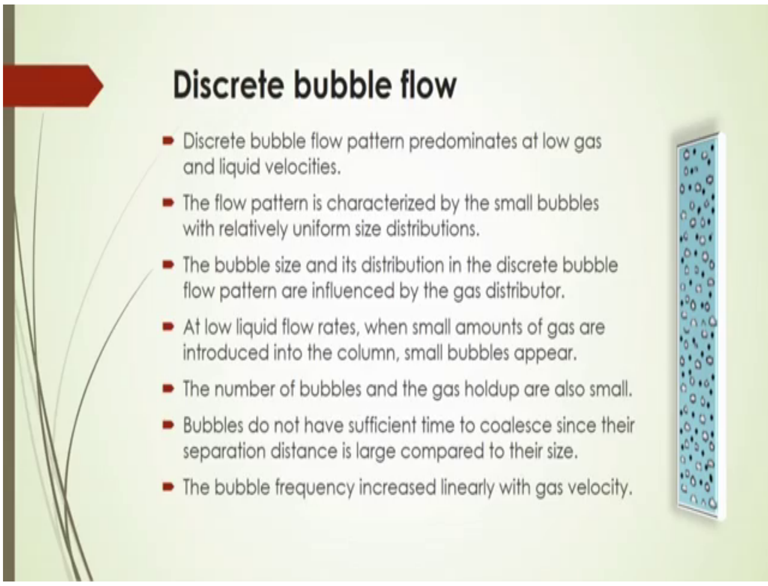

The flow pattern is characterized by the small bubbles with relatively uniform size distributions, the bubble size and it is distribution in the discrete bubble flow pattern are influenced by the gas distributor.

At low flow velocity when small amount of gas are introduced into the column or bed will see small bubbles appear and the number of bubbles and the gas hold up of course, are also a very small and bubbles do not have sufficient time to coalescence; since they are a separation distance is large in this case and of course this distance will be larger compared to the size of the bubble. The bubble frequency increased if you gas velocity increased, of course this will be linearly proportional and the bubble of course that is why it is called bubble frequency in (Refer Time: 48:50) linearly with the gas velocity here. Now in case of dispersed bubble flow, the dispersed bubble flow pattern is encountered at higher liquid velocities; the bubble flow pattern is characterized by the small bubbles with more uniform in size distribution then discrete bubble flow pattern.

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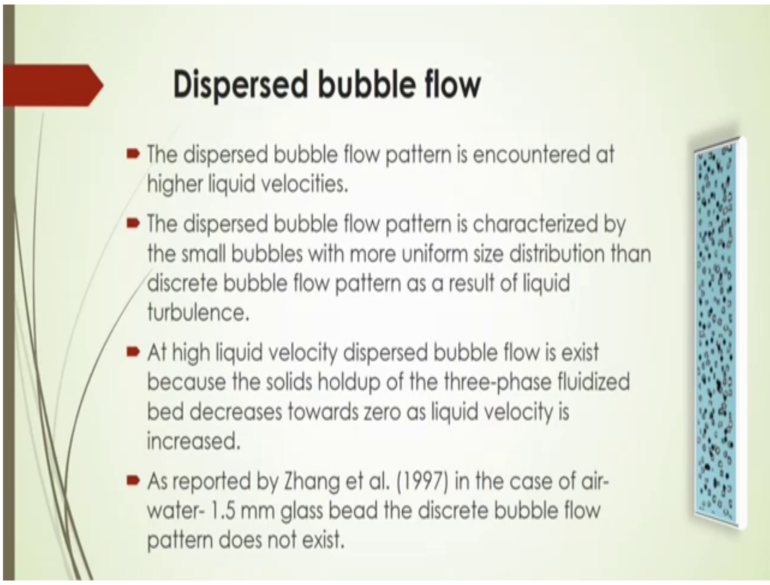

As a result you will see the liquid turbulence will be little bit higher than the earlier 1, at high liquid velocity dispersed bubble flow is exist because, the solid sold up of this 3 phase fluidized bed decreases towards 0 as liquid velocity is increased. As reported by Zhang et al 1997, they observed that in case of air water and the particles with 1.5 millimeter glass beads, the discrete bubble flow pattern may not be exist there.

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Coalescences bubble flow in this case and in this case this flow pattern is restricted to very narrow gas velocity range, so depending on the bed diameter.

Now, larger bubbles of wider size distribution are encountered with increasing gas velocity, as there population increase the distance between individual bubble decreases and small bubbles sometimes travel with lower buoyancy and in this case the overall behavior of the multiphase mixer is represented as a coalescence bubble flow, just by coalescing of the smaller bubbles to make it larger bubbles and bubble coalescence is more intensive in air water system containing glass beads less than 2.5 millimeter in diameter.

Then the corresponding gas liquid system since the particles increases both the emulsion phase viscosity and the density. Here important that see why coalesced bubble flow observe that, here viscosity physical properties of the fluid is very important. In this case if you increase both the viscosity and density of the slurry inside the bed, you can have the different phenomena of the bubble coalescence; the tendency or you can say that intensity of the coalescence of the bubble inside the bed will be higher.

The pattern of course, the gas passes through the liquid solid mixture has bubbles of irregular shape and larger in size and this differs from the 1.5 millimeter glass bit system where bubbles are spherical or spherical caps in the coalesced bubbles flow pattern. So, this flow patterns depends on the shape of the bubbles also, this coalescence behavior that depends on the shape of the bubbles. In this case you will see the coalescences phenomena will be more easier for spherical compared to the non spherical bubbles; sometimes caps type bubbles will give you the which is your coalescence compare to the other type of other shape of bubbles of course,. So, this coalescence behavior depends on particle diameter also, for more finer particles the coalescence behavior will be higher than the course are particles.

Slag flow as the gas velocity is increased further when bubbles become larger and more Elongated and some bubbles cross sectional dimensions approach the diameter of the column, so this phenomena.

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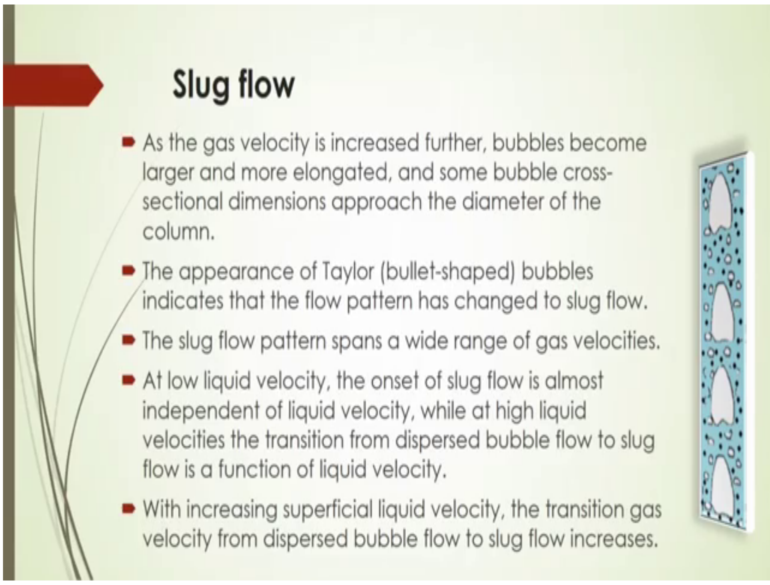

So, that is why slug will form the appearance of Taylor bubbles; that means, bullet shape bubbles indicates that the flow pattern has changed to or slug flow; the slug flow pattern spans a wide range of gas velocity here, at low liquid velocity the onset of slug flow is almost independent of liquid velocity, while at high liquid velocity the transition from dispersed bubble flow to the slug flow is a function of the liquid velocity. When if you increase the superficial liquid velocity inside the bed, the transition gas velocity from this dispersed phase to the slug flow that will increase and churn flow.

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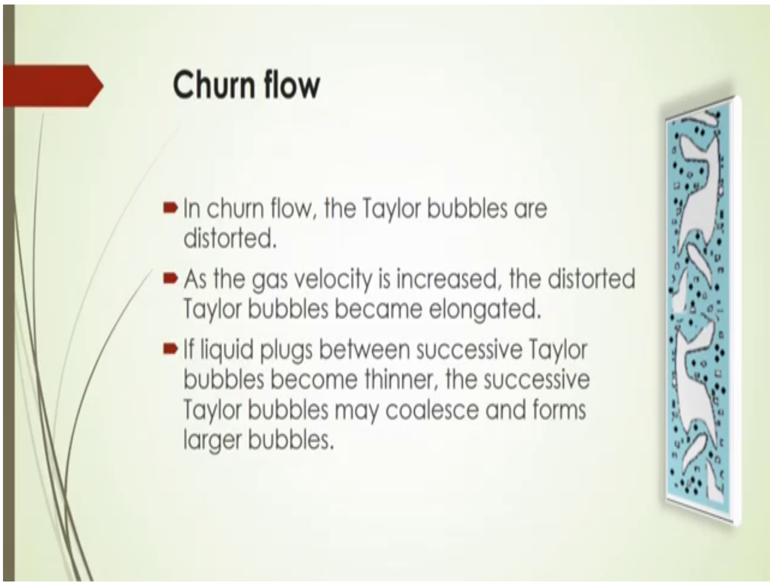

In churn flow the tailor bubbles are distorted and as the gas velocity again is increased the distorted Taylor bubbles become elongated and if liquids flux between successive Taylor bubbles become thinner, than you will get the successive Taylor bubbles coalescence and forms larger bubbles and you will get the churning condition inside the bed.

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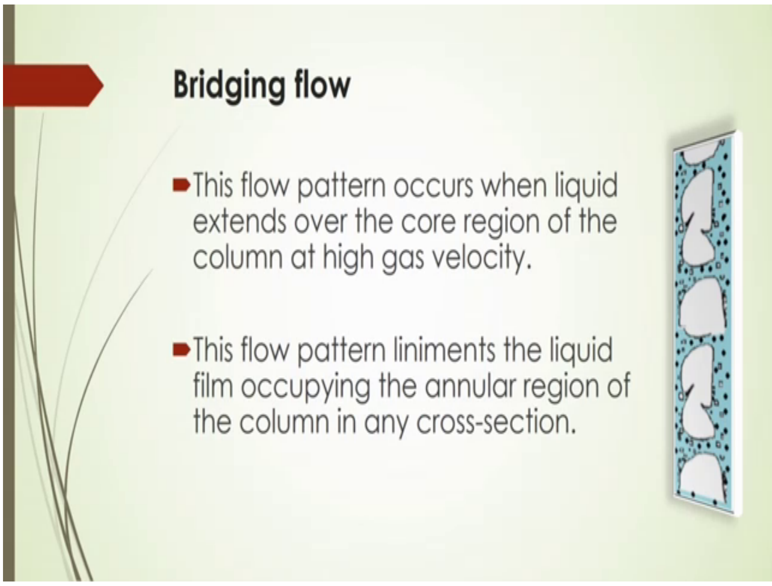

Whereas bridging flow in this case you will see a liquid extends over the co regions of the column at high gas velocity and this flow pattern of course, the intimae liniments the liquid film occupying the annular region of the column in any cross section.

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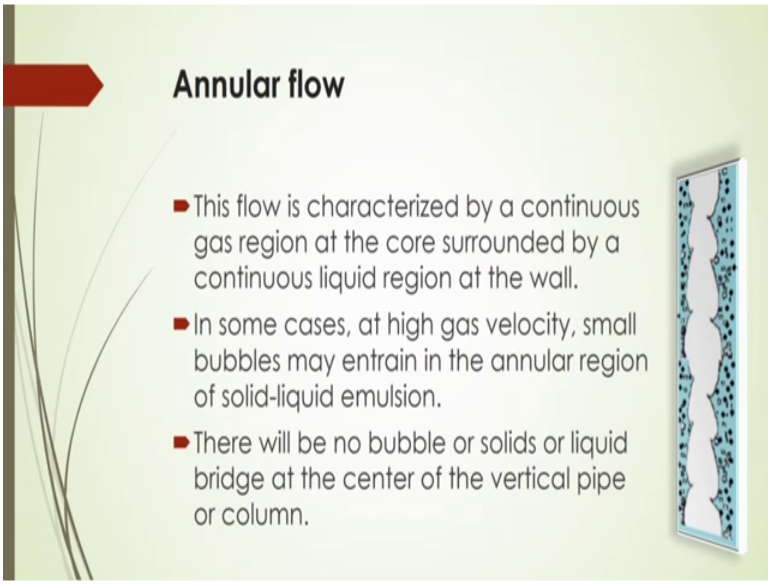

In case of annular flow we will see continuous gas region at the course, surrounded by the continuous liquid region at the wall will happen and in some cases at high gas velocity small bubbles may in train in the annular region of solid liquid emulsion; there will be no bubble or solids or liquid bridge at the centre of the vertical pipe or column or bed in 3 phase system.

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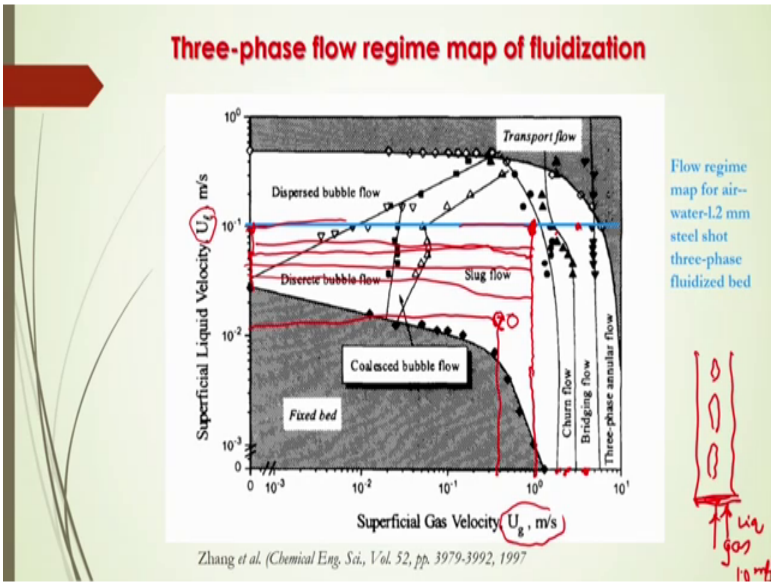

Now, here another 1 example of flow regime map of fluidization for this 3 phase instance are given, here see this flow regime is represented by the superficial gas velocity and the liquid velocity; the superficial velocity gas velocity in the x axis and superficial liquid velocity in the y axis. Now if you change these gas and liquid velocity you will observe different flow regime in this 3 phase fluidized bed and this fluidization map flow regime map is actually made by Zhang et al 1997 with air, water and steel shot of diameter 1.2 millimeter.

Now this flow regime map it will represent of these it is actually tell you, what it will tell you that what should be the dispersed bubble flow for a certain gas velocity and when you can expect or when you cannot expect and what should be the transition from 1 flow regime to the another flow regime.

Now, suppose if you want to run any fluidized bed, which is a air water or air water and this steel shot of diameter 1.2 millimeter in you lavatory; now you want to actually run this fluidized bed with as slug flow then, what should be the gas velocity what should be the liquid velocity that you can actually obtained from this flow regime map. How let us consider this gas velocity you have 1 column fluidized bed column in this case, 1 distributor will be there through which gas will be distributed and this is gas and again liquid also to be supplied from the bottom here; now you want to actually get the phenomenon of slug flow inside the bed.

Now, coming to this flow regime map here past, consider any location here for this slug flow let it be here it gas velocity is equal to 1; if gas velocity is equal to 1 if your maintaining the gas velocity is 1.0 meter per second. Now if you are fixing the point here yet this gas velocity, then what should be the liquid velocity to be maintained or to be supplied in the bed at which liquid velocity you can get this slugging condition let it be here; if you are maintaining the liquid velocity inside the bed as 10 to the power minus 1; that means, 0.1 meter per second then you can have this slugging behavior inside the slugging bed.

Even fixing this gas velocity, if you decrease the gas velocity may be here; in this case then again you can get the slugging behavior. So, by fixing the gas velocity if you change the gas velocity below these point or above these point of 0.01, you can get different combination of the gas liquid velocity to get this slugging condition, because you are here in this location of slug flow; you can get at this point also the slug flow. Here what should be the gas velocity and what should be the liquid velocity here. So, from this condition you can get what should be the liquid and gas velocity, so that you can get the slugging condition.

Now you want to get the breezing flow, what to do now you have to maintain the gas velocity here at this point here, suppose here this is 1 2 3 4 this is your suppose 4. So, 4 meter per second if you are just maintaining the gas velocity as 4 meter per second, then what should be the liquid velocity to get this breezing flow here; suppose this is the point. So, if you are maintain this 0.1 liquid velocity and 4 meter per second gas velocity then you can get the breezing flow. So, this is the nice way to identify which flow regime you can you can expect for your for your operation.

Now you can control you can change the different flow regimes or suppose if you want to apply the fluidization operation for a particular application, where this flow regime is more suitable.

Suppose in this case the churn turbulent flow for highly mixing condition to get this supposes reaction any reaction. So, you have to maintain this gas velocity as 2 meter per second by changing the liquid velocity, like this here from 0 to up to this here also. So, different way different combination of the liquid and gas velocity; if you are changing you can get the different flow regime map.

So, this is the map by which you can just obtained what flow regime you can expect from your bed. Now what are the different transition of course, this transition to get the dispersed bubble to calls this bubble. So, this correlation will be helpful to calculate the transition or you can say the boundary at which gas or liquid velocity to be maintained and coalescence to slug flow of course, the liquid velocity should be less than this correlation whatever it is.

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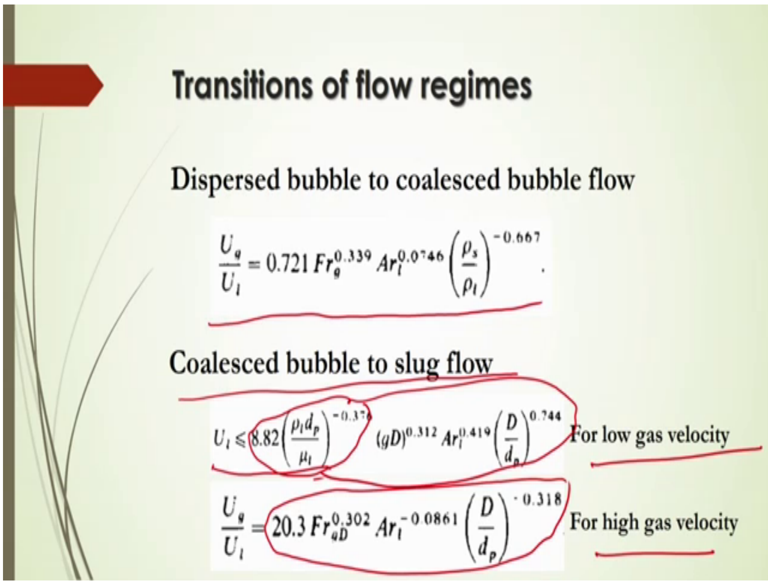

So, for low gas velocity for high gas velocity this correlation will be helpful to get this minimum velocity to have this slug flow come coalescence flow.

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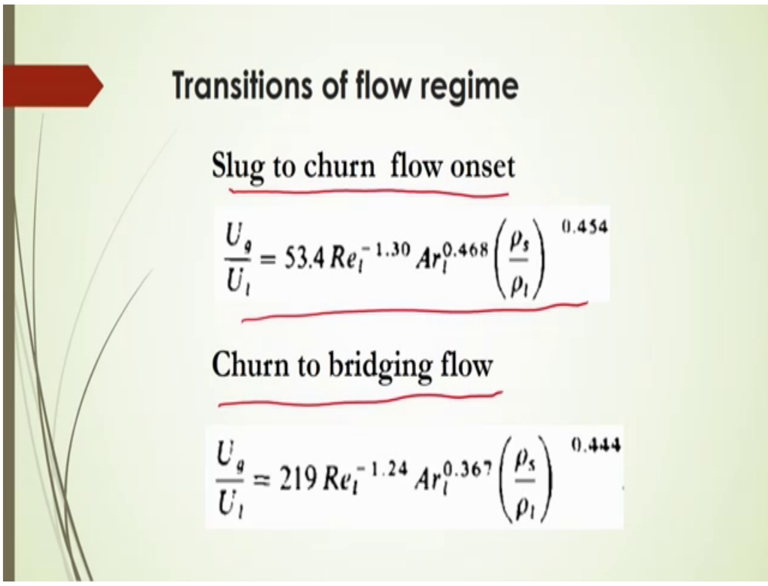

Similarly, for other transition of flow regimes have slug to churn turbulent flow and churn to bridging flow, you can calculate the minimum gas velocity for which you can get the transition of the different flow.

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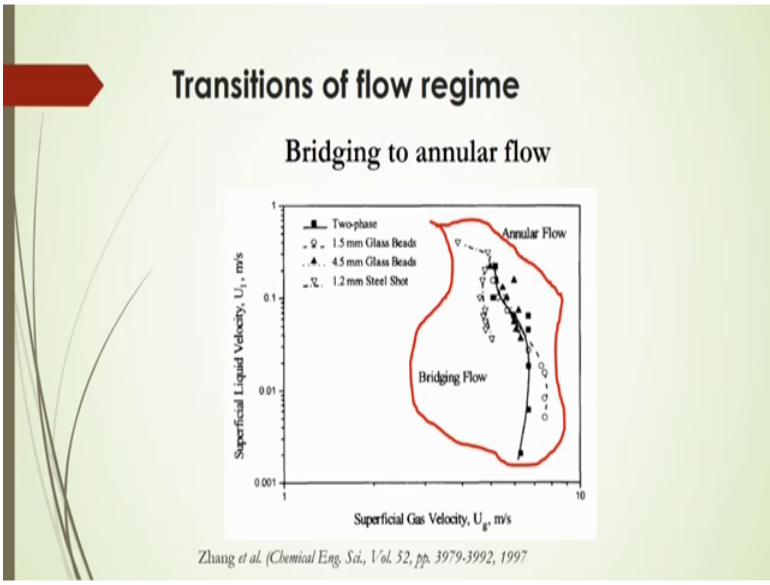

Regimes now transition of flow regime bridging to annular, also this is one diagram from which you can calculate to get this bridging to annular flow what should be the liquid velocity or gas velocity to be maintained. So, next class on what will be discussing another topics like pressure drop and other things. So, this is the flow regime map and flow regime different flow regimes you can expect for liquid solid and gas liquid solid system. So, that is for all today thank you next lecture will be continuing with other topics.

Thank you.