**Fluidization Engineering**
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Lecture – 06
Flow regime and its map: Gas-solid Fluidization

Welcome to massive open online course on fluidization engineering, today the lecture will be on flow regimes and its map especially on gas solid fluidization.
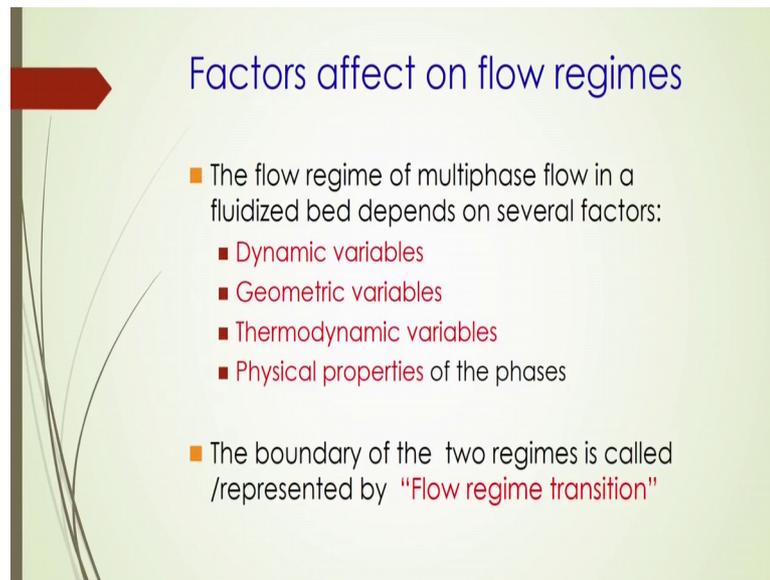
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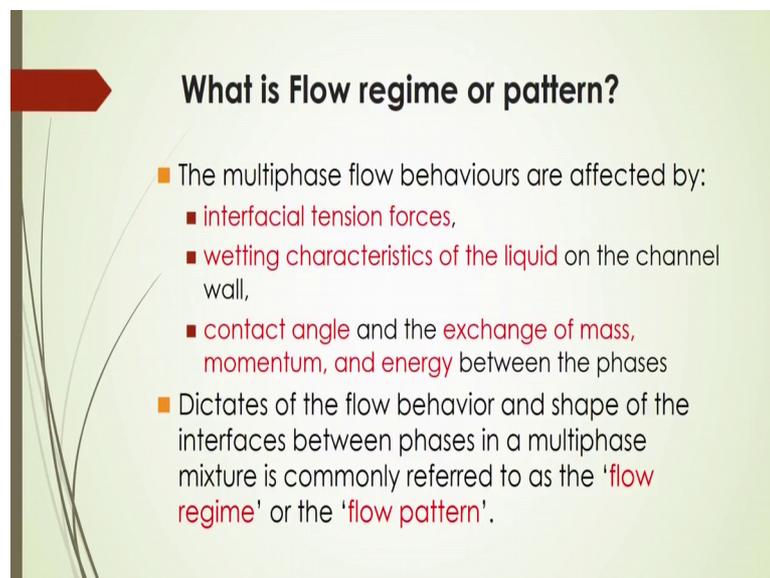
So, what is flow regime or pattern, basically the multiphase flow behaviors that are affected by interfacial tension waiting characteristics of the fluid on the channel wall or you can see bed wall, and also contact angle and the exchange of mass momentum and energy between the phases. And this flow regime dictates 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 sometime this is called flow pattern.

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What are the factors that effect on this flow regime? The flow regime of multi phase flow in a fluidized bed, that depends on several factors like dynamic variables what are the dynamic variables like what are the flow rates in the fluidized bed flow rates of gas and liquid, even if any other suppose phase like solid if it is continually flowing in into the bed then the solid velocity also will be a one dynamic variables here. And geometric variables of course, what should be the size of the bed, that is what is the diameter of the bed what is the cross sectional area of the fluidized bed, and what is the particle diameter, what is the four diameter of the distributor to which the fluid is distributed into the fluidized bed.

And thermodynamic variables like what is the pressure inside the bed, how it can be changed and or if I change the pressure inside the bed then what should be characteristics of the fluidized bed, and what should be the different hydro dynamic and transport processes inside the bed that depends on the pressure and another thermodynamic variable it is called temperature of course, temperature is the main effect here sometime since the drying operation in the fluidized bed you have to maintain certain temperature and also this is increase the temperature or decrease the temperature, how this fluidization characteristics will change that depends on the temperature variation.

And the other different transport processes like mass transfer heat transfer the, depends on the variation of the temperature that is controlled in the fluidized bed. So,

thermodynamic variables like pressure in temperature are the main important factors here. Physical property is of course, any fluidized bed whether it is gas solid or gas liquids and solid multiphase fluidized system of course, the physical properties like density surface tension and viscosity of the fluid medium, it will be effect the fluidization characteristics like flow regimes. Suppose you if you change the properties of the fluid and also other dynamic geometric and thermodynamic variables, then you will of course, have the different type of flow regimes inside the bed.

The boundary of the two regimes is sometimes referred as the flow regime transition of course, one regime to another regime you will get to make the to make change of one flow regime to another flow regime, the what should be the barrier, what should be the point from which you can get the another flow regime that point is called transition point or the certain reason certain that is profile from that profile onward are beyond that point you will get the different type of flow characteristics.

So, the transition point that is called flow regime transition, that also very important in this case you have to know in which flow regimes actually this fluidization operation is being carried out. And different flow regimes you will get the different behavior applications different, hydrodynamic characteristics different, mass transfer characteristics inside the bed.

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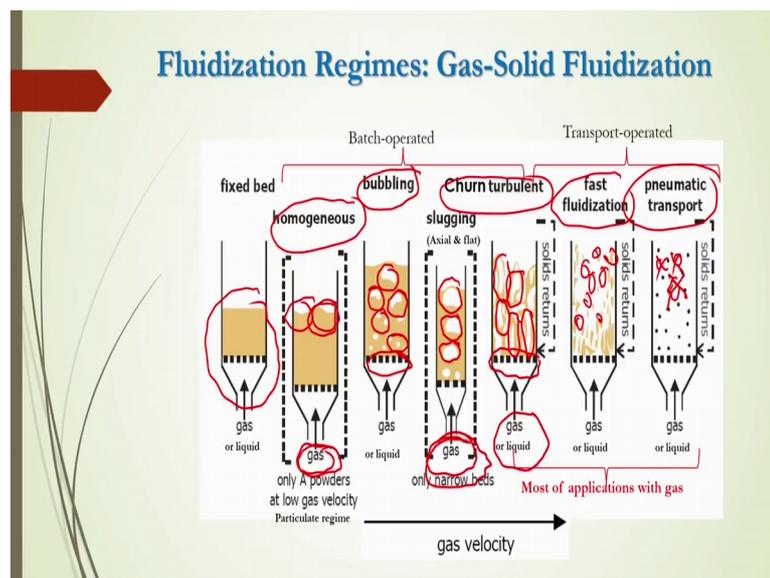
Now, see the diagram here in this bed there are different types of flow regimes or flow patternin gas solid fluidization system. Here initially you will see this is called fixed bed; that means, here the solid particles are not being suspended at this gas velocity.

So, here it is fixed bed operation. So, we cannot say this is the fluidized our condition. So, this is the before that fluidization operation; after a certain change of gas velocity beyond this fixed rate operation you will see, there will be a change of characteristics of the fluid bed inside the fluidized bed, like if you increase certain minimum gas velocity then you will see this type of particulate or you can say homogeny homogenous fluidization operation. Here you will see there will be a significant change of the level of the bed here there will be some tilting or you will see that where we shape of the a bed; that means, here beyond a certain minimum velocity of this fixed bed operation, you will see certain this fluid are going to the suspended here inside the bed. So, this is here one operation this is called particulate regimes.

So, whole this fluidization gas liquid gas solid fluidization system, you can divided into two parts here batch operated and transport operateds flow regimes. Now batch operated flow regimes here you will see some flow regimes like homogenous or particulate you can say, sometimes bubbling bed and also churn turbulent fluidized bed. And under this gas operated system you will see gas operated fluidized bed this bubbling fluidized bed, slugging fluidized bed and also the churn turbulent fluidized bed we will have different characteristics and different hydro dynamic characteristics. And also transport operator here see first fluidization and pneumatic transport. There are two types of fluidization flow regimes and all this flow regimes will be changing if you just changed the gas velocity inside the bed, but you cannot say that all this flow regimes will be changing only based on the gas velocity no.

If you fixed some gas velocity and if you change the other variables like a geometric variables, if you like our that particle diameter, if you change the what is that physical properties of the system, if you see different gas with higher density gas has been you will get different type of flow regimes also. So, let us see at a certain gas velocity here particulate bed, the characteristics of the particulate bed here the just particles are tries to you are trying to suspended inside the bed, and there will you know bubble formation here. Whereas, in this case if you increase certain amount of gas velocity, you will see

there will be a formation of certain gas and there will be a certain shape of the bubble here.

So, here gas will be distributed through a distributor and from the distributor there will be a formation of bubble inside the bed. So, this is this type of phenomena is called bubbling fluidized bed; and when if you increase little bit the gas velocity this bubbling fluidized bed will behave and will form a bubble in such way that the bigger bubbles will form and those bubbles are going up through the centre of the bubbles, as a large the bubbles. And this large bubble sometimes it will be almost equal to the cross sectional area of the bed that is diameter of this bed will be equals to the diameter of the bed. So, if it is diameter then of course, you will see slug you will form even sometimes we will see if it is not the same the diameter with the fluidized bed, then you can get the plug flow type fluidized bed here.

So, there will be plug and slug. So, this is under the bubbling fluidized bed fluidizing condition. Even if you increase the fluid velocity or you can say the gas velocity, there will be a see the churn turbulent condition will from here, the bubbles will be forming or you can say (Refer Time: 10:00) will be there, but that (Refer Time: 10:01) will not be exactly the bubble shape and it will be sometimes longitudinal long bubble here long bubble and remain in between this two bubbles there will be a channel of the solid particles or channel of the gas along with the solid particle, in such a way that there will be a churning phenomena inside the bed. So, this is called churn turbulent fluidized bed and slugging fluidized bed you will see you will obtain very narrow tubes narrow beds in that case slugging condition you can get.

Whereas the churn turbulent flow you cannot get in the narrow tubes, in that case you have to have the diameter of the column at least five centimeters, otherwise it will be very difficult to get this churn turbulent. Because this churn turbulent will actually follow there will be a internal circulation of the cell internal circulation of the fluid particles and solid inside the bed and there will be churning condition formation. So, this is this gas operated whereas, in transport operated cases if you increase further this gas velocity you will see, there will be very dilute solute that is concentration of the solid that distribute inside the bed in such way that maximum portion will be the gap or you can say the void inside the bed. So, here, but smaller particles also will be moving up small amount of particles will be moving up.

But this will be first fluidization and particles will try to moved up as early as possible along with the gas. And in this case of course, the fluidization condition will be far more than this minimum that is the settling velocity of this particles or you can say terminal velocity of the particles and pneumatic transport here very dilute phase of solid particles all the solid particles will try to go up and it will be coming out from the top and it will be again re used even for first fluidization also you can use or reuse this solid particles here.

So, in pneumatic transport there be no bubble formation specifically shape of bubble formation will not be there, and there will be very dilute concentrated of solid particles and it will be flowing up many a case. So, in this case at least 20 times larger than the terminal velocity of the fluidization bed inside the bed should be there. So, here you can get that from the fixed bed we can get different fluidization or different fluidized regimes like homogenous bubbling, churn turbulent first fluidization pneumatic transport.

Now, to get the minimum fluidization of course, you have to maintain; you have to maintain certain a gas velocity that is called incipient condition, and that incipient it is called incipient fluidized bed or minimum fluidization condition. So, of course, to get the fluidization that minimum fluidization velocity should be required for you will be discussing that how to calculate the minimum fluidization condition later and also. So, in this case we are then we are getting the different fluidization, different fluidized fluidization regimes, based on this solid and gaseous system. And you can get other different types of flow regimes ,if you if you the fluidized bed is operated with the liquid and solid and also gas and liquid and solid.

So, will be discussing subsequent in lecture that what are the different types of flow regimes will be there in the fluidized bed.
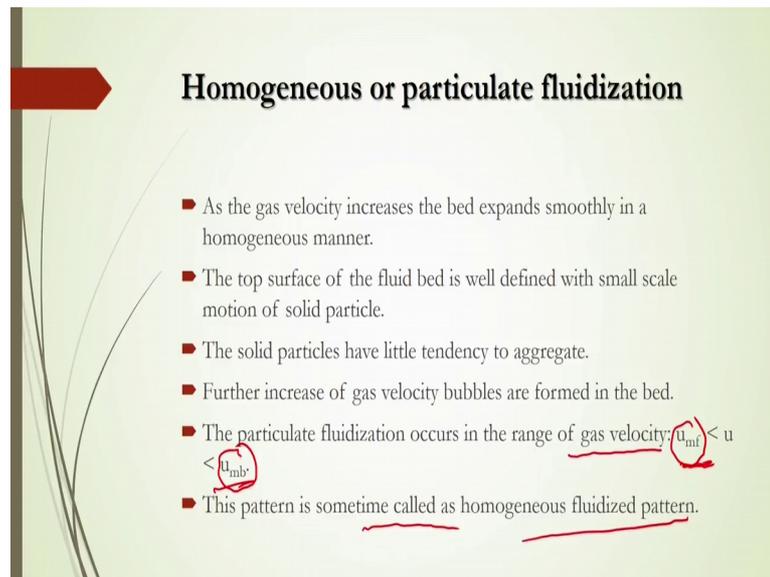
Now, let us consider let us discuss, what should be the wherein characteristics of the different flow regimes in the fluidized bed. Now homogenous or particulate fluidization this is as the gas velocity increases the bed expands smoothly in a homogenous manner. So, in this case you will see there will be a gap between two particles; there is small gap between two particles through which the gas will be flowing upward without making any bubble inside the bed or either making churning condition without making any dilute phase, without making any other slug condition you will get the simply homogenous flow inside the bed.

So, this will be happening in a condition which is called homogenous fluidized bed. The top surface of the fluid bed is well defined with small scale motion of the solid particles here of course, the this minimum fluidization condition you will see the top surface of the fluid bed will be well defined and it will behave like a liquid here if in this case the surface of the bed of course, will be tilting or it can it may change according to the operation. And then also it will be well defined and there will be a little bit motion of the solid particles at this homogenous fluidization regime the solid particles have little tendency to aggregate also in this case there will be no actually formation of agglomerate inside the bed, and in throughout the cross section we will see there will be a uniform distribution of the gas through the space between. The solid particle that is called voids in the bed.

And further increase of gas velocity bubbles are formed; in this case in this particulate fluidized bed with the same particle, you will see if you just changed the gas velocity little bit higher and you will get this. So, there will be a change there will be a change of phenomena from this particulate to the bubbling phenomena. Inside the bed there will be a formation of small amount of bubble small bubbles and it will be going upward at the certain velocity. And the particulate fluidization occurs in the range of gas velocity that will be of course, that will be higher than the minimum fluidization velocity, but it should be less than the fluidization condition of the bubbling fluidized bed.

So, here UMA we are denoted this minimum fluidization velocity and UMB is the minimum fluidization velocity for bubbling condition. So, in this case you will see this particulate bed fluidized regimes can be defined only when the fluidized bed is operated within this minimum fluidization form to this bubbling fluidization condition, and this pattern is sometime called as homogenous fluidized pattern. So, this is the characteristics of the homogenous or particulate fluidization.

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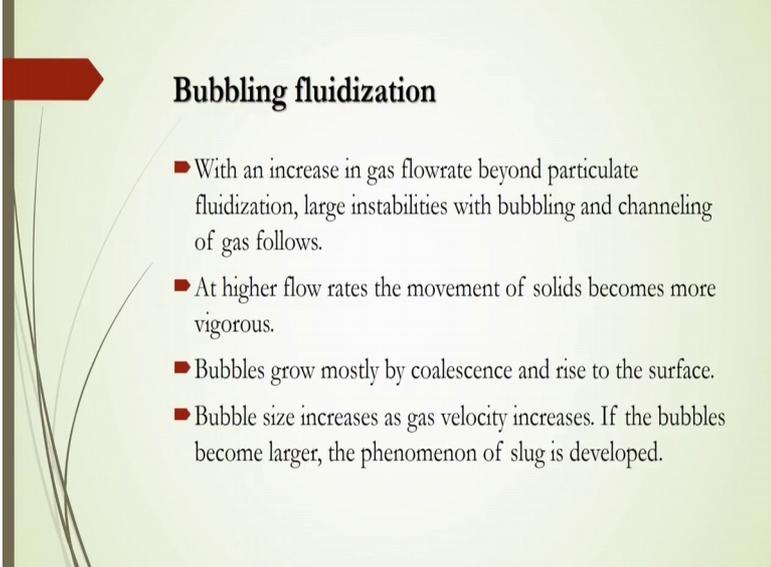
Bubbling fluidization

- With an increase in gas flowrate beyond particulate fluidization, large instabilities with bubbling and channeling of gas follows.
- At higher flow rates the movement of solids becomes more vigorous.
- Bubbles grow mostly by coalescence and rise to the surface.
- Bubble size increases as gas velocity increases. If the bubbles become larger, the phenomenon of slug is developed.

Whereas bubbling fluidization of course, you have to increase the gas flow rate beyond this particulate fluidized bed so, that you can have large instabilities or some instabilities in such way that there will be a formation of bubbles and channeling of the gas that will follows inside the bed. And higher flow rates of course, the movement of the solids becomes more vigorous in that bubbling condition, and in this bubbling fluidization

condition whenever bubbles will moving bubbles will move up, they are of course, the bubbles will carry some solid particles from its behind by making way. So, and also from the top there will be just; there the bubbles will move a side that the solid particles from its top portion and whenever bubbles will move up at the surface it will be collapse and solid particles will be a throwing out at the surface.

So, this type of phenomena will happen inside the bubbling fluidized bed. So, there will be a some bubbles will form and those bubbles will be forming from the distributor region the bubbles will be very smaller and whenever it will come to the top we will see the bubbles, will coalescence to each other and it will make big bubbles and after coalescence and then it will go up very fastening. So, initially bubbles will move slowly because its size is very small near about the distributor, in it depends on the whole diameter of the distributor, and the size of the bubble depends on the whole diameter of the distributor and because of which you will get the bubble size very small.

But whenever it will move up due to the coalescence of two or three bubbles at a time, there will be a formation of big bubbles and it will go up very fastly because of their buoyancy effect. So, bubble size increases as gas velocity increases of course, you will get the different sizes bubbles as a function of gas velocity. If the bubbles become larger the phenomena of slug is also developed. So, of course, if you are making high gas velocity, then you will see the two bubbles will come to each other and making a big bubbles and if this bubbles are almost equals to the diameter of the bed, then it will make one slug. Even flag also it will be there because the sometimes two bubbles whenever it will be coalescence making a big bubble, it may be approximately 85 percent of the cross diameter of the bubble then it will go up.

But it will be very large and as a slug; that means, as a plug it will be moving up. So, it will be plug flow; and slugging the gas bubbles or void coalescence and grow as they rise.

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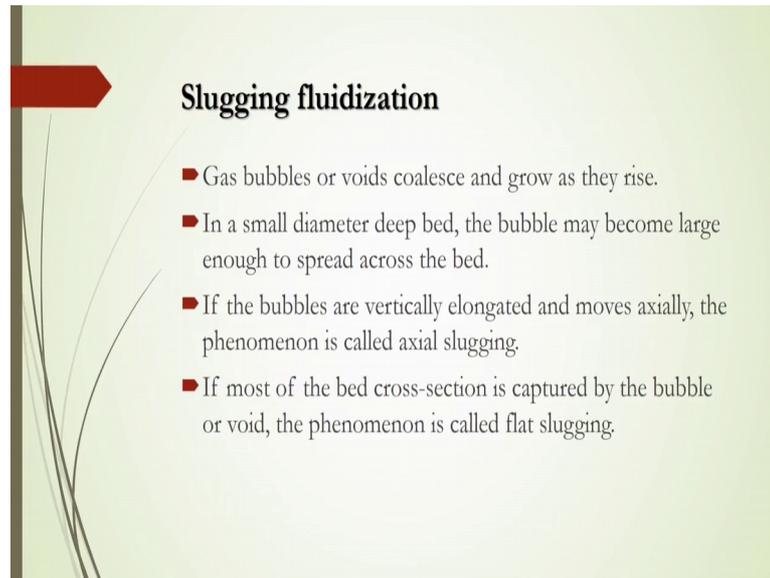
So, in that case it will be forming a slugging fluidization. In a small diameter did bed you will see the bubbles may become large then up to spread across the bed. So, in that case we will see the slugging tendency will be there in the bed. And if the bubbles are actually vertically elongated and move axially and move axially the phenomena some time it is called axial slagging. So, there are two types of slugging will be there flat and axial slugging.

So, if most of the bed cross section is a captured by the bubble or void the phenomena is called plug slugging and so, that is why there if axial slugging means there of course, the bubbles are vertically elongated whereas, the plug slugging the bubbles will be horizontally elongated, and it will occupy most of the cross section of the bed.

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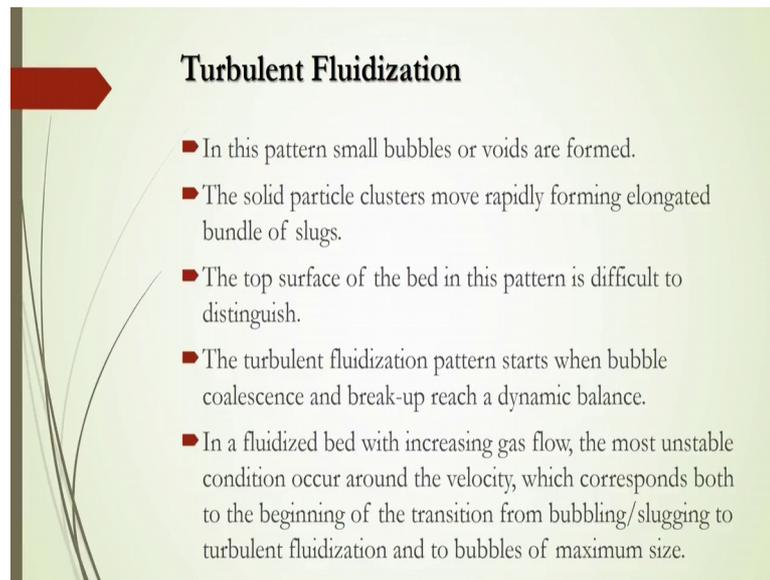
Turbulent Fluidization

- In this pattern small bubbles or voids are formed.
- The solid particle clusters move rapidly forming elongated bundle of slugs.
- The top surface of the bed in this pattern is difficult to distinguish.
- The turbulent fluidization pattern starts when bubble coalescence and break-up reach a dynamic balance.
- In a fluidized bed with increasing gas flow, the most unstable condition occur around the velocity, which corresponds both to the beginning of the transition from bubbling/slugging to turbulent fluidization and to bubbles of maximum size.

Whereas turbulent fluidization in this case small bubbles or void or form. So, the solid particles of course, clusters and it will move rapidly by forming elongated or you can say that form elongated bundle of slugs.

So, the in this case you will see the some clusters of particles will be forming, and that clusters will move upward and sometimes this clusters whenever it will be collapsing or it will be just reaching to or to the bottom of another slug, it maybe elongated and bundle of slugs will form. And the top surface of the bed in this flow pattern of course, it is very difficult to distinguish, because you will see there will be the unstable condition of this turbulent fluidization, and at the same time solid and the gas both will be flowing in such a way that the particle and gas that is particle fluid interactional will be more higher, and because of fluids that you will not get the particular shape of the surface inside the bed and it will be very unstable in this case. The turbulent fluidization pattern it will starts when bubble coalescence and the break up reach dynamic balance.

Of course there will be a simultaneous happening of coalescence and breakup of the bubble inside the bed, but you thing this turbulent fluidization. So, for smooth bubbling condition smooth coalescence, but breakup will be less whereas, in the turbulent condition because there are what is that intermixing and also the internal circulation of the fluid that will sometimes this stuff the uniform movement of the bubbles, and it may

break the bubbles and also bubble bubble interaction will grow up, and also coalescence also because of that it will be there.

So, simultaneous operation simultaneous actually process of coalescence and break up will be there inside this turbulent fluidization. And in a fluidized bed with increase in gas flow in this case most unstable condition will occur and of course, the this correspondence both the beginning of the transition of bubbling and slugging to turbulent fluidization and to bubbles of maximum size here.

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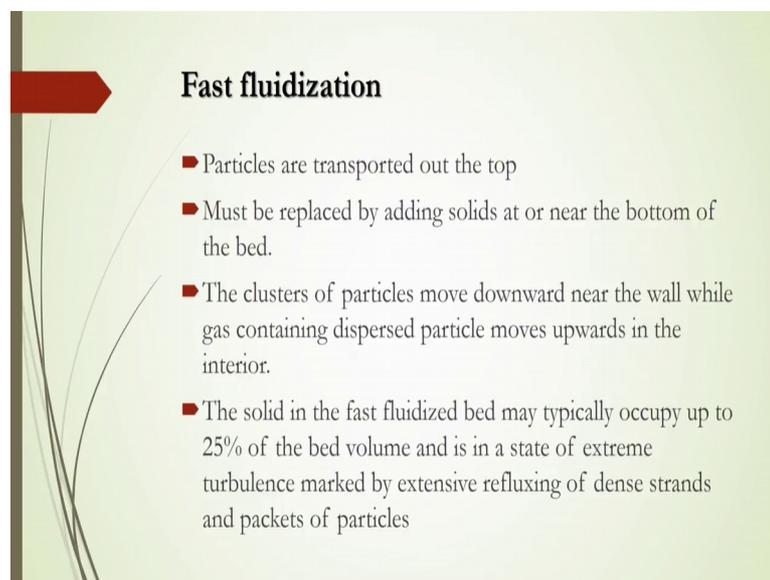
Fast fluidization

- Particles are transported out the top
- Must be replaced by adding solids at or near the bottom of the bed.
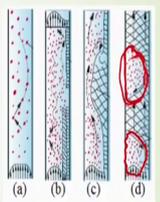- The clusters of particles move downward near the wall while gas containing dispersed particle moves upwards in the interior.
- The solid in the fast fluidized bed may typically occupy up to 25% of the bed volume and is in a state of extreme turbulence marked by extensive refluxing of dense strands and packets of particles

And first fluidization in this case particles are transported out the top of course, the gas velocity will be so high, at least 20 times of the terminal velocity of the particles there. So, if 20 times of the terminal velocity of the gas, you will see particles will not be coming back to its original position and it will move up and it will be transported out the top and that transported out solid of course, it will be separated from the gas mixture by some what is that (Refer Time: 25:33) and after that it will be again used for this fluidization.

So, in this case particles are transported by the gas here, back mixing of the solid particles will be less because high kinetic energy here. And in this case you will see the must be replaced by this by the adding solid set or near the bottom of the bed. Of course, you have to add the solids here near the bottom of the bed otherwise if you cannot actually add this solids at the certain height because at this operating condition, if you

supply from a certain height of the bed, it will go immediately to the top and it will not having that much of retention time inside the bed.

And the clusters of the particles move of course, downward near the wall, while gas containing dispersed particles moves upward in the interior. Of course, it will be they are if you are using very fined particles there will be sounds to form of clusters or you can say agglomeration and different sizes of clusters will be there inside that bed, that depends on the gas velocity and also the weight ness of the solid particles they are.

And if there are big size of the clusters or form inside the bed of course, it will not be reaching immediately to the stop, sometimes because of this weight, it may go back to its previous position; that means, there will be a tendency of formation of circulation to its downward, and that is why the downward movement of the solid particles near the wall. Because to get back to it is it will have enough space if for the very narrow tube, you may not get this type of backup movement or downward movement of the solid particles inside the bed. So, to get this backward; that means, downward movement of the solids there will be a plus diameter of the fluidized bed.

And the solids in the first fluidized bed may typically occupy up to 25 percent of the bed volume, and is in a state of extreme turbulence marked by extensive refluxing of dense strands and packets of particles there. So, we are the, it is very important point to note that in the first fluidized bed occupy at up to 25 percent of the bed. So, otherwise it is very difficult to get this type of fast fluidization condition.

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Now, pneumatic conveying fluidization in this case homogenous dilute phase of the solid fluid are observed in this case, there will be no bubble formation, there will be know what is that chunk churning condition. there will be know what is that first fluidization condition here.

Only the solid particles will straight forward going up and it will be coming out from the top of the bed. The particles are fully suspended in the gas and particles travel like a piston with relatively high pressure drop and high feed rate of particles here. So, there will be you will see there will be a velocity of the solid or you can say the some flow rate of the solids along moreover the gas velocity harm. Of course, in this case also more than more than 20 times of terminal velocity of the solids, the fluidized bed will be operated here. Now all particle spread in this transported all particle that is spread in the spread that will be transported out the top of the bed as a lean phase here.

So, in this case this pneumatic conveying fluidization of course, it will depend on the velocity and the solid content of the air flow, and different transport states may occur in this case. And there will be see there will be different transport states like suspension flow or dilute phase transport intermediate flow or you can say strand transport, and dense phase dilute or you can say dune transport phase here, and also dense phase plus transport of course, will be there as per figure it is there.

So, here this will be your suspension flow or dilute phase transport and this is b here intermediate flow or strand transport here you will see this how the solid particles are moving, here flow pattern in is section will be almost same here. Whereas, in the see that is called dune transport here in this case the flow pattern will not be same in the middle section maybe or the depending on the gas velocity and solid particles type, it depends on the also cross sectional area of the bed that how the solid particle should be transporting here. And also g is called plug flow here some plug or bubble formation will be there in the bed (Refer Time: 31:40) dense portion will be formed here instead this pneumatic conveying fluidized bed.

So, this this happens because what this cross sectional area of the fluidized bed.

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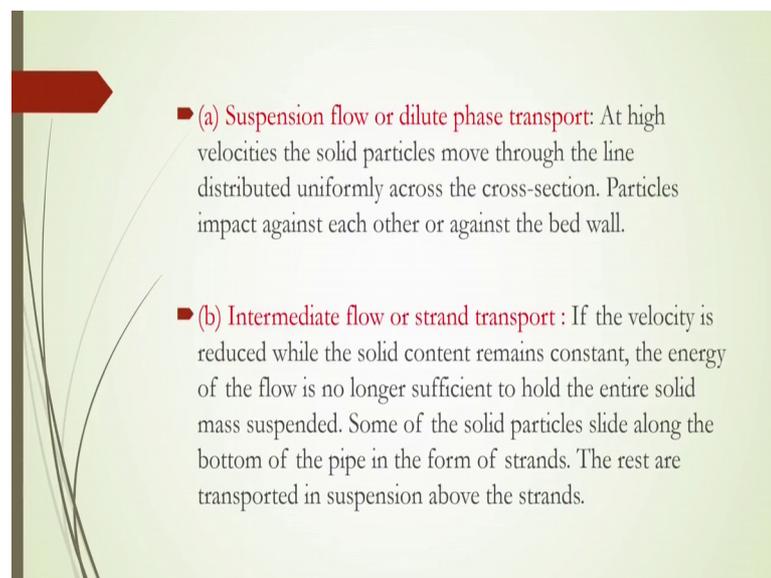
And suspension flow dilute phase transport at high velocity is the solid particles move through the line distributed uniformly across the cross section of course; the particles in fact, against each other or against the bed wall will be there. And intermediate flow or strand transport the velocity is reduced, while the solid content remains constant you will see the energy of the flow, that will not be sufficient to hold the entire solid mass that is suspended in the bed.

And some of the solid particles you will see slide along the bottom of the pipe in the form of strands, and the raised are transport trade in suspension above the strands. Or as dense phase dune transport if the velocity is reduced further you will see the solid

particles move like a dune and particles are moved over the summit of the dune and are deposited on its sheltered side if the velocity is reduced further in insipient plugs may be formed from the dunes which occupies a major part of the cross section of the bed.

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▶ (c) Dense phase dune transport: If the velocity is reduced further, the solid particles move like a dune. Particles are moved over the summit of the dune and are deposited on its sheltered side. If the velocity is reduced further, incipient plugs may be formed from the dunes which occupy a major part of the cross-section of the bed.

▶ (d) Dense phase plug transport: At very low velocities the material occupies the entire cross-section of the pipe and plugs are formed. Plugs advance slowly. If the air compressor does not have sufficient pressure reserves, plug transport may quickly lead to blockage of the pipeline.

And dense phase plug transport in this case a very low velocity, the material occupies the entire cross section of the pipe and plugs are formed, and plugs advanced slowly, if the air compressor does not have sufficient fresher of course, plug transport may quickly lead to blockage of the pipeline. So, this will of course, this this regime of course, will be having the beyond this 20 times of the terminal velocity of the solid particles.

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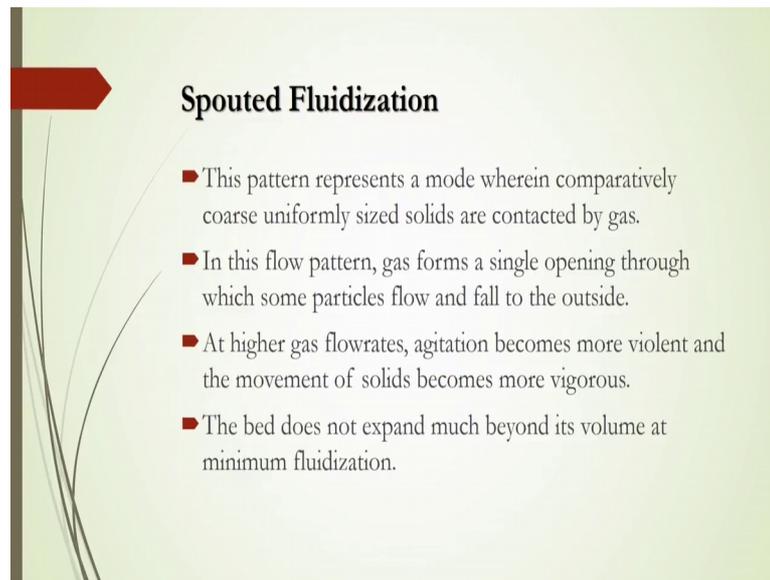
And then spouted fluidization this is another important fluidization regime here, this pattern represents a mod wherein comparatively course, uniformly sized solids are contacted by gas.

In this case you will see that solid size or particle size will be little bit higher than the other particle. So, in this flow pattern gas forms a single opening though the distributor and which in which the some particles flow and fall to the outside. At higher gas flow rate you will see hesitation becomes more (Refer Time: 34:45) and the movement of the sides becomes more vigorous and the bed does not expand must beyond its volume at minimum fluidization. Now in this case you will see principle features of flow regimes here. So, we are getting different flow regimes like fixed bed here that is before fluidization particulate regime.

There will be some region that is u range the velocity that is U m f is minimum fluidization velocity, U m b the bubbling fluidization this for minimum bubbling fluidization condition, in this bed expands smoothly in a homogenous manner top surface well defined the small scale particle motion will be there whereas, bubbling regimes in this case beyond this minimum bubbling fluidization velocity whereas, the less than the minimum velocity for slugging condition. In this case gas voids form near distributor the bubbles will coalesce and grow rise to surface and brake through.

Whereas slug flow bubble size approaches column cross section, top surface rises and collapse with regular frequency here. And the turbulent fluidization flow regime these cases because you will see pressure fluctuation gradually decrease until turbulent fluidization flow regime is reached. And turbulent regime small gas voids and particle clusters dirt to and flow top surface is very difficult to identify. And first fluidization no upper surface to bed and particles transported out the top in clusters and must be replaced there, and pneumatic conveying in this case now bed of course, you will see that particular bed that will be some level, it will not being having in your the pneumatic conveying.

All particles spread in a transported out the top as a lean phase there.
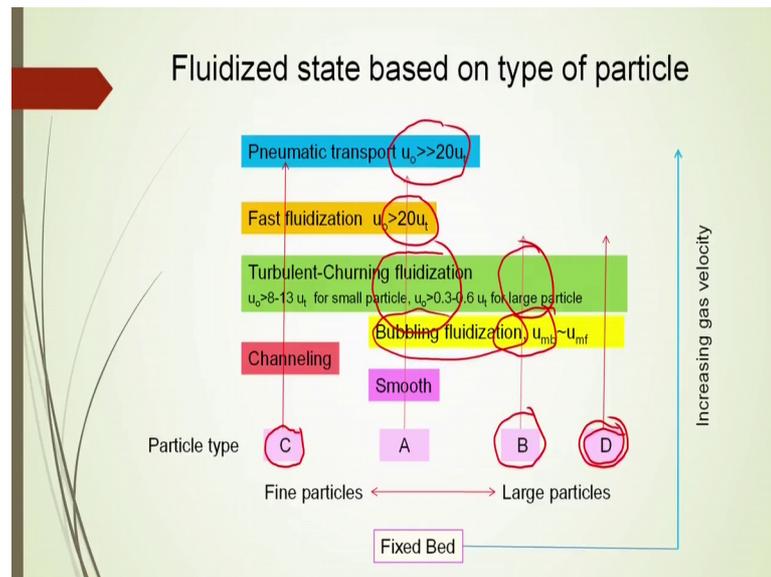
Now let us classify this different fluidization condition as for fluidization regime, and also based on the classification of the particle. Now I think we have discussed in previous or earlier lecture there four different types of gilded particles like C A B and D. Now you will see if you consider the c particles and if you increase the gas velocity then how the, what type of fluidization regime you can except in your fluidized bed. Suppose here this particle type is c c type; that means, very cohesive in nature very find particles here inter particle attraction is very high, and there will be a cohesiveness nature because of which you may expect in the fluidization bed as channeling and also you can have the flow regime of turbulent churning fluidization with this fine particles, and also you can get the first fluidization of course, if the gas velocity if it is greater than 20 times of terminal velocity.

And you can get the pneumatic transport which will be of course, greater than 20 times of terminal velocity of the particles here. So, this c type with this c type particles you may expect this channeling turbulent channeling first fluidization pneumatic transport. Whereas, either particle here the particle size is little bit higher than this cohesiveness that we have earlier discuss that greater than 100 micrometer. In this case you can get the smooth fluidization bubbling fluidization whereas, in c type particles you may not get the bubbling fluidization in this a type fluidization you can get the bubbling fluidization here.

The you can get the turbulent churn turbulent fluidization and also first fluidization, but it is very difficult to get the pneumatic transport with this particles. So, this. So, all this flow regimes you get only by increasing the gas velocity with fixing this solid particles time whereas, with b type particles in this case you get bubbling fluidization, and turbulent fluidization, but you cannot get this what is the smooth channeling fast fluidization on pneumatic transport type fluidization with this b type particles because here the size higher the size matters. So, but d type particles here only two types of fluidization you may except here bubbling fluidization and turbulent churn turbulent fluidization you cannot get any smooth channeling fast or pneumatic transport fluidization.

So, only the d type particles applicable to get this fast oh sorry turbulent and the bubbling fluidization. So, it is very difficult to get this other types of fluidization by switching one particle type, but you can infer what type of fluidization regime can get from this can be can be obtained from this particle from this knowledge.

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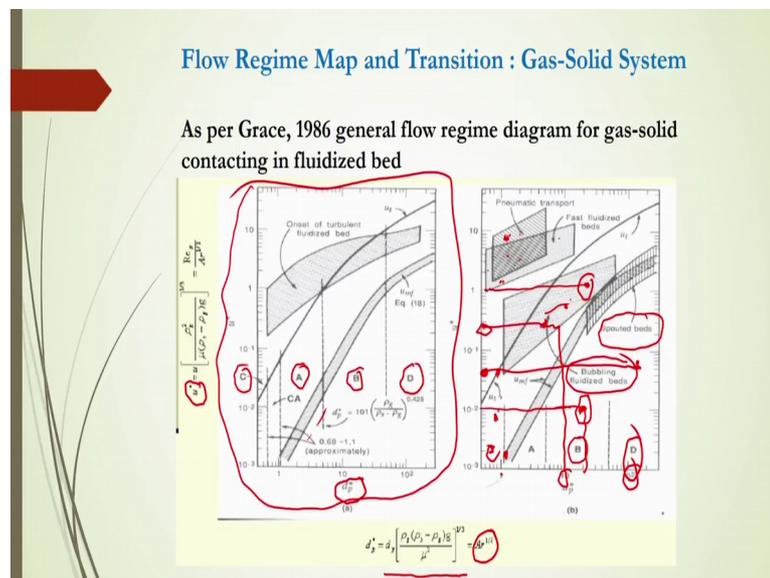
Now, flow regime map and its transition very important here, grace 1986 based on lot of experiment with different type of particles and with varying gas velocity in void range of course, with here they got different results of results of different fluidization phenomena and they have actually suggested one map by representing the transition of different flow regime, based on their experimental data. And they have represented the transition of

different flow regime or different patterns flow patterns inside the fluidization bed, by just choosing just choosing to the choosing the axis in different way, to represent it graphically in this case you have see this here flow regimes in this case very important in this case you will see the x axis is d p star, d p star is what is that non dimensional particles diameter which has made which has been suggested in this way this will be d p into; that means, here rho g into rho s minus rho g by mu square into z to the power 1 by 3 or you can say d p star is equal Archimedes number to the power 1 by 3.

Whereas this y axis that is u star, u star is the non-dimensional velocity of the gas which is defined by R e by Reynolds number, that is Reynolds number by Archimedes number to the power 1 by 3. Now if you see this figure here we are getting different type of phenomena here you first we will see this C A B and D, these are the different type of particles here and this lines this is the lines this lines form line will be representing the transition line or the data on this line will give you the transition data, from beyond which you can get the what is that different flow pattern. Here see here very interesting here is that here if you consider the c here c in this case you will see some flow pattern map, here this is called this region is called this is spouted bed this is bubbling a fluidized bed this region is bubbling fluidized bed, and here pneumatic transport fluidized bed and this region is called fast fluidization bed.

So, here see here if you consider c particles this is the c particles flow regime here, what happened if you consider the c particle here or the point, any point at this point if you go you will see at this location what is this flow regime here, this is the point where you can get at this point like suppose 1 d p star is equal to 1, d p star is equal to 1 if you go up here you can get this this one, this here this is your minimum fluidization condition and this is you terminal velocity profile and at this point. So, this 1 d p star you can get one terminal velocity and here if you go this and if suppose u star is somewhere here one what will happen this is the beginning of the first fluidization condition and then beyond which after they suppose up to10, here you will see at this location you can get the first that is pneumatic transport condition.

Now, if you considered the B particle here and if you considered the d p star is equal to this like what is the value here like suppose10 then it is 11, then d p star is equal to 11 what will happen you can get up to this here any point here whether it will be spouted or some other that you can; obviously, you can take from this regime that it will be the

spouted region here. Because here in this case at this any location you just pin point here g by this combination of this point you can get here spouted. Even if you considered here suppose this is what that? This is d p star is equal to suppose eleven and you can get this bubbling fluidization only when the u star is equal to 1. So, this is the phenomena. So, from this graph you can read actually or before going to the experiment, you can have some rough idea from this flow pattern map whether you are getting the bubbling fluidized bed or not or you are getting a sliding condition or you are getting pneumatic condition or you are getting spouted beds, that you can of course, I have some idea from this flow regime.

Any before going to start any experiment you can of course, suppose you want to have the bubbling fluidization condition, then what you have to do you have to select b type particle first select B type particles. So, if I select the b type particle, and if you want to offer it at one point what is this? This is the d p start is equal to ten then you have to have the velocity at least minimum velocity should be here at here at this point. So, this is your point from which you can get if this b particle what should be the velocity of the gas by which you can get the bubbling fluidization condition; and other also if you want to get the spouted beds like you have the p d.

So, type is d type where d p star is equal to this, and then you want to get the spouted bed, suppose want to get this sprouted bed at this (Refer Time: 47:56) what should be the velocity from which you can calculate this should be your velocity by which you can get the spouted bed. So, in this way before going to start your experiment you know and if you want to apply this fluidization operation for specific operation, and if you know that the operation you will be favorable in bubbling condition, then the operation condition you can select from this fluidization map also.

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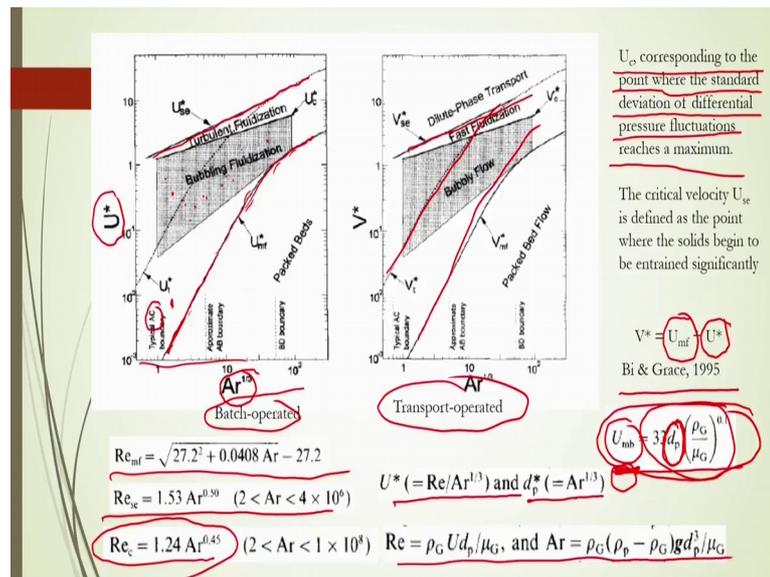
Other type of fluidization regime here you can say here some gas operated here Bi and Grace, 1995. So, they have given this fluidization map.

Here gas operated and transport operated two types of fluidization map they have presented here and these are the lines you can get the transition points and also here this is the transition point these are the transition points or transition line here beyond which you can get the fluidization operation whereas, below this line or less than this point you can get the packed bed at a different what is that boundary of the particles here. Now this in x axis it is represented by Archimedes number to the power 1 by 3 and we are y axis this is U star, U star here this is defined as Reynolds number by Archimedes Reynolds number to the power 1 by 3 and d p star is the Archimedes number to the power 1by 3.

Here again this at this suppose here type a and c this is mixture of a particle a and c and if you go this here in this region you can get this some minimum fluidization or particulate fluidization and beyond which at this location, these are the locations in you can get the bubbling fluidization this location means at any point you select, and you read the data of this A r and U star and from which you can have the idea what should be the value of gas velocity and what should be the value of Archimedes number. From which you can get what should be the diameter of the size if you know if you know the all other parameters constant here and also the turbulent fluidization this is here also this is the transition line beyond which you can get the tabular transportation and also below

this point you can get the turbulent fluidization. So, these are the transition points, these are the transition points, these are the transition points.

So, these are the transition points and the data with this transition points, they have developed they have suggested some correlations from which you can get the transition data; that means, that that particular value, you can get either this packed bed or suppose particulate bed, that depends on the operating condition and other different variables of course. Suppose to get the pneumatic condition. So, in that case of what should be the minimum velocity you can get from this correlation, what should be the minimum velocity to be maintained so, that you can get the pneumatic transport condition here. So, in this case you can from this correlations these are the correlation that is been developed from this experimental data, from which you can get the minimum fluidization condition.

So, we will be discussing what should be the minimum fluidization condition, and the different flow regime transition will be discussing later. And also and here of course, you will see one terms is here U c, U c see is a very interesting point, this U c is the corresponds to the point where the standard deviation of differential pressure fluctuation reaches a maximum. In the fluidized bed you will see whenever it is operated under the certain operating condition the fluctuation of the pressure inside the bed of course, will be there. Now this pressure from this pressure fluctuation you can also obtained what type of flow regimes there in the bed.

Generally the standard deviation of differential pressure fluctuation when it will be reaching a maximum, you may expect there will be a choking that is called pneumatic transport there. And the critical velocity that is s e which is defined as the point where the solids begging to be entrained significantly inside the bed at this particular fluidization operation, then it will be called as a c; that means, here the significant entrainment will be occurring. Now this very important, but whenever you are considering you are working with the transport operated fluidization bed you have to consider the fluidization velocity as a b which will be of course, the beyond the minimum fluidization and you have to add this minimum fluidization along with the operating fluidization condition there.

And another important point the bubbling fluidization how you can get when exactly at which velocity you can get or you can expect to the bubbling fluidization there. You can

get the minimum fluidization velocity for bubbling condition by this correlation here. See here see 33 into d p into rho G by mu c to the power 0.1 for does it signify it signifies that if particular d p, if you are just keeping it constant and if you increase the density of the gas you will see the bubble velocity; that means, here the velocity of the gas inside the bed will be so, higher that you can get the operation of the bubbling fluidization, but what should be the minimum. You just if you considered that a r and particle size is 100 micrometer and here if you substitute here the d p is equal to 100 microns, that is you have to converted to the meter and then if you substitute a rho g that is 1.2 and by mu G mu means here what should be the viscosity of the water viscosity of the A r here.

So, in this case viscosity 0.00018. So, if you substitute you will get the minimum bubbling condition. So, you can directly apply to get the minimum bubbling condition this range here. So, you can easily calculate before starting the bubbling fluidization condition operation.

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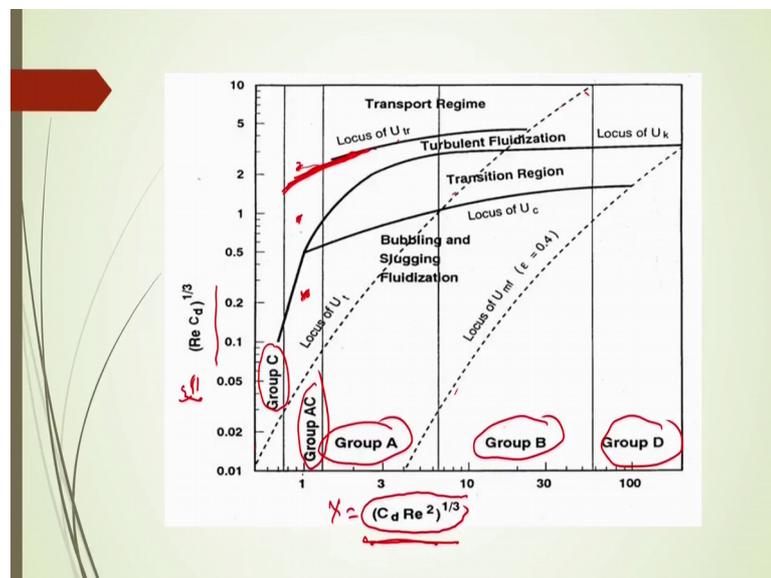
Another important fluidization map for flow regime map here given in different way; that means, here then x axis you will see this is the c d into Reynolds number to square whole to the power 1 by 3 this is one parameter and also here another parameter here r e into C d to the power 1 by 3 what is C d? C d is nothing, but the drag coefficient it will be discuss later and also even previous earlier class also what is drag coefficient has been

discussed. So, this is drag coefficient. So, here in x axis you will see for different particles here group C, even mixture of group A and C, group A and group B and group D geldart group Dparticles.

For this type of particles you will see different flow regime, different flow pattern you can get by this axis. Here these are the dotted lines are represented by the low cast of u and f; that means, at this point you can get the minimum fluidization to come, what is that packed bed to the particulate fluidized bed. Whereas, that this line will give you the terminal velocity of the particles here. Now if you consider any group c particles here c at this what is that if the value of this x axis, this x is equal to this then and here y, y is equal to this then you will get this value for a particular x is equal to 1 and then here what should be the value of what will be the flow regime you may except here.

So, this regime is nothing, but see locus of u t r from transition; that means, the transport flow regime. So, here at this. So, even you can get transport regime whereas, in this position you can get the turbulent fluidization condition, and with this y value of this you can get the, what is that bubbling and bubbling fluidization condition and slug in fluidization condition also. So, this is one way to represent the different flow regime map here.

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Now, what should be the transition from particulate to the bubbling fluidized bed? The equation here it is given that is developed by Geldart and Abraham.

So, to get the minimum bubbling fluidization velocity you can use this correlation to calculate for minimum bubbling fluidization condition.

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For minimum bubbling velocity also there are another correlations it is the important from which you can calculate the minimum bubbling from fluidization condition. Here in this case this is the function of density of the gas viscosity particle diameter, solid density and also there will be a what is that a fraction of powder, which has the particle diameter is 45 micrometer generally for FCC catalyst of size 5 to 100 micro at gas velocity, U g is equal to 3 U m f bubbles begins to form here. In group a powders when U m b; that means, minimum obligation condition is greater than minimum fluidization are constantly splitting and coalescing and maximum stable bubble size is achieved.

This makes good qualities smooth fluidization here, and also through splitting and coalescence of course, the bubbles achieve a maximum stable size and it will be effectively independent gas velocity or vessel size non bubbling expansion of a fluidized bed of group a powder as the gas velocity is gradually increased to there.

Or transition from bubbly to slugging fluidization of course, (Refer Time: 59:04) this minimum fluidization condition for slugging is u m a is equal to 0.07 into g D to the power 0.5, from this correlation you can get what should be the minimum velocity for slugging condition and then minimum velocity you can calculate from this equation.

And other criteria for slugging also here, it is seen that there are several other criteria to get the slugging fluidization here. If velocity terminal velocity is by g d p; that means, it is called cloud number if it is greater than 140.

Then you see there will be a stability of upward flow of a uniform unbounded suspension you can expect here no allowance for wall effects will be there. If this number is greater than 0.35 of course, you will be see there will be a slug stability based on the equation of here Harrison et al they have produced here. And this criteria will give you slug stability based on the empirical evidence and this correlations here this correlations will give you the slug postulated not to be able to rise faster than porosity waves into of course, these correlation has been developed by smith 1978 whereas, Guedes and Carvalho 1981, they have observed or some mechanism of slug stability based on the modified Harrison equation and they have developed one criteria for which you can get the slugging condition based on bubble splitting from the real wall.

So, these are the criteria other criteria from which you can except the different slugging condition.

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Now, this slugging transition you come this is the condition from which you can get the slugging transition. And if the bed is differ then this critical height then the slugging will occur when the gas velocity exceeds u m s given by the equation B here this. This is your minimum height of the fluidized bed, now if the bed is differ than this critical height than slugging will occur then the gas velocity exceeds g m s given by this equation. And slugging will not occur provided the criteria in equation A is satisfied this criteria works well for most powders.

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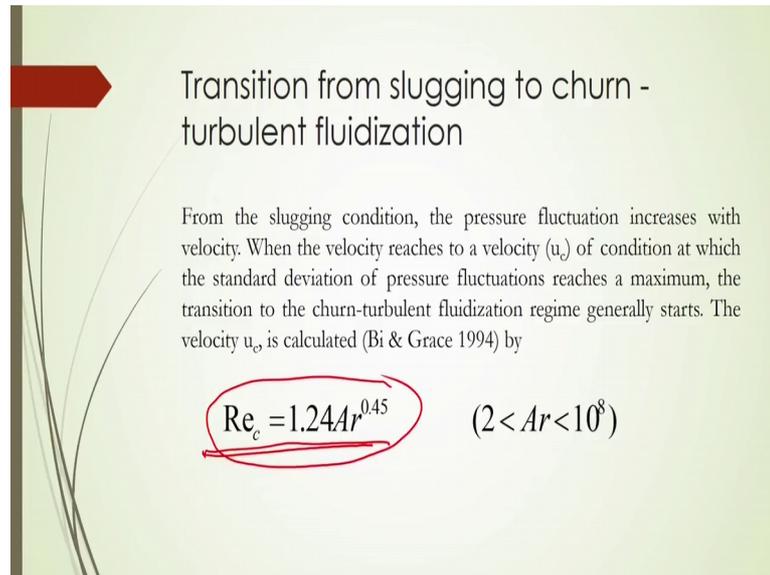
Transition from slugging to churn - turbulent fluidization

From the slugging condition, the pressure fluctuation increases with velocity. When the velocity reaches to a velocity (u_c) of condition at which the standard deviation of pressure fluctuations reaches a maximum, the transition to the churn-turbulent fluidization regime generally starts. The velocity u_c, is calculated (Bi & Grace 1994) by

$$Re_c = 1.24 Ar^{0.45} \qquad (2 < Ar < 10^8)$$

And this is the condition from conditioner or transition of slugging to churn turbulent condition and from this transition you can expect for type of either the slugging or turbulent of from slugging to turbulent how can I get to operate.

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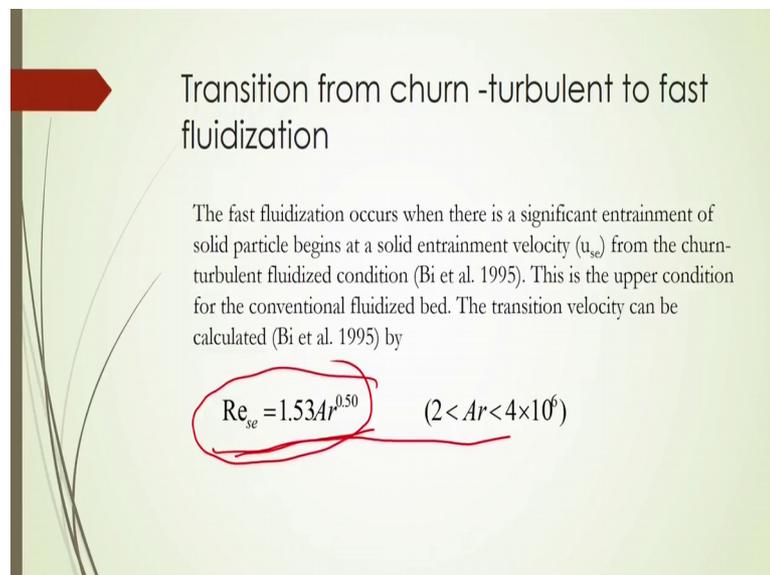
Transition from churn -turbulent to fast fluidization

The fast fluidization occurs when there is a significant entrainment of solid particle begins at a solid entrainment velocity (u_{se}) from the churn-turbulent fluidized condition (Bi et al. 1995). This is the upper condition for the conventional fluidized bed. The transition velocity can be calculated (Bi et al. 1995) by

$$Re_{se} = 1.53 Ar^{0.50} \qquad (2 < Ar < 4 \times 10^6)$$

And this is your transition from churn turbulent to first fluidization of course, the and by this equation you can calculate to get the minimum churn turbulent flow or just to start the first fluidization.

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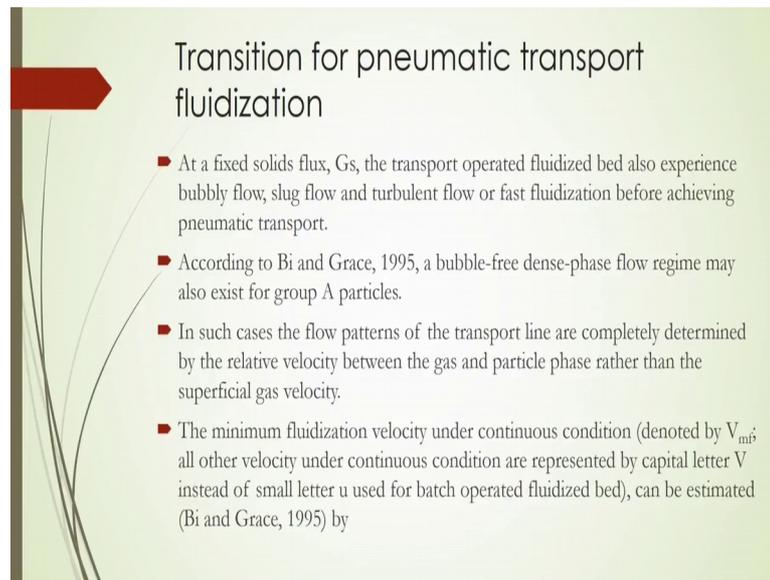
And transition for pneumatic transport fluidization of course, at a fixed solid flux the transport operator fluidized bed experiences bubbly slug flow turbulent flow or first flow fluidization before assuming pneumatic transport. Now according to Bi and Grace 1995 you will see a bubble free dense phase flow regime may also exit for group a particles. So, in such cases the flow patterns of the transport planner completely determined completely determined by the relative velocity between the gas and the particles phase rather than the superficial gas velocity.

The minimum fluidization velocity under this condition how to denoted by u m v m f all other velocity under continuous condition are represented by capital here latter B instead of small letter u use for based operated fluidized bed can be estimated.

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And the minimum fluidization for pneumatic transport condition you can get from this equation here.

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Pneumatic transport condition here minimum pneumatic bubbling condition here, this is your minimum pneumatic transport bubbling fluidization and minimum pneumatic slugging condition also here.

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So, this is the case transition for pneumatic transport fluidization from which you can get this type of equation from which you can calculate what should be the choking velocity in the pneumatic transport condition.

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What is choking? Choking actually as an generally used for to describe a phenomena which occurs, when there is an abrupt change in the behavior of a gas solid conveying system the soaking point therefore, has been characterized by the formation of slugs of plugs or there will be is there any severe in stability or not. Three types of choking

generally are observed in fluidization operation accumulative choking, classical chocking (Refer Time: 63:49) strength pipe induced choking.

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So, different chocking. So, we will give you the different phenomena.

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And there are various definitions of the chocking, that observed in the fluidized bed that observe.

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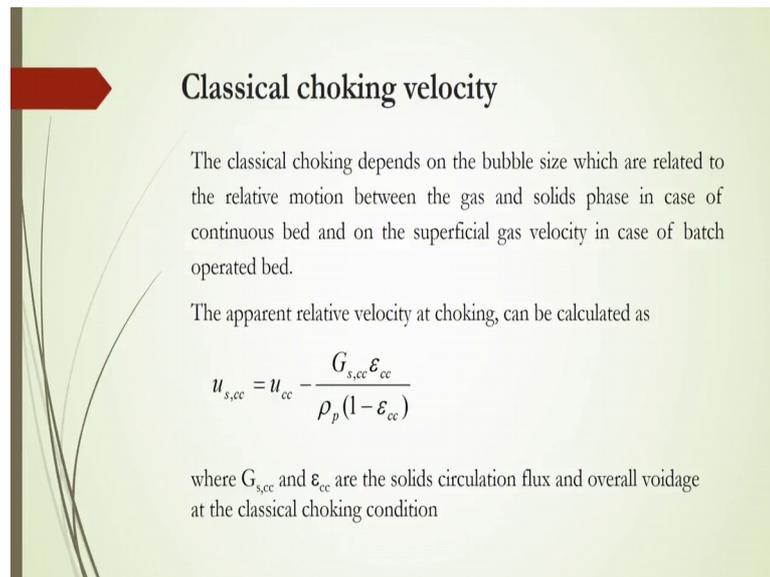
Classical choking velocity

The classical choking depends on the bubble size which are related to the relative motion between the gas and solids phase in case of continuous bed and on the superficial gas velocity in case of batch operated bed.
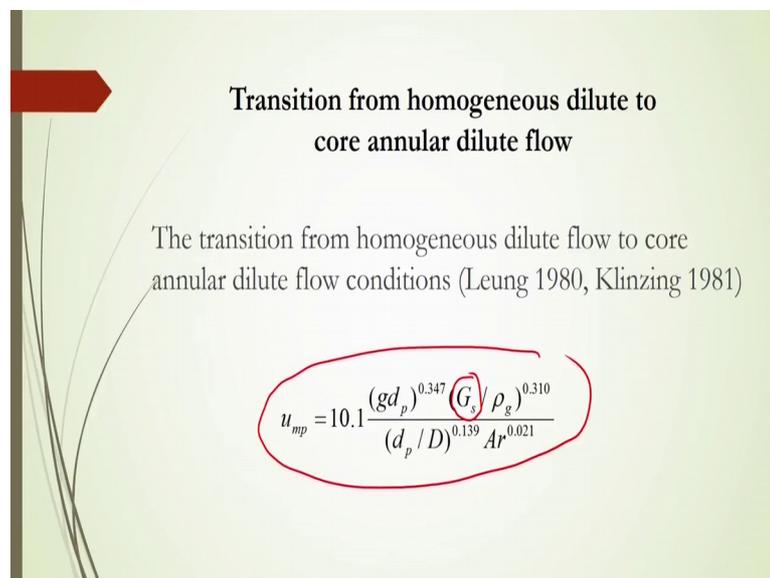
The apparent relative velocity at choking, can be calculated as

$$u_{s,cc} = u_{cc} - \frac{G_{s,cc}\varepsilon_{cc}}{\rho_p(1-\varepsilon_{cc})}$$

where $G_{s,cc}$ and ε_{cc} are the solids circulation flux and overall voidage at the classical choking condition

And here classical choking of course, you can get the apparent relative velocity at choking that can be calculated by this equation here.

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Transition from homogeneous dilute to core annular dilute flow

The transition from homogeneous dilute flow to core annular dilute flow conditions (Leung 1980, Klinzing 1981)
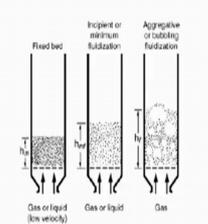
$$u_{mp} = 10.1 \frac{(gd_p)^{0.347}(G_s/\rho_g)^{0.310}}{(d_p/D)^{0.139}Ar^{0.021}}$$

Transition from humongous to dilute to core annular, this is very important correlations you can directly get from homogenous to the annular dilute flow by this equation. Only thing is that you have to change the solid flux here, and also you can change the diameter of the pipe, if you change then you can get the annular condition of the fluidization.

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So, next class from what do will be discussing some other part of the fluidized bed, like implication of what would be the ratio of this minimum fluidization to minimum bubbling condition how it will be affecting in that ok.

Thank you.