Fluidization Engineering
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Lecture – 18
Bubbling Fluidization-Part 6: Slugging Bed

So, welcome to massive open online course on fluidization engineering today's lectures will be on bubbling fluidization as a part here bubbling characteristics in this part the slugging characteristics of the fluidized bed will be discussed now we have discussed in the previous lectures what are the different shape of bubbles that formed in the bubbling fluidized bed and what are the characteristics of coalesce and the breakup for the bubbles in the bubbling fluidized bed and how the mechanism for those characteristics and.

What will be the different phenomenon of that bubbling characteristics based on different concentration of the solid particle size particle movement and also what would be the particle movement when bubbles will rise slowly or bubbles will move very fast in that case how this characteristics of the solid movement that is will govern the mass transfer and heat transfer phenomenon also that depends on that characteristics that already been discussed some extent.

Here also out of that bubble characteristics slugging bed is also one phenomenon for characteristic characterization of the bubbling fluidization now in this case of course, the slug means here bubble slug will be or gas slug that will be forming as a that is bubble.

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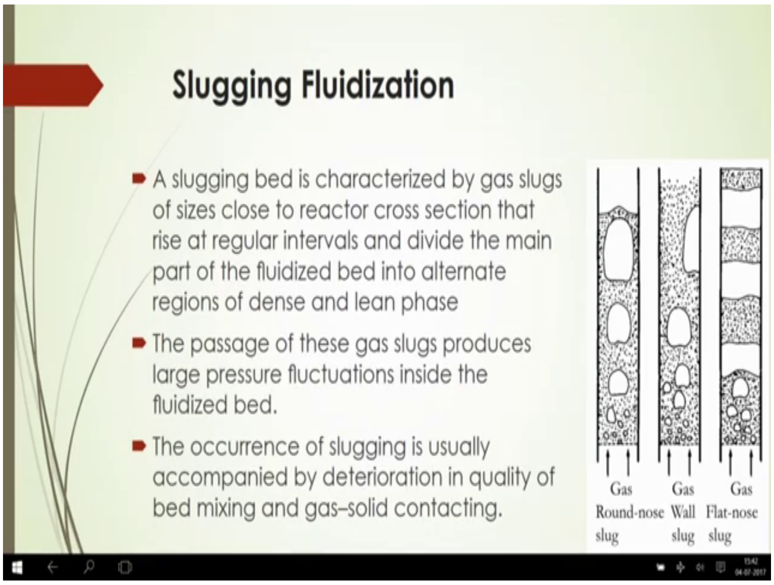

So, here again the bubble characteristic will come into picture, but here the formation of the bubbles shape of the bubbles will be something different and it will be something like elongated. So, in that case you are seen that in the picture you will see that the slugging bed is characterized by gas slugs of sizes that is close to reactor cross section that is at regular intervals and divide the main part of the fluidized bed into alternate regions of dense and lean phases and when this gas slugs passes of course, this passes of this gas slugs that produces large pressure fluctuation inside the fluidized bed.

Now, the occurrence of the slugging is usually accompanied by deterioration in quality of bed mixing and gas solid contacting. So, here the slugging of course, this phenomenon will govern the mass transport even heat transport phenomenon in the fluidized bed and if it is applied for a specific application there.

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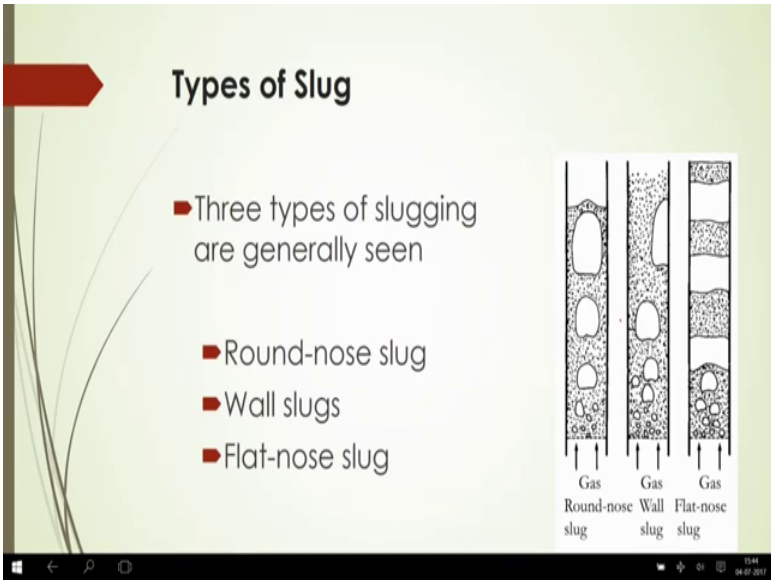

And here based on the fluid based on the flow rate of course, this slugging phenomenon will be there and there will be a different types of slugging that formed in the fluidized bed.

Here generally three types of slugging is seen in the fluidized bed and here one is called round nose slug and another is called wall slugs. Whereas, out of these round nose slug and wall slug. So, sometimes this slugs will be coming in such a way that they may occupy whole cross section of the bed and it will form a different type of slug that is called flat nose slug here.

So, mainly these three types of slugging are seen. So, here seen this picture that this one is called here the round nose slug you see that the bubbles which are forming in such way that there will be a nose shape of this round. And here all those round shape bubbles will be continuously flowing to the centre of the bed. And some these slugs or bubbles will be moving in such way, they will be touching the wall of the bed and some other slugs may be based on the flow rate of the operation of that the slug will occupy or bubble will occupy whole cross sectional of the bed.

So, based on the that is reactor diameter even other operating variables you will see these are three common types of slugs will be formed in the fluidized bed.

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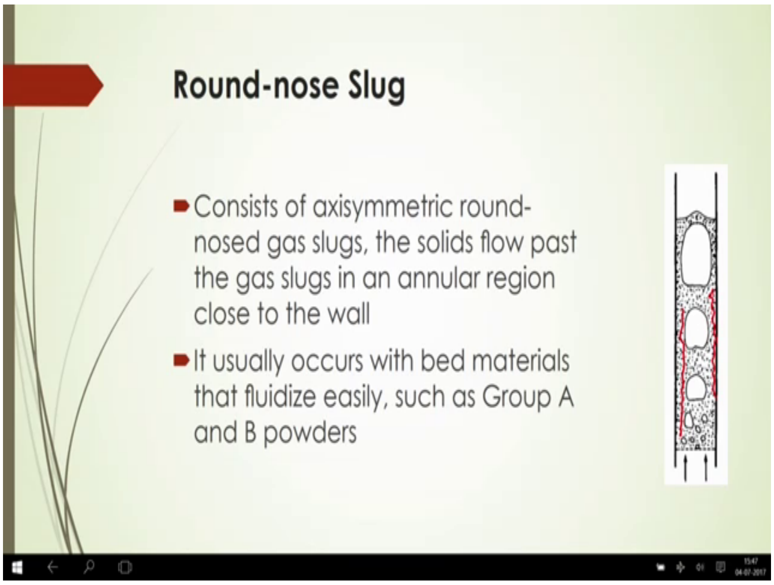

And here in this case a round shape or round nose slug that consists of axi symmetric round nosed gas slugs. The solids flow past the past the gas slugs in an annular region that is close to the wall. And it usually occurs with bed materials that fluidize easily such as like group A or group B particles as per that Geldart classification.

So, in this case very important that this round nose slugs of course, it will be axisymmetric and the solids that is flow past the gas slug in an annular region here annular region here in the picture is shown. And these occurs the bed material that fluidized easily of course, and basically for group A and group B powders this type of phenomenon you can see, but for D type particles or C type particles; you will not be having this type of this round nose slug.

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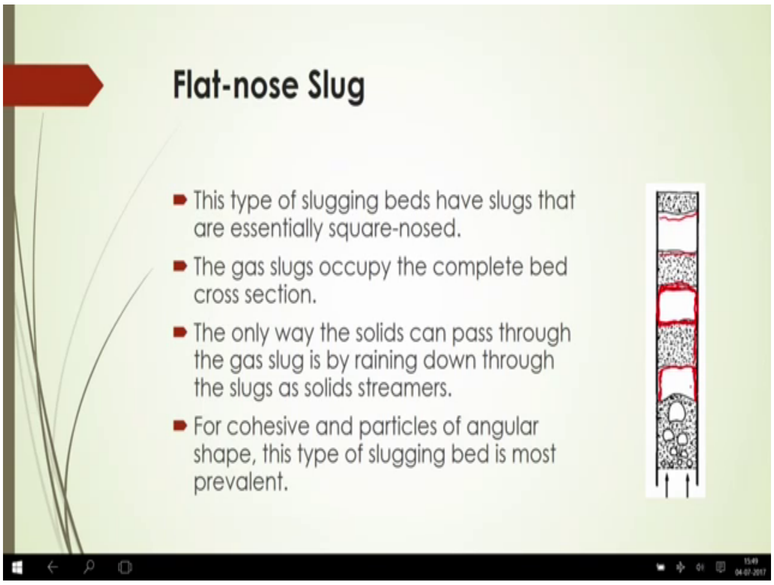

Whereas, flat nose slug this type of slugging bed have slugs that are essentially square nosed and the gas slug occupy the complete bed cross section. And the only way the solids can pass through the gas slug is by raining down through the slugs as solids streamers. For cohesive and particles of angular shape this type of slugging is most prevalent.

So, very important that you cannot get this type of phenomenon for group A or group B particles; it will be having only for the C type particles; that means, those particles will be very cohesive in nature and this slugs of course, the shape of the slugs will be square nosed; here see this is the square nosed, here this type of this shape of the slugging it is happening for this case.

And in this case you will see that this slugs which will occupy total cross section of the bed. And here in this case you will see that the solids of which pass through the gas slug is by raining through the slugs as a solid streams here. In this case through the or adjacent to the wall of the bed the solids are moving downward here.

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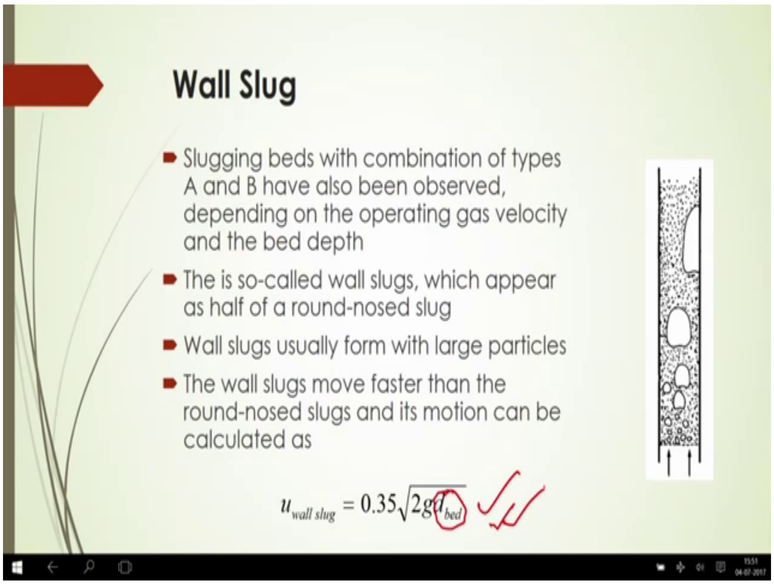

Whereas wall slug in this case you will see the slugging beds with combination of types A and B have also been observed. So, depending on the gas velocity and the bed depth this type of phenomenon will be observed.

This is so, called wall slugs which appear as half of a round nose slugs occupy the whole cross section occupy the cross section of the bed. And wall slugs usually form with large particles and also the wall slugs move faster than the round nosed slug and its motion can be calculated as by the equation given in slides that wall slug velocity will be is equal to 0.35 into root of a 2 g d bed here g will be considered as a diameter of the bed.

So, very interesting that this wall slugs because here the slug of course, will be touching the wall of the bed and it is seen that the slug which will occupy only half portion of the cross section of the bed. And here this in this case you can get this type of phenomenon for large particles also. And then this slugs generally moves faster than the round nosed slug and motion can be calculated as per this rise velocity here as given by Kunii and O. Levenspiel.

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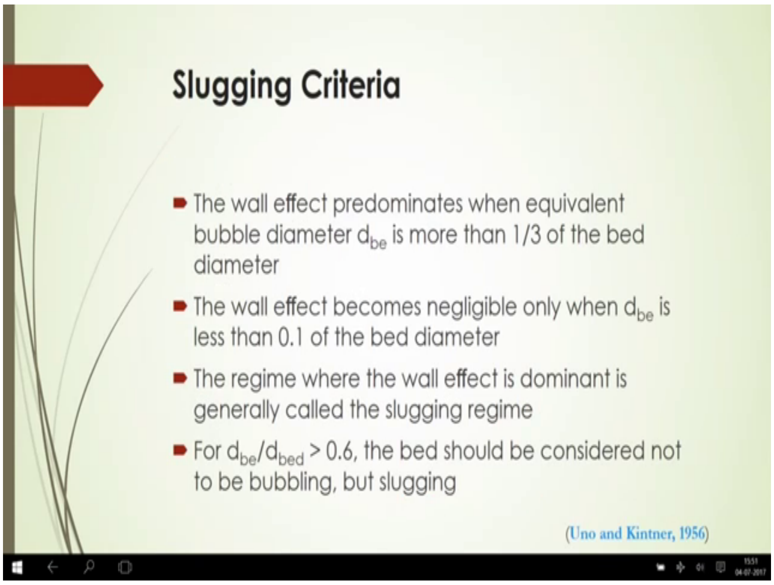

And what should be the then criteria for slugging that is very important when we can get the slugging phenomenon out of that bubbling fluidized bed. So, we are getting bubbling fluidized different types of bubbling fluidized bed of course, that is bubbling and past circulation and also that that is chant turbulent and they are also and then slugging fluidized bed; that is as a bubbling fluidized bed part of the bubbling fluidizing bed.

Now, when you will increase the gas velocity; you have seen that different flow pattern observed in bubbling fluidized bed. Now what should be the criteria for slugging that when gas velocity increased at a certain velocity, the slug formation will be start. Now in this case you will see it is observed from the experimental results that actually reported by Uno and Kintner 1956 that the wall effect parameters when that is predominant when equivalent bubble diameter is more than one third of the bed diameter.

So, it will observe only that when you will see that there will be a formation of bubble in the fluidized bed. Now you will see the bubbles its size is is suppose one third of the bed diameter; then immediately fluidization will be as per this slugging fluidization; that means, here bubbles will form as a slug and also very interesting that the wall effects becomes there negligible when this equivalent diameter is less than 0.1 that is 10 percent of the bed diameter

What does it mean that you will see that wall effect; that means, there will be some frictional effect of the bubble surface and the wall. So, this wall effect if becomes negligible; if this equivalent by whole diameter is 10 percent of the bed diameter; that means, there maximum bubble will be this size in such way that maximum bubbles will be in the medium not adjusting to the wall of the bed. And whichever portion of the bubbles will come to the wall of the bed; they will get that wall effect otherwise very small effect of this wall will be there.

And also it is seen that if the bubble size is very less and the delusion or you can say concentration of the bubble forms in the fluidized bed there; that means, the size of the bubbles in such way that its that is the size is 10 percent of the bed diameter; then there will be a collision will be less and in that case the wall effect that is bubble wall effect also will be negligible.

But if the concentration of the bubble is very large; that means, concentration of the bubbles means here number concentration of the bubbles in the bed; there may be a collision between bubbles equivalencies and the bubble wall effect because of which there will be a coalesce effect and there may be a formation of the bigger bubble by the coalesce. And also when this bigger bubbles will become one third of the bed diameter of course, this slug formation will be happening.

And regime where the wall effect is dominant is generally called the slugging regime of course, there will be the wall effect dominant there of course, there will be a slugging regime because of that coalesce effect. And for if you will see that the equivalent bubble diameter and this bed diameter; this ratio that is equivalent bubble diameter to the bed diameter ratio is greater than 60 percent that is 0.60, you will see that the bed should be considered not to be bubbling, but slugging.

So, this is the criteria; so, what we observe that we can get the slugging phenomenon for a particular ah; that means, set of experiment like with the constant that is particle and also particle size, bed diameter and this and also you will see that gaseous medium. So, in that case it will increase the gas velocity, there may be fast particulate and then bubbling and then.

Now, slugging it will happen if that bubble diameter equivalent bubble diameter is that is more than one third of the bed diameter; there just formation of slug. And also if suppose the equivalent bubble diameter and bed diameter is greater than 0.6; the bed should be considered not to be totally bubbling it will be totally slugging phenomenon; that means, whole cross sectional area of the bed may occupy by occupy by the gaseous slug.

And in that case one important point that we observe that this this slug; that is wall effect important here. If the wall effect is dominant then you will get the slugging regime. And also here the Stewart and Davidson they have actually developed one mathematical expression that is simple expression to calculate or to observe the slugging phenomenon there.

So, they gave one correlation like; if they told that or they stated that if the fluid velocity is greater than this summation of minimum fluidization velocity and the 20 percent of 0.35 into 2 to the power g d b; then you will get the slugging bed there; so, this type of lugs will form.

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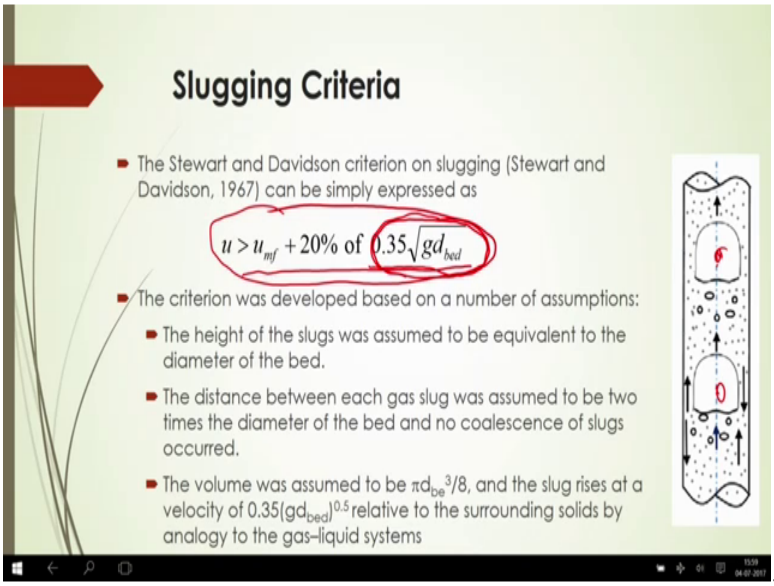

So, this is one important criteria when you can get the slugging phenomenon inside the bed. And the criterion was developed based on some assumptions; so in that case their assumption was there that the height of the slug that they have assumed that is to be equivalent to the diameter of the bed.

And the distance between is gas slug; that means, this gas slugs and this gas slug between this two gas slugs, between this two gas slugs to be two times of the diameter of the bed. And no coalesce of the slug occurred and also the volume was assumed to be that is 75 percent of the equivalent bubble volume and the slug rises at a velocity of 0.35 into g d to the power 0.5 relative to the surrounding solid by analogy to the gas liquid system.

So, important point that when we will get the slugging then if the velocity you are controlling is greater than summation of the minimum fluidization and the 20 percent of this that is 0.35 into g root to the power g d b this parameters. Now of course, in this case they told the height of the slug will be equivalent to the diameter of the bed.

And the distance between two slugs of course, will be two times of the diameter of the bed and the volume of this slug each slug; what should be volume of each slug? So, they told that it should be it should be the 75 percent of the volume of the volume of the bubble which should be equivalent to the total volume of the slug.

So, in this way we can get what should be the slugging criteria in the bubbling fluidized bed.

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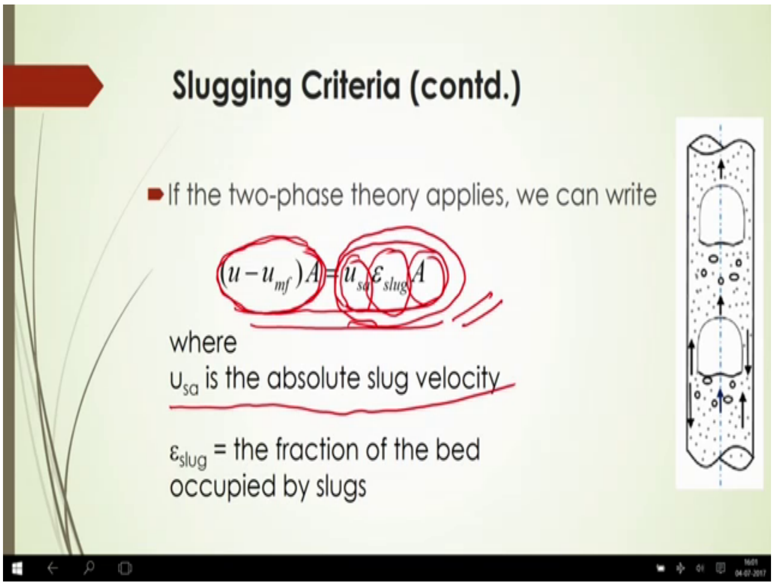

Another important criteria that is given by the that means Davidson; Stewart and Davidson; there they told that if the two phase theory applies then it can be written u minus u m f; that means, relative velocity of the based on the minimum fluidization velocity. And upon which you multiply by cross sectional area then what should be the total volume of the gas supplied to the bed and which will be equals to the volume of the gas which is used for formation of the slug. So, what is that? If we know the slug absolute slug velocity as s; u s a and the volumetric fraction of the slug inside the bed and then multiplied by the cross sectional area.

So, this portion will be the what will be the volume of the gas that is used for formation of the slug. Whereas, this one is the volume of the gas which is being used for the fluidized bed operation to get this slugging fluidization. Now based on this you will be able to calculate what should be the minimum velocity for which you can get the slugging phenomenon.

So, in this case what is u s a? us u s a is the absolute slug velocity and epsilon slug that will be is equal to the fraction of the bed which is occupied by the slugs. So, this is the criteria. So you have to calculate what will be the amount of a gas which is used for slug.

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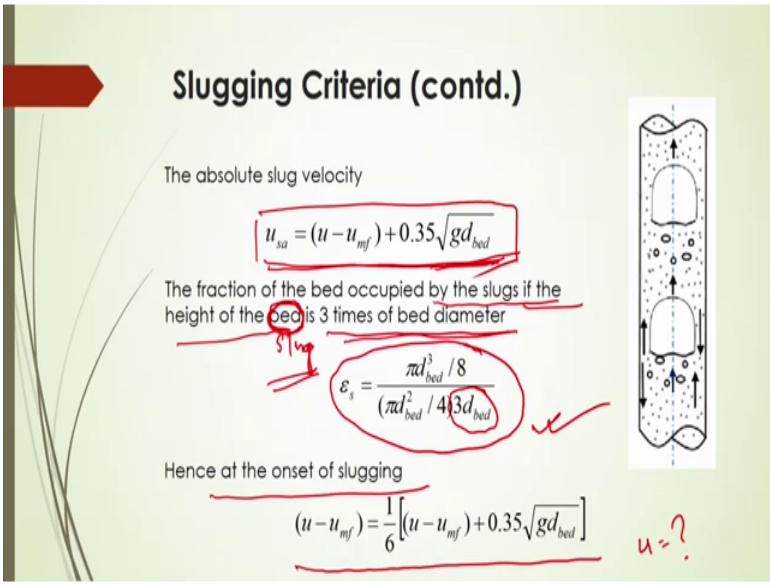

Another important point is that you can calculate from those principles that the absolute slug velocity can be calculated from the mass balance equation. And also based on the rising velocity of this here slug, it will be as that absolute slug velocity here it will be equals to u minus u m f plus 0.35 into root to the power g d b.

So, from this equation you will be able to calculate what should be the absolute velocity of the slug. And the fraction of the bed that is occupied by the slug if the height of the bed is three times of the bed diameter. Now very important that if the height of the height of the slug this will be slug; not bed this will be slug. So, the fraction of the bed occupied by the slugs if the height of the slug is three times of the bed diameter, then you can say that this will be is equal to this fraction of the slug will be equals to pi d b cube by 8 divided by pi d b e d square by 4 that is cross section of the bed into 3 into b d bed.

So, here this is a slug that is based on if you consider here slug; it will be the epsilon of based on this small slug volume. But if you are considering the total slug inside the bed then you have to consider here the what should be the height of the bed. Because total portion of the bed will be will be occupying total that is summation of all slugs inside the bed. There only one slug will not be there; there may be more than two slugs will be there.

So, if you are considering the total bed inside the ; that means, occupying all the slugs then here of course, the fraction of the bed occupied by the slugs if the height of the bed is three times of the bed diameter. So, in this case the slugging criteria for this if you substitute this epsilon S there; in this previous equation, then you will be able to calculate what should be the absolute slug velocity.

Hence on the onset of the slugging; just you substitute there this value then u minus u m f will be is equal to 1 by 6 into u minus u m f plus 0.35 root to the power g d bed.

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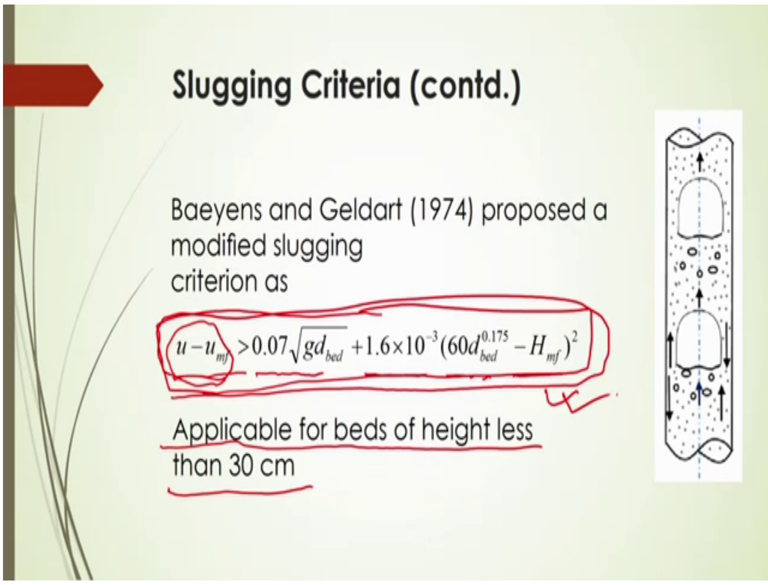

So, from which what should be that criteria for u here from this; u will be is equal to what?

So, this u will give you the what will be the slugging velocity for which you can get the fast slugs formation inside the bed Baeyens and Geldart 1974 they have proposed a modified slugging criteria as; here this they have give this relative velocity of the gas or fluid; you can that u minus u m f should be is greater than 0.07 root to the power g into d b plus 1.6 into 10 to the power minus 3 into 60 into d bed to the power 0.175 minus H m f.

So, from this correlation you can get what should be the slugging criteria for a particular operating condition of the bed height or bed diameter and then what will be the solid particles and its size. So, this correlation is applicable for beds of height which will be less than 30 centimeters.

So, they have done their experiment by taking the bed height of less than 30 centimeter and they from their experimental data; they have come to this point here for the slugging criteria by this and they propose this correlation for the slugging phenomenon.

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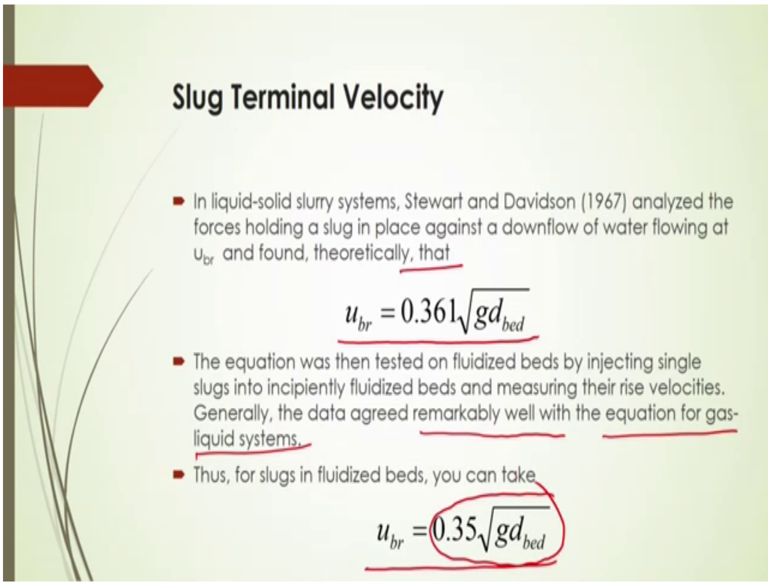

And then what should be the terminal velocity of the slug? We have already came to know that what should be the terminal velocity of the bubble for a particular its diameter. And what should be the bubble rise velocity when there will be only single bubble rises.

And what should be the bubble rise velocity if more than one bubbles is moving parallel; if there is a bubble interaction then how this bubble rise velocity will be effective that we have already calculate or we have already learnt about that the bubble rise velocity.

Now, what should be slug terminal velocity? In liquid solid slurry systems Stewart and Davidson 1967, they have analyzed the forces holding a slug in place against a down flow of water flowing at bubble rise velocity and found theoretically that that u b r that is bubble rise velocity will be is equal to 0.361 into root to the power g into d bed.

Now, the equation was then tested on fluidized beds by injecting single slugs into incipiently fluidized beds and measuring their rise velocities. Generally the data agreed remarkably well with the equation for gas liquid systems; thus for slugs in fluidized bed that you can take as u b r; that means, bubble rise velocity for the slug here, it will be is equal to 0.35 into root to the power g into d bed here. So, in this way you will be able to calculate or you can estimate what should be the slug terminal velocity.

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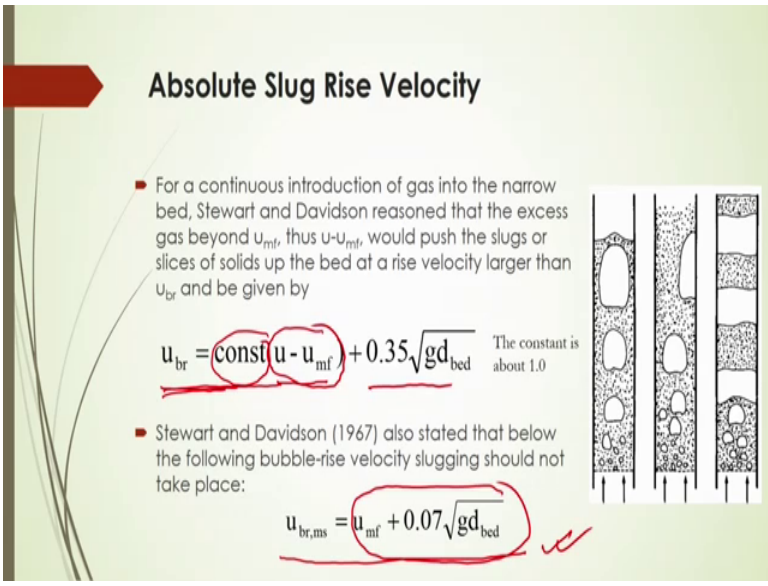

Now, if suppose more than 1 slug rising and 1 disturbing others then of course, there will be a some absolute slug rise velocity which will be considered in that case. Now for a continuous introduction of gas into the narrow bed then Stewart and Davidson reason that the excess gas beyond u m f; that means, minimum fluidization velocity; thus it will be u minus u m f would push the slugs or you can say slices of the slides of the bed at rise velocity larger than a bubble rise velocity.

And that can be expressed as this bubble rise velocity will be is equal to some constant factor into this this is called that relative velocity ah; that means, beyond the u minimum fluidization velocity plus 0.35 into root to the power g d bed. Now this in this case constants here generally it is seen that it will be almost equals to 1. So, then bubble rise velocity for this slugs; it will be is equal to u minus u m f plus 0.35 into root to the power g d bed.

Now, Stewart and Davidson 1967 also stated that below the following bubble rise velocity slugging should not take place. So, if you are having the bubble rise velocity here this u; u m f plus 0.07 root to the power g d b of course, there will be no formation of the slugging. And this bubble rise velocity in this case will give you the demarcation point of where or whether this slugging should take place or not.

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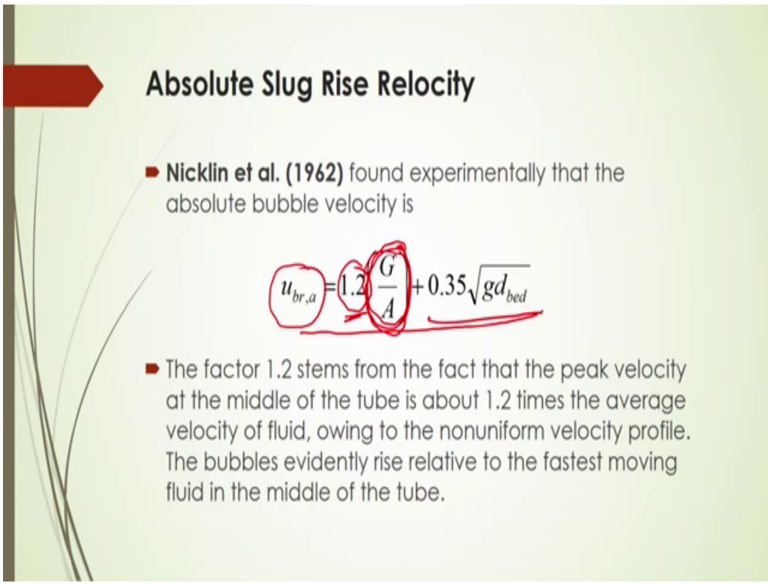

Now, Nicklin model is also important one; they have studied and they have developed another important correlations from their experimental observation. And they found experimentally that that absolute bubble velocity should be is equal to that 1.2 into g a plus 0.35 into root to the power g d bed; here constant is 1.2 see that the previous equation here where as this u b r absolute here this constant is 1.2 instead of 1 this G by A is nothing, but the fluid velocity here; whereas in this case u minus u m f is the effective fluid velocity; that means, just beyond the minimum fluidization velocity.

Here also this gas velocity by cross sectional area gas flooded by cross sectional area that is called fluid velocity plus 0.35 into root to the power g d b. Now the factor here 1.2 stems from the fact that the peak velocity at the middle of the tube is about 1.2 times the average velocity of the fluid. Very interesting that this 1.2 (Refer Time: 29:59) is coming it is seen that that means at the middles; that is middle section of the fluidized bed, you will see there will be a velocity of the gas that will be highest velocity of the gas that is called peak velocity at the middle of the tube; that will be is equal to 1.2 times of the average velocity of the fluid.

What should be the cross sectional area average velocity inside the bed? And what should be the that is centre line velocity of the fluid inside the bed? So, as per this Nicklin model they observe that this centre line velocity or middle line velocity of the gas will be is equal to 1.2 times of the average velocity.

Whereas without any disturbance only single fluid you will see that the centre line velocity or actual velocity will be is equal to two times of the average velocity it is generally seen. But here this case they observed that if there is a slug formation or the bubble formation this centre line velocity will be is equal to 1.2 times of the average velocity. And the bubble usually rise here in this case relating to the fastest moving fluid in the middle of the tube. Because here they have given the reason for that that here in this case owing to the non uniform velocity of this profile and the bubbles eventually rise that is relative to the fastest moving fluid in the middle of the tube.

And what should be the slug length whenever slug will be forming inside the fluidized bed, the slug length can be calculated from the material balance that is of solids and gas here inside the fluidized bed. So, if you are considering that material balance ah; that means, what will be the amount of gas is supplied and what will be the amount of gas is utilized for the formation of the slug and from which you will be able to calculate what should be slug length there.

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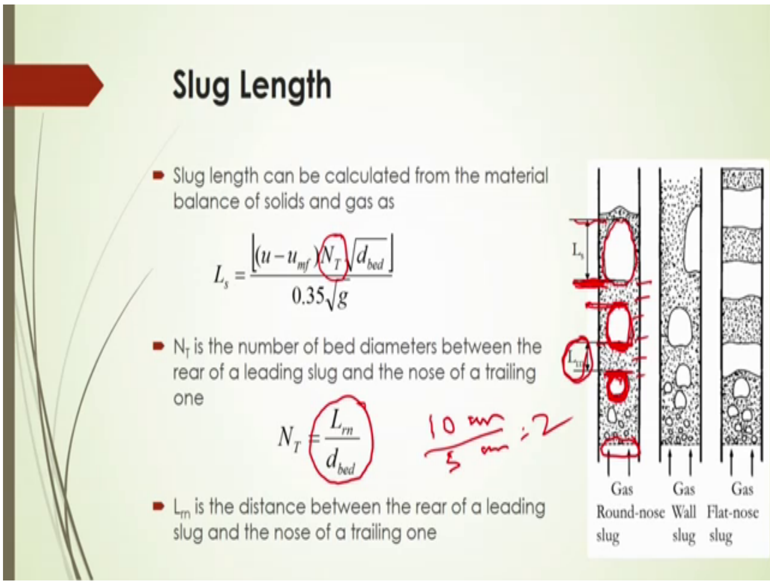

Now, in that case of course, you have to take the snapshot of each slug and what should be the volume what will be the length; what will be the diameter, what will be the cross section everything is to be known and also, how many numbers of the how many how many slugs will be formed and for the distance between the each slug and whether this distance will be some multiplied of that bed diameter or not.

So, based on which you will be able to calculate what should be slug length. If we consider this slug length here as shown in the picture here this will be the this is length this length is the slug length as considered as L S or denoted by L S then this L S should be is equal to u minus u m f into N T into root to the power d bed by 0.35 g.

What is this N T? N T is the number of bed diameters between the rear of a leading slug and the nose of the trailing one. Let us see this two slugs are there; so, this is your trailing portion and this is your nose portion of the trailing slug. So, this is the nose of the trailing slugs this portion and this is the; what is that rear of the leading slide leading slugs.

So, this one leading slug, this one is what is called ma trailing slug. Now this what is the rear? This one what is this? This is called nose, so between this two points what is the distance this is called length that is called you say this that some distance this distance between the rear of leading slugs and the nose of the trailing one, which will be obtained by just taking the snapshot and thus calculate each by analyzes by suitable software.

And this here N T is defined if you know these gap between this two bubbles or slugs that is denoted by L m. Now this L m; that means, here number of bed diameters what should be the number of bed diameters between this rear or leading slug and this? That means, here by this length if we divide; if we if we divide this length by the diameter of the bed then of course, it will be the number of that is called bed diameter number of bed diameter; yes.

So, what will be the length? If suppose this length is suppose 10 centimeter and if your diameter of the bed is suppose 5 centimeter, then what should be the number of beds will be here? This is simple 10 by 5; that is will be is equal to 2.

So, this N T will be equals to 2; so, if you know this N T then only you will be able to calculate what should be the; that is length of the slug. Because this length of the slug that actually depends on the this number of bed, as well as the diameter of the bed; of course, there will be the main factor is the gas velocity.

So, at a certain gas velocity; that means, if you are talking that minimum slug velocity just you have to do; you have to take the snapshot by highest speed camera of those slugs and then you have to calibrate with a certain distance or actual distance; actual length by just by marking on these before taking this snapshot and by scale. From that scale if you take along with that scale of these slug, then you will be able to analyze what should be the actual length of this length between this two slugs and from which you will be able to calculate what will be the slug length.

Even this slug length may not be calculated from this equation you can directly calculate from the; what is that picture what should be the length there. Of course, you will get the different length for different slugs. So, further for uniform calculation or you can get from the mass balance equation at for any slugs what should be the slug length you can calculate from this equation?

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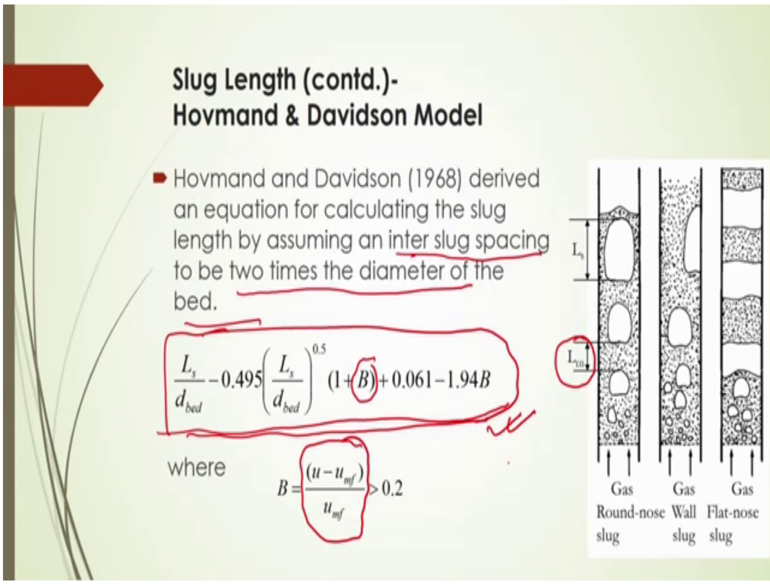

Now, Hovmand and Davidson 1968; they have derived an equation for calculating the slug length by assuming and inter slug spacing to be two times the diameter of the bed. They have taken a straight forward that bed number of beds is equal to 2 here.

In this case, this L S that is slug here slug length by assuming inner inter slug spacing; that means, here between two slugs what will be the distance that is called L m here again this L m that is called in inter slug spacing that is 2 v two times the diameter of the bed. In that case, they have done several experiment and by changing the diameter of the bed and also the fluid velocity and with this different particles. And they came to that observations and formulated one correlation to calculate the slug length which is given as here like this.

So, from this correlation you will be able to calculate what should be the slug length. In this case B is one important parameter that depends on the ratio of the effective fluid velocity to the minimum fluid velocity. And this applicable only if these ratio is greater than 0.2; that means, here u should be is greater than of course, 80 percent of the minimum fluidization velocity.

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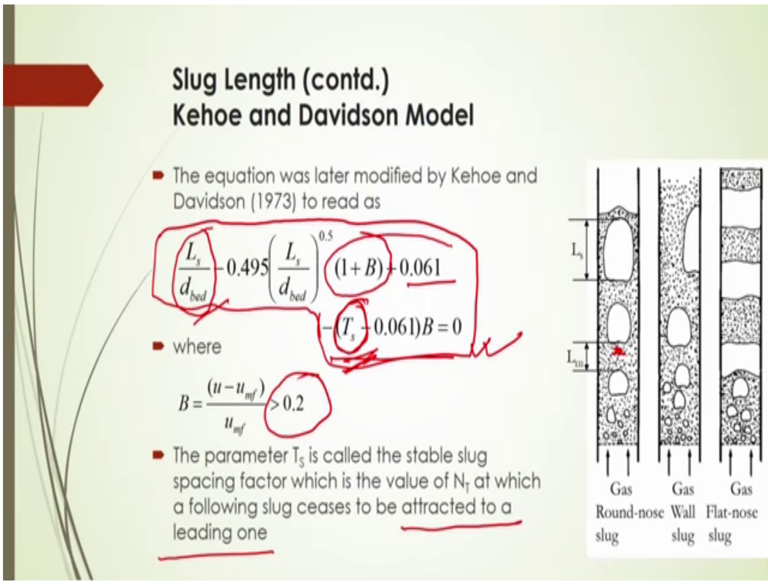

And the equation was later modified by Kehoe and Davidson 1973 to read as here in this case L S by d bed; that means, slug length to the bed diameter ratio minus 0.495 into L S by bed to the power 0.5 and into 1 minus into 1 plus B plus 0.061 minus this T S minus 0.061 into B that will be equals to 0.

So, this correlation from this correlation of course, holding this equation, you have to up in this B value is should be greater than 0.2 from which you can say if this equation satisfied then you will be able to calculate the L S value.

Thus this is the non-linear equation from which you have to solve by just getting the other parameters here. This T S very important point here this parameter T S is called the stable slug spacing factor which is the value of N T of which we already have calculated as follow slug ceases to be attracted to a leading 1 here as per this.

So, here T S will be calculated based on this whether this rear bubble will come to the leading one and forming another one big slugs or not. So, if it is coming very near to each other then this T S value will be very small that case you will see that slug length will be accordingly.

So, this parameter T S is very important point that you have to find out whether this slug will be stable or not.

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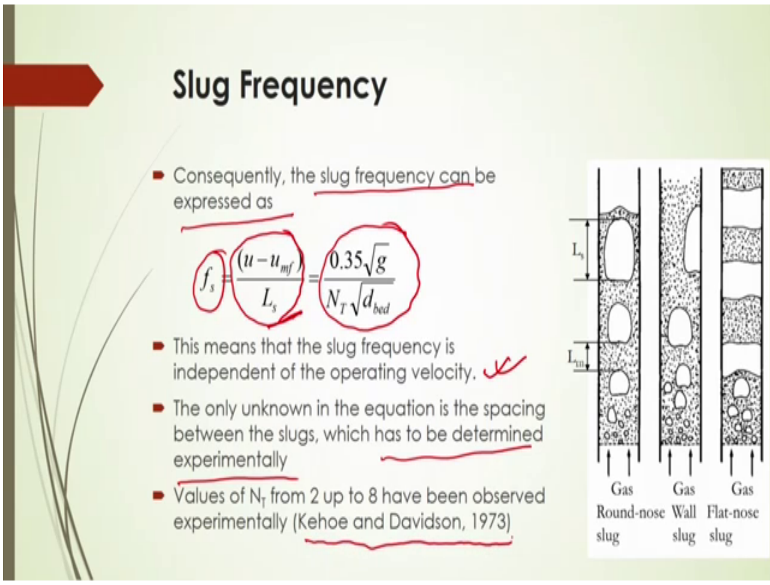

Another important point is that how many slugs will be formed inside the bed for a particular operation of the slugging condition. Now the slug frequency that is can be calculated of (Refer Time: 40:24) is denoted by f s to be calculated in this way that is u minus u m f by L S.

Once you know this L S; that means, slug length; then if you divide it if you divide of this flow rate of fluid by the cross section by this length of the slug, then you will be able to calculate what will be the number of slugs formed here. So, that can be calculated from this equation.

This means that the slug frequency is independent of the operating velocity here very interesting point. And also the only unknown in the equation is the here spacing between the slugs which has to be determined experimentally to know that how many slugs will be formed.

Now, values of N T generally varies from 2 up to 8 and it is observed experimentally by Kehoe and Davidson 1973.

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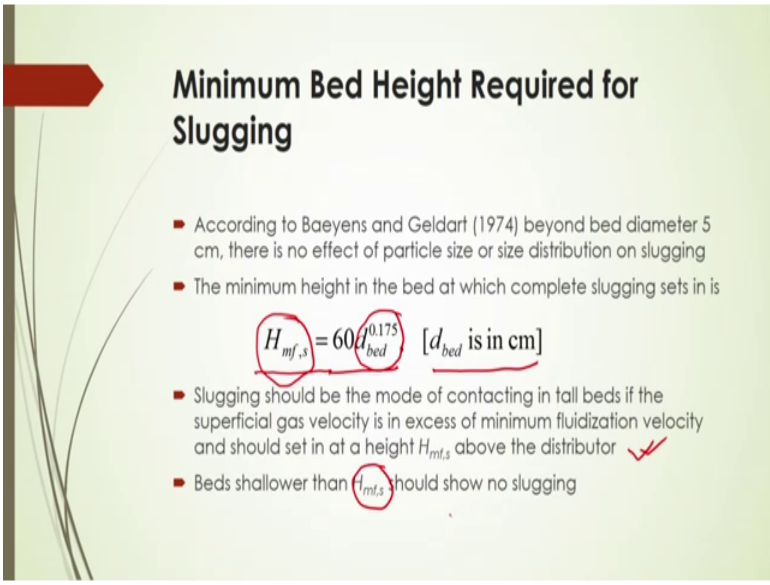

Now, what should be the minimum bed height required for this slugging of course, at any height you cannot get this slugging condition.

According to the Baeyens and Geldart 1974 beyond bed diameter 5 centimeter; there is no effect of particle size or size distribution on slugging. And the minimum height in the bed at which complete slugging sets in is will be is equal to H m f s which is denoted by this and then it will be is equal to 60 times of this is bed diameter to the power 0.17 5 of course, this d bed is in centimeter.

And slugging should be should be the mode of contacting in tall beds if the superficial gas velocity is in excess of minimum fluidization velocity. And that should set in at a height that is called H m f s; above the distributor. Beds shallower then this minimum height should show no slugging.

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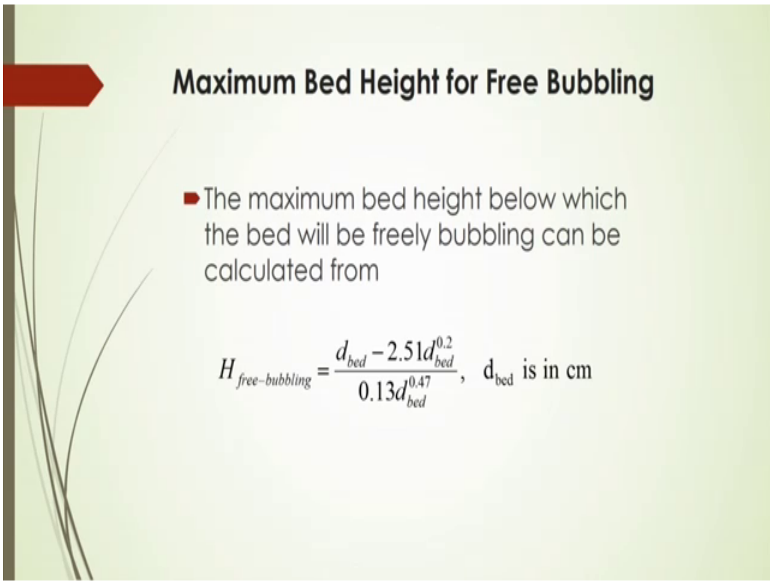

And what should be the maximum bed height? The maximum bed height below which the bed will be freely bubbling can be calculated from this correlations is given here.

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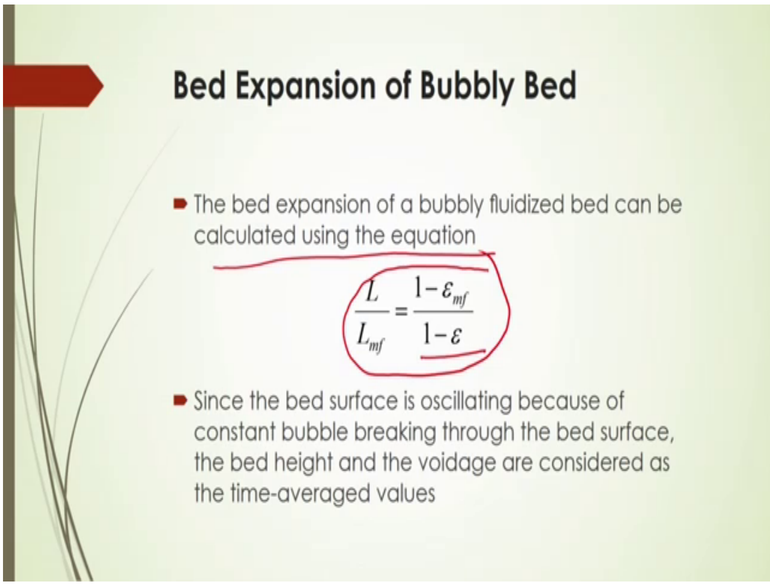

Bed expansion of bubbly bed; here the bed expansion of the bubbly the fluidized bed can be calculated using this equation from the ah; that means, material balance here L by L m f will be is equal to 1 minus epsilon m f by 1 minus epsilon. Since the bed surface is oscillating if any way because of constant bubble breaking through the bed surface, the bed height and the voidage are considered as the time averaged values here; this is very important.

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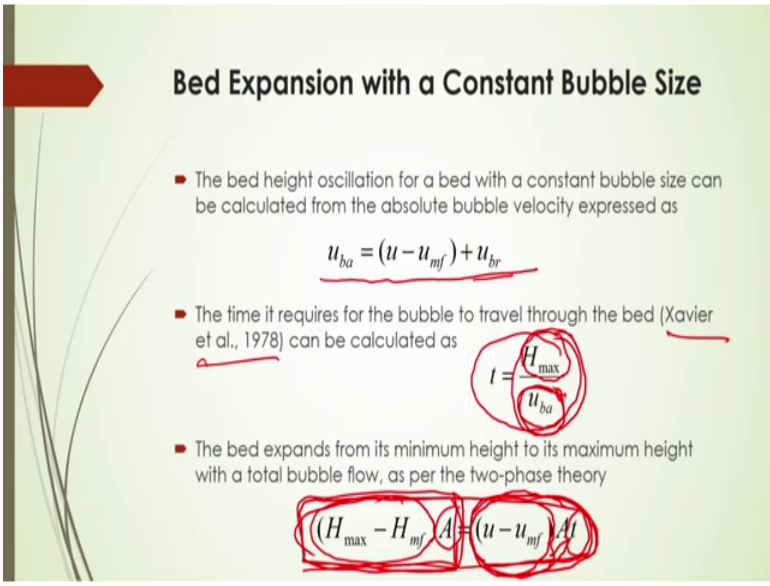

Again the bed expansion with a constant bubble size it is seen that that the bed height oscillation for a bed with a constant bubble size can be calculated from the absolute bubble rise velocity. Here this absolute bubble rise velocity will be is equal to u minus u m f plus u b r. The time it requires the bubble to travel through the bed that is as per Xavier et al 1978 can be calculated as this.

So, what should be the time required to actually travel the total length of the; a fluidized bed if the absolute bubble rise velocity is u b a. So, if we know the maximum height of the bed and if we know the bubble rise velocity then what should be the time average time to be taken to travel or travel that is the whole bed by this bubble.

Now, the bed expands from its minimum height to its maximum height with a total bubble flow; as per the two phase theory you can just get it from the material balance here. If we know that H max minus H m f; this is the effective height of the fluidized media and cross sectional area of the bed A; then what will be the amount of; that means, fluid mixture inside the bed.

What will be the volume of the bed here and what will be the volume of the what will be the volume of the bed here or fluid you can say that u minus u m f into A; this is the velocity and if you multiply it by the that means time requires for travelling, then you will get the total height and then if you multiply it by the cross sectional area; then you will be able to calculate what should be the total amount of fluid inside the bed.

So, from which this material balance you will be able to calculate what will be the maximum height which is required to actually get this slugging phenomenon here.

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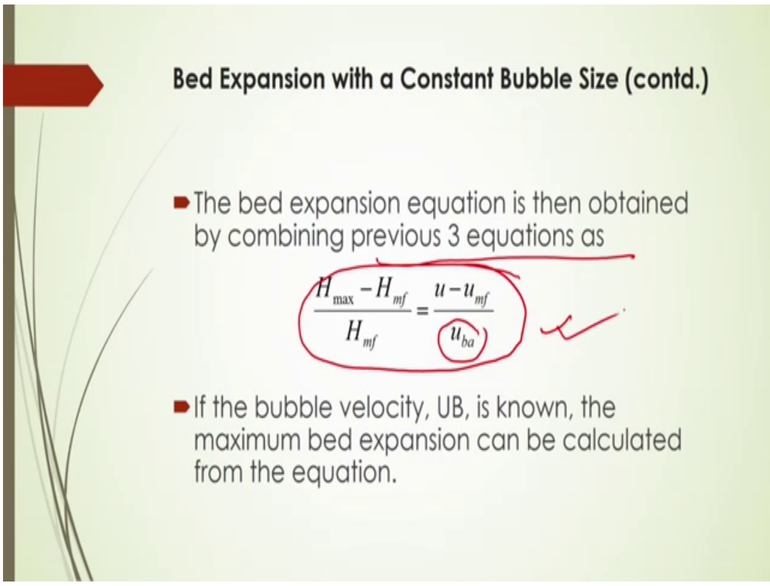

And the bed expansion equation is then obtained by combining previous three equations as this. So, this is the criteria for getting this maximum height of the bed.

If the bubble velocity u b is known; that means, this here u b is know the maximum bed expansion can be easily calculated from this equation.

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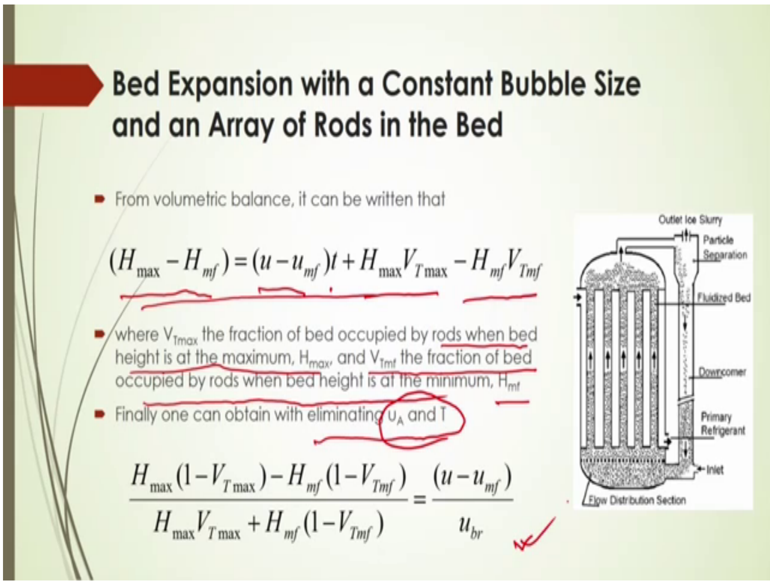

Now, bed expansion of course, it will be changing if you are just disturbed; if you are disturbing this fluid movement inside the bed by means of any mechanical device.

Now, if you suppose insert some or if you make this fluidized bed as a compartment by inserting some mechanical rods or you can say occupied by some rods; if these fluidized bed, then the bubbling velocity or you can say the bubble rise velocity or slugging slug velocity will be disturbing by this rod because of this that wall effect.

Now, from the volumetric balance; it can be written that H max minus H m f that will be is equal to u minus u m f into t plus H max into V T max minus H m f into V T m f; what is that V T? Here of course, this V T max is the fraction of bed occupied by the rods here; how many rods you are just inserting based on which what will be the volume of rods, then what will be the fraction of volume of rod that is inserted inside the bed out of total volume of the bed.

So, the fraction of bed occupied by the rods when bed height is at the maximum H max; and V T m f; the fraction of bed occupied by the rods when bed height is at the minimum that is H m f. So, based on which you will be able to calculate what should be the maximum height of the bed to be required; if you are inserting any rod inside the inside the bed.

Finally, one can obtain with this elimination of u A and T from this you will be able to calculate what should be the H max there.

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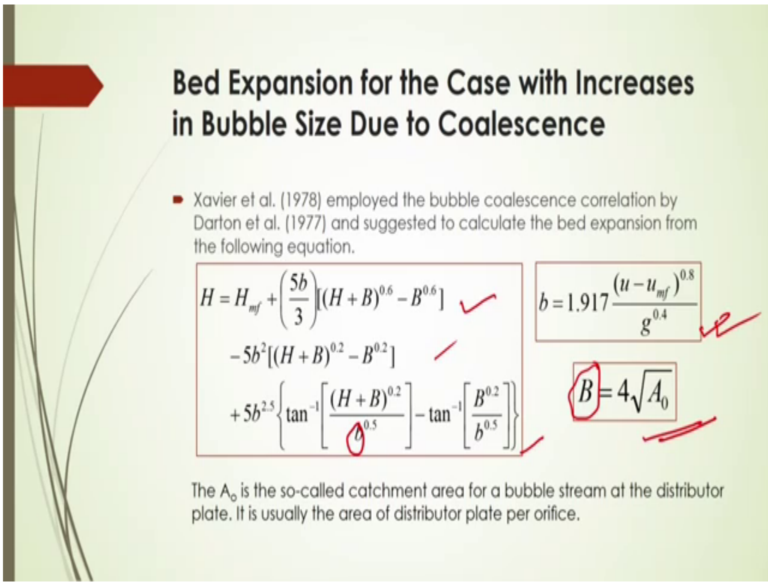

And then bed expansion for the case which increases in bubble size due to the coalescence. If there is a coalescence of bubble inside the bed and then bed expansion of course, will be changing in that case Xavier et al 1978 employed the bubble coalescence correlation by Darton et al 1977 and suggested to calculate the bed expansion from the following equation here.

So, from this equation you will be able to calculate what should be the height of the bed if is there any coalescence of the bubbles happened and formation of the bigger bubbles due to this bubble coalesce. Here important parameter is B; B is the parameter which depends on the gas velocity important and also another important capital B here; this B is a function of A 0; A 0 is called catchment area of the bubble stream at the distributor plate.

What will be the here; that means, bubble catchment area; that means, there bubble will come to each other immediately to get the bigger bubbles there. So, because of which that catchment area already we have discussed in the earlier lecture what should be the catchment area there in the around the distributor plate. And based on which you can calculate what should be the height of the bubbles, height of the bed in the case of increase in bubble size due to the coalesce.

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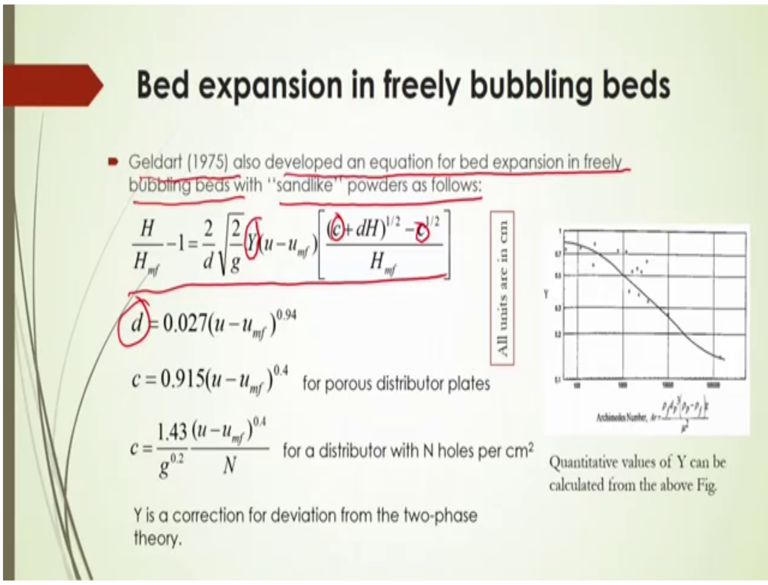

And also bed expansion if there is no coalesce or there is no breakup; that means, called freely bubbling beds in that case Geldart 1975 developed an equation for bed expansion in freely bubbling beds with sandlike powders as follows here like this.

So, from this correlation you will be able to calculate; in this case one important parameter is called Y. This Y depending on the Archimedes number; this it is seen this Y will be decreasing if the Archimedes number is decreases; increases then y will be decreases. So, here again important parameter is called d that depends on the minimum fluidization velocity and also what will be the effective gas velocity or fluid velocity inside the bed.

And some other parameters here like all c; this c will be depending on the how many number of holes in the spa jar or distributor you are just maintaining that how many holes; that means, called distributor holes. And then if you are increasing the number of holes, you will get the less value of c of this parameter. And from which you will be able to calculate what should be the actual height of the bed that is to be maintained for this free bubbling bed to get the bubble characteristics inside the bed.

And then another important that the bed surface of the slugging bed of course, whenever it will be operating; there will be a oscillation of the bubble or you can say media of the bed will be oscillating; that means the surface of the bed will be oscillating. So, in that case maximum or minimum ah; that means, oscillation from which you will be able to calculate what should be the height should be maintained so that you will be getting the less number of oscillation.

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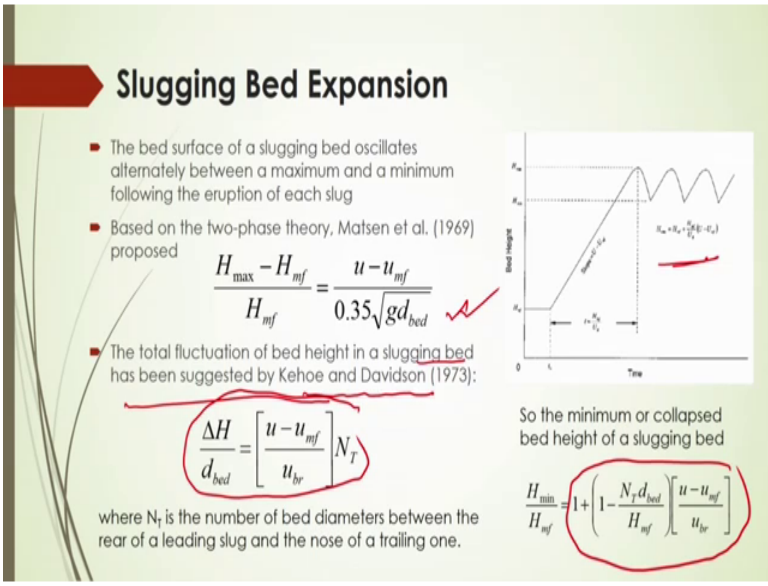

So, based on the two phase theory; Matsen et al 1969 they have proposed this what should be the height of the maximum bed and because of which that there will be a negligible amount of oscillation there. The total fluctuation of the bed height in the slugging bed has been suggested by this Kehoe and Davidson by this equation here. In this case, N T; N T is the number of bed diameters between the rear of a leading slug and the nose of the trailing 1 and because of which there will be a; some oscillation that happens.

So, minimum or collapsed bed height of a slugging bed will be calculated from this equation; if you know the that means N T; N T that is number of bed inside the that is slugging condition of this bubble bed.

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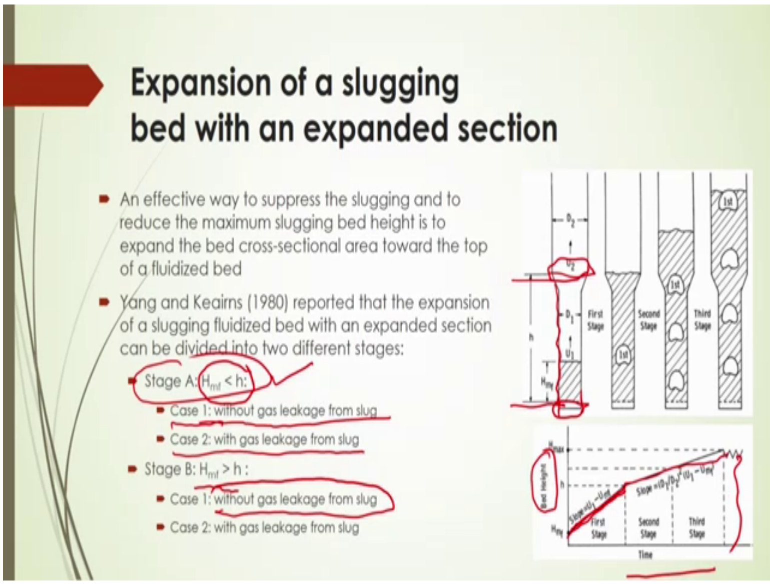

Expansion of the slugging of course, this expansion bed ah; if your slugging fluidized bed is expanding with the certain section then the effective way of suppression of the slugging and to reduce the maximum slugging bed height that can be of course, obtained from this minimum condition of this height.

So, Yang and Keairns 1980 reported that the expansion of a slugging fluidized bed with an expanded section can be divided into two different stages here. See this one is one section of this fluidized and this is the expand expansion section. So, in this case the stage A that H m f minimum height should be is less than h here.

This is the H; H is nothing, but what should be the lower cross sectional portion of the bed. And case 2 that here in this case if H m f is greater than h then what will happen? So, bed height generally you will see for this H m f ah; that means, here first stage; in this case the slope of this will be more stiffer than the second stage here.

So, in the case 1 for each stage the case one without gas leakage from the slug and with gas leakage from slug. So, in this in each stages there will be a phenomenon for slugging; that means, for leakage of gas and without leakage of gas. And from which will be you will be able to calculate bed height with respect to time; how it will be changing based on the rise velocity of the slug there.

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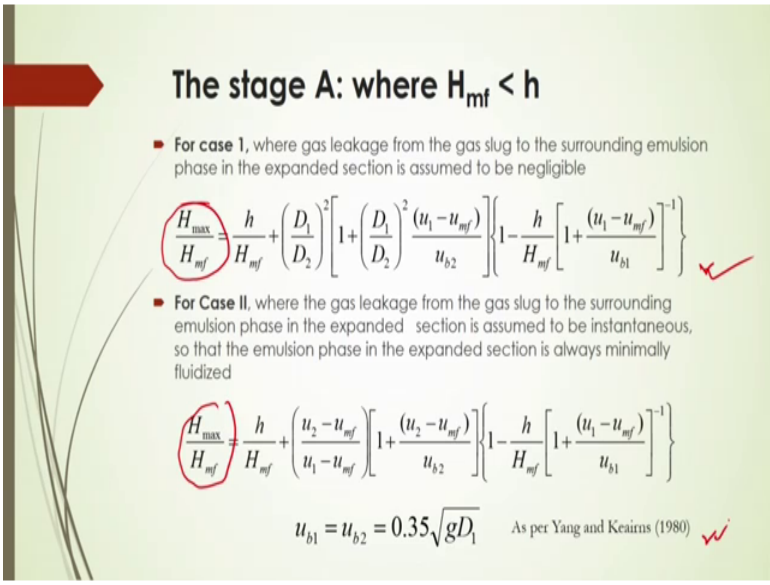

And then this the stage A where H m f is less than h; then you will be able to calculate this H max from this equation that is given in this graph. And also for case 2; that H max also to be calculated from this equation as per Yang and Keairns 1980.

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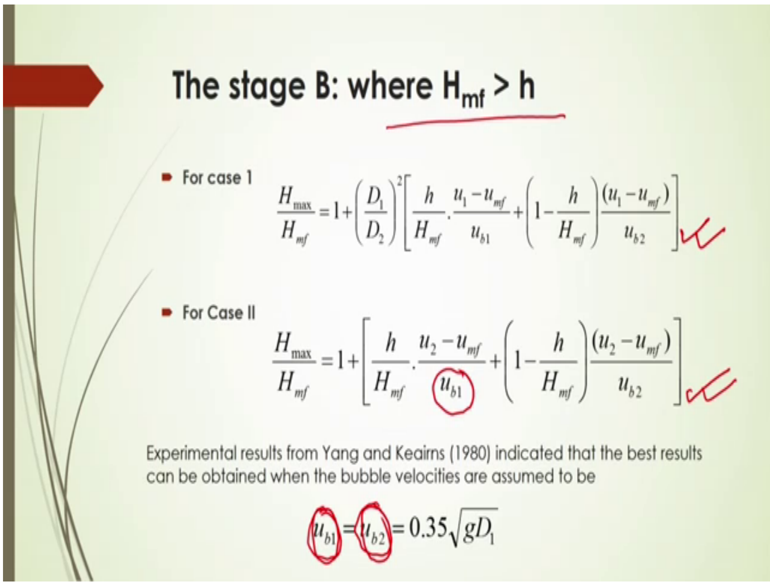

If the stage where H m f is greater than h then you have to use this equation to calculate the H max or; that means, maximum height and for case 2; it will be here.

In this case, you will see that there are two bubble rise velocity u b 1 and u b 2; that means, here the bubble of size of group 1 and bubble of size group 2; there will a velocity of this u b 1 and u b 2. And if you are considering the almost the same size of the bubble or slug; then you have to consider the same velocity and it will be as like this.

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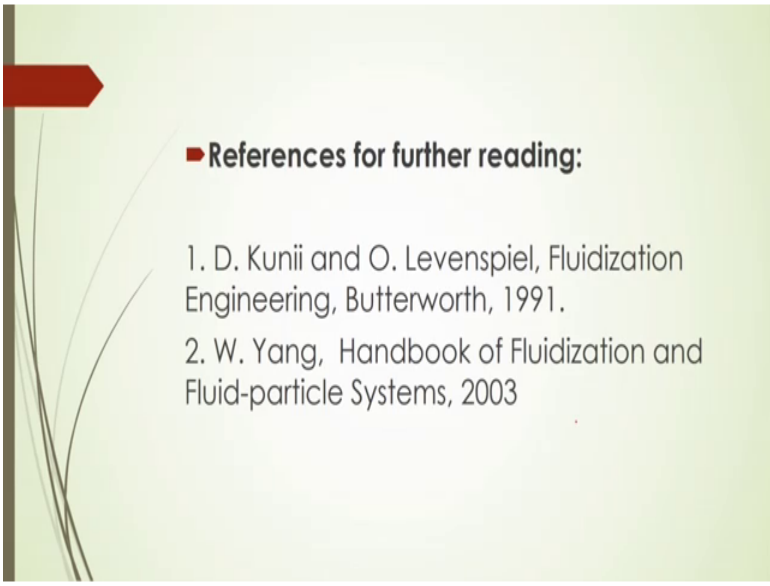

So, further for further reading you can get more information about this slugging condition from this text book. And so, in this lecture we have observed how this bubble is forming and how this bubble will make the slug; if there is a coalesce and then bigger bubbles and bigger bubbles will make the longer one and there are the different shape of that longer bubbles, one will be the nose shape, one will be the elongated, another will be the flat shape.

So, there are three types of slugs we have observed there we have considered. And also those slugs what should be the number of slugs are formed and what should be the rise velocity of the slug that is formed inside the bed. And for each slug condition; is there any disturbance of the slug or not, if is there any disturbance by just inserting rods; then how this absolute slug velocity will reduce or increases that has already been discussed.

And what should be the maximum bed height based on this slug phenomenon that also can be calculated that is suggested by different correlations and we have learned in this lecture. And also and is there any suppose breakup of bubbles or not and if there is no bubble breakup; is there is no parallel ah; that means, disturbance of the bubble, then also what should be the maximum height of the bed that also been discussed here.

So, I think it will be helpful for further that is application of the fluidized bed in this slugging condition and this fluid mechanics of this slugging condition. And next we will discuss more about the other portion of the fluidization engineering like what should be the that means entrainment in the fluidized bed, how bubbles will carry the solid particles and entraining the solid particles.

And then again how this entrain particles will be reentering to the fluidized bed and reuse to the fluidized bed. And also what will be the mechanism of this entrainment and how to predict these entrainment characteristics inside the bed because; because of these entrainment, you will get the segregation of the different sizes particles which is very important to know. And if you are using a different distributed particle size and what will be the effect on mass transparent and heat transfer that is important here.

So, entrainment characteristics will be discussed in the next class and subsequently more about that fluidization engineering.

Thank you.