Fluidization Engineering
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Lecture – 13
Bubbling Fluidization Part 1: Bubbling Characterization

Welcome to massive open online course on Fluidization Engineering. So, in this lecture bubbling fluidization and bubble characteristics will be discussed. Now, what should be actually learnt in this bubbling fluidized bed?

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Now, you have to know that what are the basic characteristic features of bubbling fluidized bed? How bubbles are formed? What is maximum shape or size of the bubble? And how to estimate the bubble size? How bubble rise velocity is related to the bubble size or fluidized bed diameter? Is there any model to represent the bubble size or not? How bubbles are interacting to each other during the interaction?

How coalescence or breakup of the bubbles happen inside the fluidized bed? How slug is formed? And what are the characteristics feature of the slugging phenomena inside the slugging fluidized bed? How does this entrainment of particle happen in bubbling fluidized bed how bubble size effect the mixing of phases in the bed even more will be discussing in successive lectures in this fluidized bed operation.

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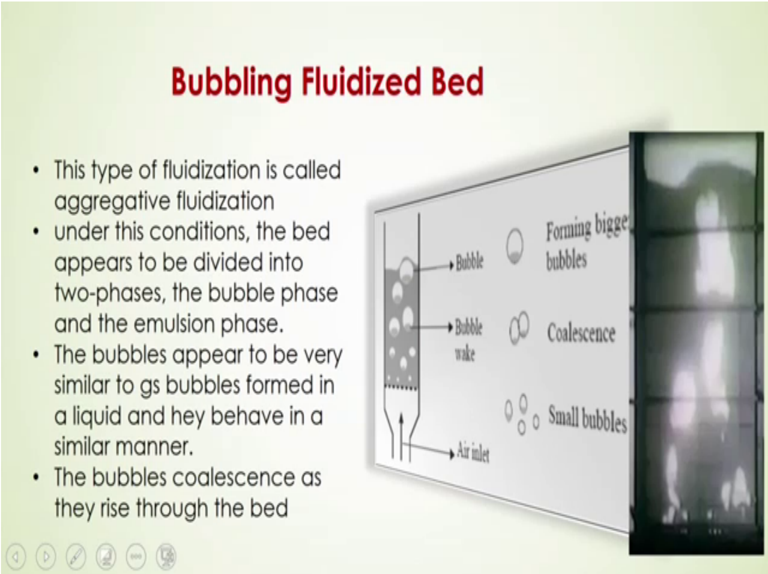

Now, what is bubbling fluidized bed? What is that fluidized bed? Already we have discussed in earlier lecture that how bubbles are forming inside the fluidized bed and what will be the characteristics of the bubbling fluidized bed.

Now, this type of fluidized bed you will see aggregation of the phases will be happened and because of which there will be a gap between solid particles and formation of bubble is during the distribution of gas through the distributor. Now, under this aggregative fluidized bed or bubbling fluidized bed condition the bed appears to be divided into two phases, the bubble phase and the emulsion phase. The bubbles appears to be various similar to gas bubbles which is formed in a liquid or they behave in a similar manner in the fluidized bed; the bubbles coalescence of breakup as they rise through the bed that depends on the different operating conditions.

Now, here see in this figure this bubbling fluidized bed here you will see the video from the distributor how would see this is the distributor from this distributor how gas is how gas is distributed from the bottom through the distributor and near this distributor the size of the bubbles is very smaller. Whereas, whenever it will be going up then due to this coalescence or interaction of the bubbles some bubbles are becoming bigger bubbles and also some bigger bubbles again may be breaking into two parts and again it may coalescence and forms at the bigger bubbles. And this bigger bubbles you will see going upward on the higher flowrate or higher velocity because of their size and higher size of this bubbles will have more rise velocity and because of which it will go very fast and at the top it will be dissolved and it will be separated from this raw solid.

So, these are the phenomena bubbling fluidized bed here in this case you will see in this bubbling fluidized bed some bubbles are there and this bubbles are form in such way that it will have some wake at this bottom part of this bubble this is called bubble wake and then this bubbles are at this top the size of this bubbles will be maximum. And the smaller bubbles will have inside the near this distributor and at middle section there is a probability of coalescence of this two or more bubbles whenever come into each other and interact and because of some mechanism of the coalescence that will be discussed later on that because of that mechanisms the bubbles will coalescence to each other and will go off. So, this is this phenomena.

So, if this type of phenomena is called aggregative fluidization phenomena. So, at this condition of course, it can divide this fluidized bed into two part, one is called bubbling phase another is called emulsion phase where only solid and gas will be there without formation of bubbles. And of course, this bubbles whatever it is forming you are you see this will be forming as like whenever gas is distributed through the liquid as like that formation of bubbles in the liquid how this bubbles is formed.

Here also in this gas solid operations the bubbling fluidized bed will be occurred, and here also the same nature of the bubbles will form and you will see the bubbles will grow up, bubbles will breakup, bubbles will move at a certain rise velocity and it will have some size. So, all this characteristics as per this gas is distributed in the liquid also.

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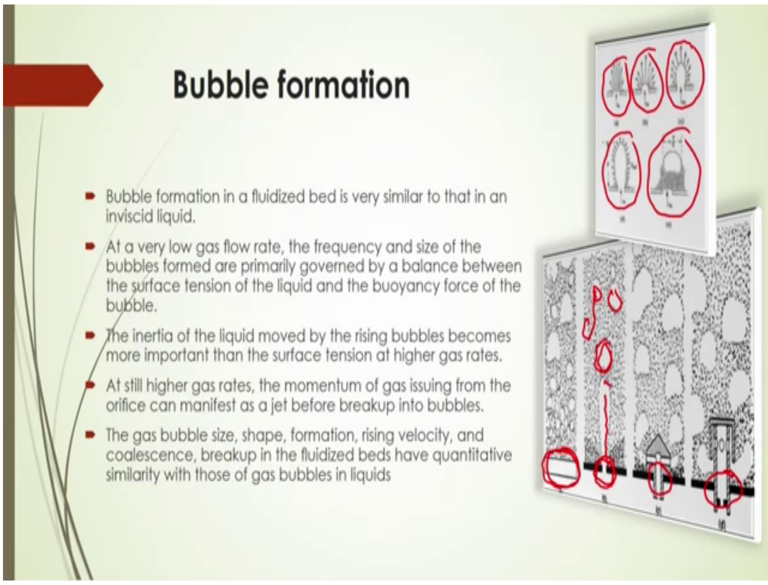

And you will see how then bubble is a formed inside this bubbling fluidized bed here see. The bubble formation in fluidized bed is very similar to that in an inviscid liquid of course, at a very low gas flow rate the frequency and size of the bubble formed primarily governed by the balance between the surface tension of the liquid are here in this case emulsion and the buoyancy force of the bubble.

The inertia of the liquid that moved by the rising bubbles becomes more important than the surface tension at higher gas flow rates. At still higher gas rates you will see the momentum of gas issuing from the orifice or distributor can we can manifest as a jet before breakup into bubbles. Here you will see this case here from this distributor the bubbles are distributed how it will be distributed whereas, from a certain type of distributor or the gas is manifested as a jet here before breakup into its bubbles here. So, this jet into breakup into bubbles and then it will be going up like this.

So, the gas bubble size and the shape and the formation rising velocity and coalescence breakup in the fluidized bed have quantitative similar with those of gas bubbles in liquid. And that depends on this type of distributor and the energy of distribution and also what the distributor pressure and what will be the system that is being used here for gas solid what will be the gas is being used if density of the gas is there higher or lower of course, that may change this size of the bubbles coalescence efficiency and the breakup efficiency collation between bubbles will be changed here.

And of course, in the case of gas liquid solid that is slightly bubble color reactor in that case the formation of gas and also the coalescence and breakup that depends on the physical properties of the liquid, and the particle type size of the particles all this factors that govern this bubble characteristic interaction of the bubble. And the efficiency of the formation of the bubble size with its particular shape. And here see the, from the jet how gas is distributed as a jet here, here in this figure it is seen that how bubbles is dispersing from the jet through the distributor.

So, bubble formation in the fluidized bed is very similar to that in inviscid liquid of course, you will see the inertia of the liquid moved by the rising bubbles becomes more important here than the surface tension of the higher gas flow rate, at higher gas flow rate and also this size of this bubbles depends on the different operating conditions.

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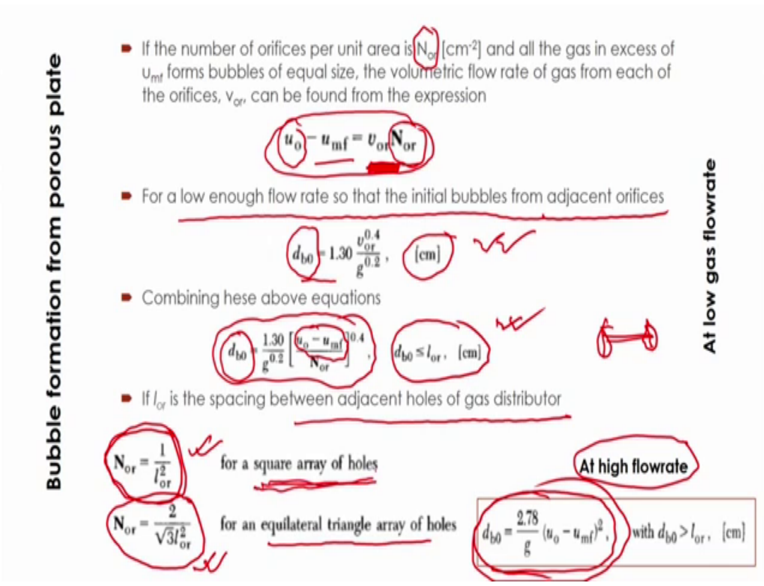

Now, you will see if I consider that bubble formation from a porous plate in this case if the number of orifices in the porous plate per unit area is considered as N or, the N or that is in 1 per centimeter square. And all the gas in excess of minimum fluidization velocity forms bubbles of equal size the volumetric flow rate of gas from each of the orifices if it is v c r then there will all these quantity will be inter related to each other by this equation here where this u 0 will be is equal to u mf, that u 0 will be is equal to u mf plus v or into N or, where u 0 is the gas velocity at which the gas is passing though distributor and u mf is the minimum fluidization velocity, and v or is the volumetric flow rate of gas from each of the orifices and N or is the number of orifice holes per unit area.

So, for a low enough flow rate so that the initial bubbles from adjacent orifice that can be obtained as what should be the initial bubble diameter if we know that volumetric flow rate of the gas through this orifice as v or, then initial bubble diameter can be calculated as 1.30 into v or to the power 0.4 divided by gravitational acceleration to this 0.2 power. So, this will be in centimeter. So, by this equation you will be having what should be the initial bubble diameter that is being formed from this orifice hole of the porous plate distributor. So, in this case you have to know only what should be the volumetric flow rate of the gas. If suppose volumetric flow rate is suppose 10 meter cube per second you substitute here you will get the initial approximate initial bubble size that is coming out from the porous plate.

Now, combining these two equations you will get this d bo you will be equals to 1.30 by g to the power 0.2 here you just substitute to the value of v 0 here, v or; that means, the volumetric flow rate to the orifice and here then you just here v 0 minus u 0 minus u mf by N or. This u 0 minus u mf is nothing, but the effective gas velocity inside the fluidized bed. Now, if you divide this effective velocity by number of orifice hole and then from this relation you will get the initial bubble diameter and this is applicable only if l or repeats a space this is l or is the orifice; that means, whole space or you can say that here this piece; that means, the space between 2 holes, space between 2 holes if it is l or them d bo if it is less than l or then only you can use this equation for calculating the initial bubble size.

If l or is the spacing between adjacent holes of this gas distributor and in this case this greater if d bo is greater than l or then you can calculate this d bo initial bubble size will be is equal to 2.78 by g into u 0 minus u mf to the power 2 at high flow rate of the gas. Whereas, this if this holes or orifice holes be arranged or designed in the porous plate in such way that there are two types of actually arrangement of this hole in the porous plate that is the square array of holes and equilateral triangle array of holes.

For square array of holes generally if you know the space between two wholes as l or then what should be the number of orifice holes per unit area that will be inversely proportional to the square of the space of the adjacent holes so that will be calculated as

N or will be equals to 1 by l or square. Whereas, if this porous plate is arranged of this orifice hole as a equilateral triangle array of holes then this number of orifice holes per unit area will be is equal to 2 by root over 3 into l or square. So, from this relationship you will be able to calculate if this orifice plate is arranged with different types of holes.

So, combining this above equations this d b0 that is initial bubble diameter and this gas velocity will be able to calculate what should be the initial bubble diameter or at if initial bubble diameter is less than space between adjacent holes of gas distributor. This space between adjacent holes of gas distributor is represented by l or, if l or is less than dB initial bubble diameter then initial bubble diameter to be calculated from this equation of 2.78 by g into u 0 minus u mf square.

Now, this number of holes per unit area will be calculated if you know this space between 2 adjacent holes. Now, this number of holes in the orifice plate per unit area is inversely proportional to the square of this orifice, orifice space, orifice hole space as l or. So, it will be N or will be equals to 1 by l or square and for square array of holes and for equilateral triangle array of holes this N or will be equal to 2 by root over 3 into l or square.

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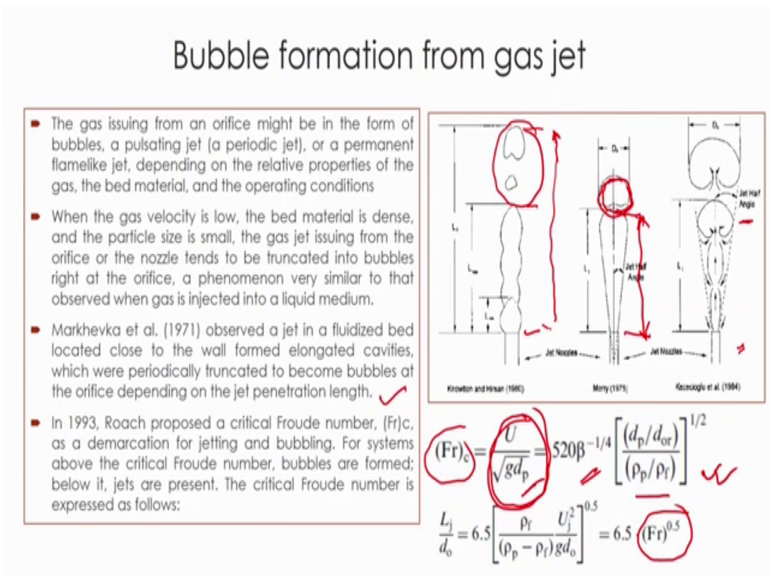

Now, how this bubble is formed from the gas jet let us see. The gas issuing from an orifice might be in the form of bubbles as a pulsating jets or periodic jet, or you can say a permanent flame like jet will be formed depending on the relative properties of the gas and also the bed material and the operating conditions.

When the gas velocity is low the bed material it is refer to as dense and the particle size is small whereas, the gas jet issuing from the orifice or the nozzle is considered to be a truncated into bubbles right at the surface. And this phenomena is very similar to that observed when gas is injected into a liquid medium and of course, a jet in a fluidized bed that is located close to the wall that formed elongated cavities which were periodically truncated to become bubbles, become bubbles at the orifice depending on the jet penetration length. And it is that this mechanism is given by Markhevka et al 1971.

In 1993 roach proposed a critical Froude number as a demarcation for jetting and bubbling. For system above this critical Froude number bubbles are formed below it jets are present, and the critical Froude number is expressed as flows here this critical Froude number is defined as U by root over gd p, U is the gas velocity or fluid velocity and g is gravitational acceleration d p is the particle diameter. And it is a function of this orifice hole diameter and this particle density and this fluid density and of course, some other factor like a beta here one characteristic factor that will governed this Froude number at this critical condition.

Generally beta is considered as one for this jetting formation and formation of bubbles from the jet here. So, critical Froude number is equal to 520 to beta to the power minus 1 by 4 and d p by d or by rho p by rho f that is ratio of the particle density to the fluid density to the power half. Here this, this you will see that of course, this bubble formation that depends on this penetration length for the jet that already we have discussed in earlier lectures how to calculate the penetration length. This penetration length depends on the different operating conditions like density of the fluid, like density of the particle, and also the orifice hole diameter, and the jet velocity.

Now, if jet velocity increased you will see the penetration length will increase whereas, if jet hole diameter is decreased then you will of course, you will see the length of the penetration also will increase. Whereas, if you increase the fluid density there is a possibility to increase the jet penetration length and also this (Refer Time: 21:38) jet penetration length also you can represent as a function of Froude number. It is seen that this penetration length depends is directly proportional to the square root of the Froude number this Froude number is defined as U by root over gd p.

Now, what is that penetration length? You have seen this figure different of course, the investigator they have given different aspects of this penetration jet penetration here. In this you will see this what should be that penetration length here this L j here, this is this jet from what is this these to this length is the penetration length. And then here up to this you will see there will be another this critical penetration length is the from which you can get that at this condition you will see that there will be a formation of bubbles just by breaking with jet by if there is critical Froude number obtained from this correlation.

And here again here this L j this is this, this length to this length it is defined as that critical jet length or you can say jet penetration length and after that based on this critical length at a particular condition of the gas velocity you will see there will be tendency to breakup this jet into a bubble. So, at this condition will be the critical Froude number at which this jet will be breaking into bubble.

Here again this see due to this pressure difference at the different location of this jet then you will see there will be a vibration or some other means by applying external course there will be a permission of bubble by breaking this jet in this case there will be another mechanism that is given by this Kececioglu et al here. So, in this case the again this critical Froude number will give you the condition for the bubble breakup.

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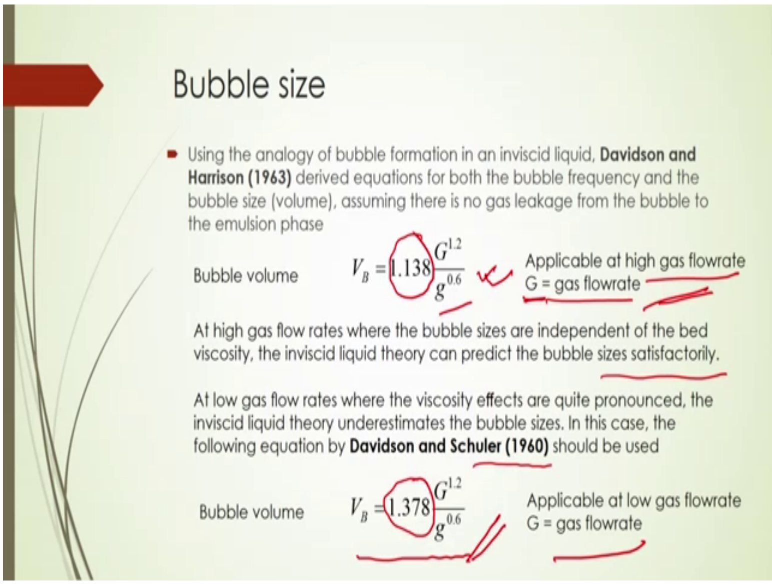

Now, what is this bubble size here? Using this analogous of bubble formation in an inviscid liquid Davidson and Harrison, 1963, derived equations for both the bubble frequency and the bubble size or you can say represented as volume here assuming there is no gas leakage from the bubble to emulsion phase.

So, according to them the bubble volume can be calculated from the, from the gas flow rate. If gas flow rate is represented by G and at high gas flow rate G then you can calculate what should be the volume of bubble that is formed from this distributor by breaking up this jet here that V B can be calculated as 1.138 into G to the power 1.2 by small g that is gravitational acceleration to the power 0.6. So, from this equation you will be able to watching the volume of gas bubble is formed.

At high gas flow rates where the bubble size are independent of the bed viscosity the inviscid liquid theory can predict the bubble sizes satisfactorily. At low gas flow rates where the viscosity effects are quite pronounced to the inviscid liquid theory underestimates the bubble size. In this case the following equation that is given by Davidson and Schuler 1960, 1960 that is V B will be is equal to 1.378 into G to the power 1.2 by g to the power 0.6.

Here only difference this 1.378 instead to 1.138 this will underestimate this bubble size as compared to this Davidson and Harrison model. So, this is actually, this is applicable for low gas flow rate whereas, this Davidson and Harrison model is applicable for high gas flow rate. So, at high gas flow rate to be bigger size bubbles compare to this lower gas flow rate.

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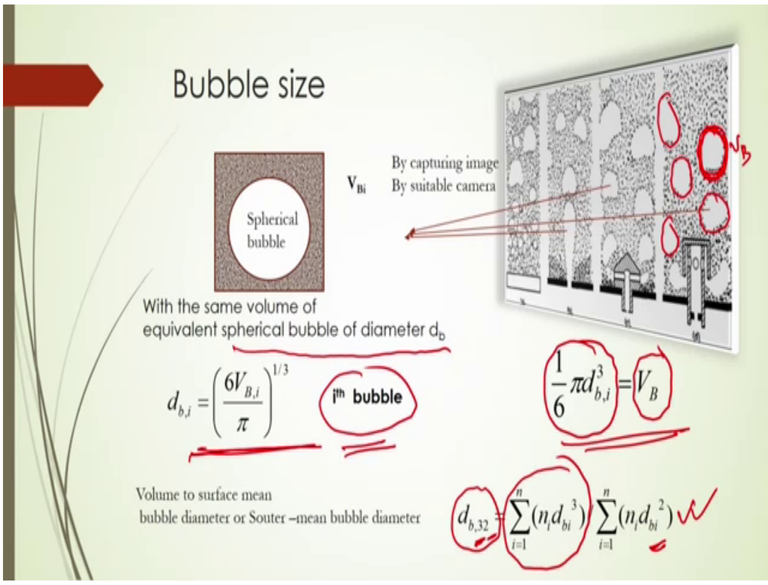

Now, question is that if we distribute the gas inside the bed then there are n number of bubbles forms inside the bed. Now, what should be the size of individual bubbles that how to calculate, how to estimate the individual bubble inside the bed? So, this is very important here to know because from this distributor whatever size of this bubbles are coming out that may not be the exact same in the middle or in the top sections. So, with respect to time because of the coalescence and breakup this bubbles will bubble size will change with respect to time also.

So, at any time instant you will see how to actually estimate the bubble size if there are n number of bubbles then nth number of bubbles how to calculate here. Now, one important thing is that that bubbles whatever formed it may not be the spherical, there may different shape of bubbles will be there sometimes it will be cap shape. Sometime it will elongated, sometimes it will be the shape like that the what is that bullet shape. So, there are different shape bubbles may form in that.

So, how to actually obtain? If we suppose take any snap shot by high speed camera and if we analyze this snap shot of this bubbles, snap shot of this bubbles in this figure if we calculate, if we measure the size or volume of this bubbles after taking the snap shot individual of this bubbles and then what should be the bubble diameter. Now, if there is not uniform spherical bubbles then you have to consider what should be the equivalent bubble diameter also will be there in the bed.

Now, what should be the; if suppose if I consider this bubbles this bubbles is not exactly the spherical in nature, but we can calculate what should be the perimeter of this bubbles. If we know the perimeter of this bubbles then what should be the length, what should be the if we consider it as a spherical bubble the, what should be the diameter that that is one type of equivalent diameter of this bubble.

If we know this volume of this bubbles and if we consider this bubbles as a spherical bubble, if we consider the spherical bubble as diameter is the dB then the volume of the bubbles with this equivalent bubble diameter is 1 by 6 phi dB phi cube and if we equalize this bubble volume of this V B, V B then from this relationship we can calculate what should be the bubble diameter by considering the same volume of equivalent spherical bubble of diameter d b.

So, by capturing image and by suitable camera we can obtain this bubble and then analyze this bubble by suitable software like image software some other software also can be used to calculate this bubble size. So, here the bubble size equivalent bubble size can be calculated if you know the volume of this bubbles and this ith bubbles will be calculated here. Now, there are n number of bubbles then what should be the average diameter or mean diameter of this bubbles this mean diameter of this bubbles in n number of bubbles environment then what will happen the sauter in bubble diameter is suitable to calculate this mean diameter.

Now, we have already discussed in the earlier lecture how to calculate the mean particle size based on that also here you can calculate the mean bubble size here. Now, volume to surface mean bubble diameter it is represented as sauter mean bubble diameter which is defined as d b 32, 32 means 3 means volume here two for surface area here. In that case this will be defined as summation of d bi cube of this n number of bubbles and if it is divided by the summation of n number of bubble surface area then you will be able to calculate what should be the sauter mean bubble diameter from this equation.

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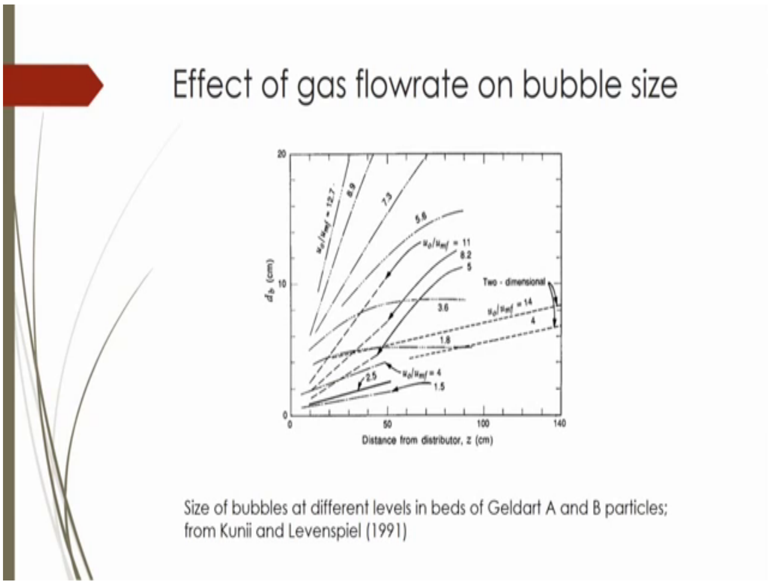

Now, effect of gas flowrate of this bubble size you will see there of course, the size of this bubbles average or mean size of this bubble will change with respect to oh the distance of the bed. At this bottom of the fluidized bed where the gas is distributed; that means, at the distributor regime you will see size of the bubbles will be very small whereas, at this successive height of this bed at the middle section; if you are considering there will be different size there is little bit higher even at the top to be more higher because of the continuous coalescence breakup, breakup of this bubbles you will see there will be effective bubble diameter will change along the axes of the bed.

Also this bubble size depends on the velocity of the fluid here as a gas if you are considering that you will see that if gas velocity increased the bubble size will also increase. At this here also bubble sizes because this collation efficiency will increase because of the increase of gas velocity. So, size of the bubbles at different levels in the bed will be different of course, and also it depends on the gas velocity. If you change the profit properties also you will see there will be change of bubble size there.

So, here Kunii and Levenspiel they have represented this bubble size that is change with distance from the distributor z with Geldart A and Geldart B type particles and it is seen that along the excess that is if z is increased the bubble size will increase and also if the gas velocity increase the bubble size also increased.

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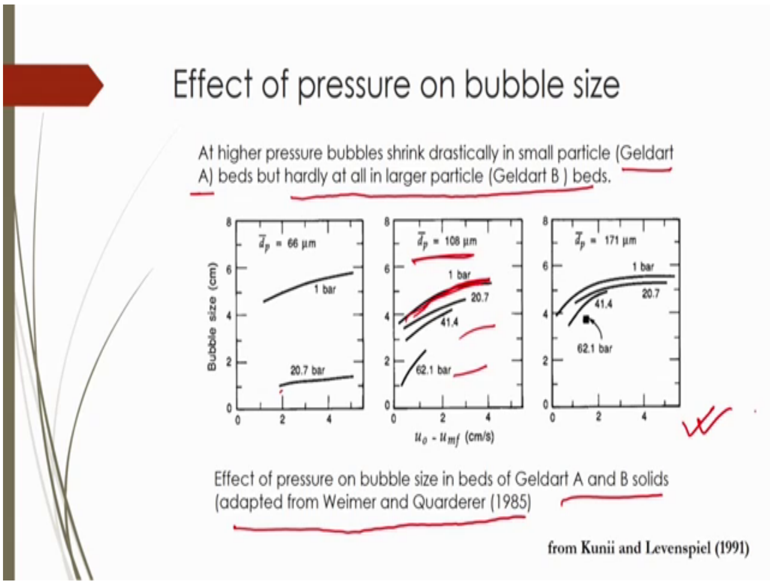

Effect of pressure on bubbles size that is very important point here; at seen that at higher pressure bubbles shrink drastically in small particles and as an example like Geldart A particles, but hardly at all in larger particle beds. So, in this case higher pressure gives the sinkage of the bubbles. So, effect of pressure on bubbles size beds of Geldart A and Geldart B solids adapted from this Weimer and Quarderer 1985, it is seen that at higher pressure the bubble size is reduced here. The bubble size at this 20.7, at this 20.7 bar is smaller than one bar at a certain gas flowrate here.

And again here in this case you will see that for particle diameter if it is increased, this bubble size also bubble size also change at different pressure. At higher pressure again it is seen that if you increase the particle diameter the bubble size will reduced as the pressure inside the bed is increased. So, we can say that that higher pressure bubble size will reduce.

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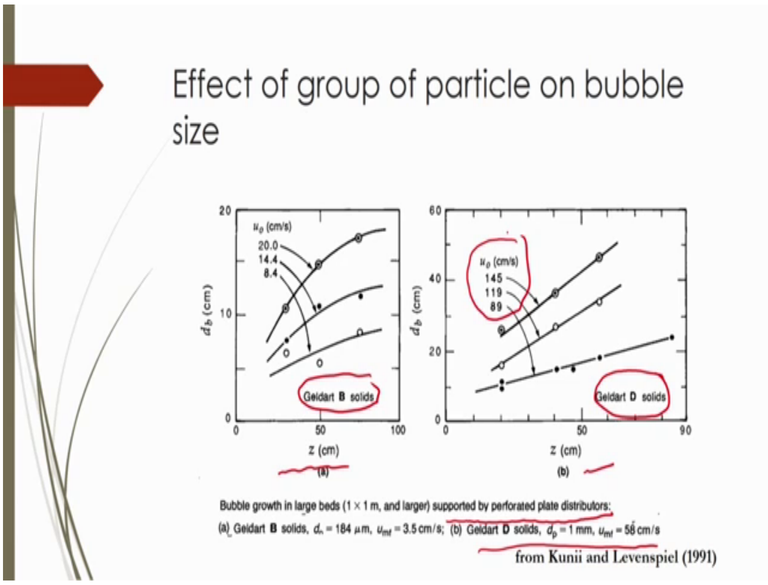

Also effect of group of particle on bubble size you will see that at different type, at different type of particles you will see if we will do the experiment to with different type of particles Geldart B or Geldart D particles you will see there will be change of particle diameter. And here bubble growth in large bed you will see supported by perforated plate distributor like here in this case for this condition you will see that how the bubble size is changing with respect to height of the bed at different type of, at different type of solids here and also at different gas flowrate.

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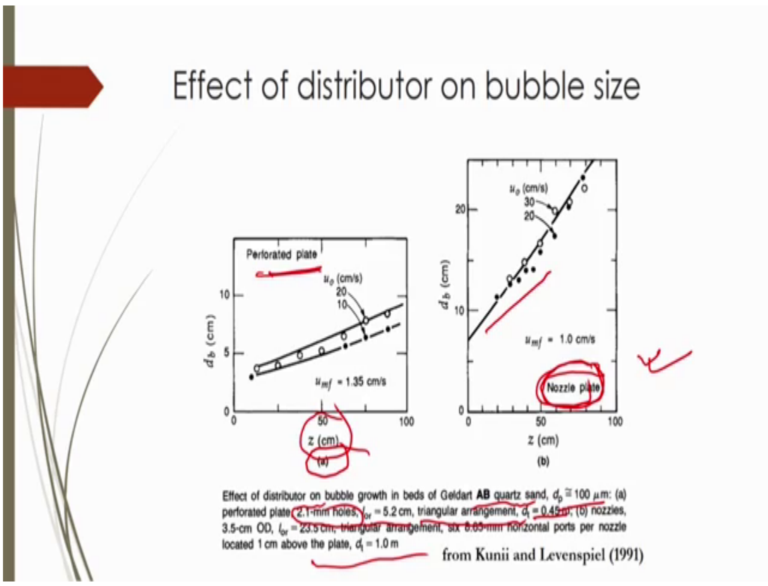

Now, the distributor also has a key role for such distribution of the bubble here. At particular jet you will see if we use the perforated plate and if we use the nozzle plate there will be drastical change of this bubble diameter. You will see, you will see that bubble diameter will be smaller in case of perforated plate whereas, in jet type distributor or nozzle type distributor the bubble size would be higher related to this perforated plate.

The effect of distributor on bubble growth in beds of Geldart AB quartz here in this case mixed particles size tends this here d p at 100 micrometer in this, in this figure it is for the perforated plate and where the hole is 2.1 millimeter in diameter and space is 5.2 centimeter for triangular arrangement and the bed diameter 0.4 5 meter. Whereas, in this case it is this diameter is given here in this case. So, this has taken from Kunii and Levenspiel; and so what we observed that if we change the distributor you will get different sizes bubbles.

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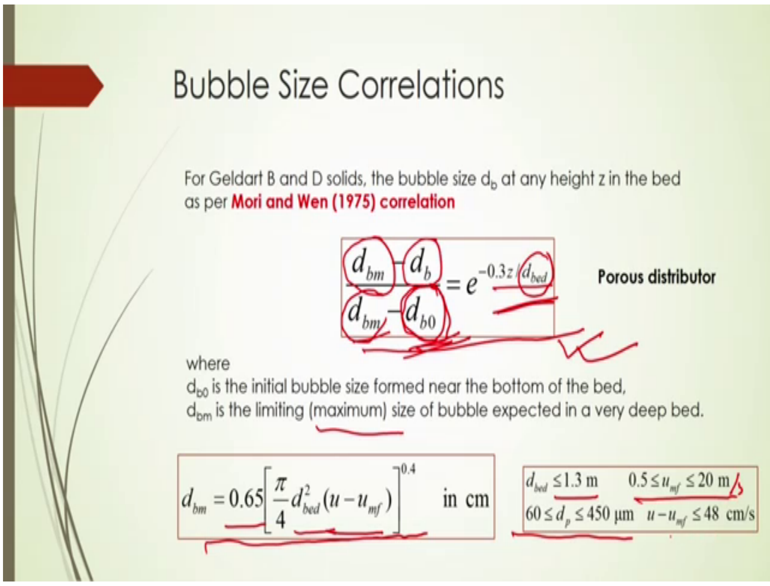

Now, to represent the bubble size or estimate or you can say predict the bubble size what should be the, actually how to estimate this bubble size. So, here Mori and Wen 1975 they have proposed one standard correlations to predict the bubble size which is depending on the axes of the bed from the distributor.

Now, for the porous plate they have developed this correlations from their experimental results by doing the experiment with Geldart B and D solids and they have proposed this correlation as d b a minus d by d bm minus d b0 will be is equal to e to the power minus

0.3 z by d bed. What is this d bm? d bm is nothing, but the maximum bubble size and or you can say limiting bubble size and d b is the bubble size or bubble diameter at particular height of the fluidized bed from the distributor. And this d b0 is the initial bubble diameter that is formed from the distributor.

This d bed is the bed diameter. So, from this correlation for the porous distributor you can obtain what should be the bubble diameter a particular location of the fluidized bed. And this d bm is the limiting bubble size or you can say sometime it is called maximum bubble size that is expected in very deep bed that will be that will be depending on the bubble diameter and the effective gas velocity or if you say relative gas velocity compare to the minimum fluidization velocity.

So, this will be is equal to 0.6 5 into pi by 4 d bed square into u minus u mf to the power 0.4. So, from this correlation you can obtain the d bm. So, once you substitute this d bm here and also d b0 already we have shown earlier how to calculate this initial bubble diameter and if you substitute this initial bubble diameter and this maximum bubble diameter here then you will be able to calculate what should be the bubble size at particular location.

Now, this correlations of course, is valid only for if bubble, if the fluidized bed diameter is less than 1.3 meter and the minimum fluidization velocity is in with the is with the 0.5 to 20 meter per second and the particle diameter is within the range of 60 to 450 micrometer. And of course, the relative velocity of the gas to be less than 48 centimeter per second then only this correlations to be valid to predict the bubble size at a particular height of the fluidized bed.

Now, bubble size correlations of course, different correlations developed by different investigators from their experimental data.

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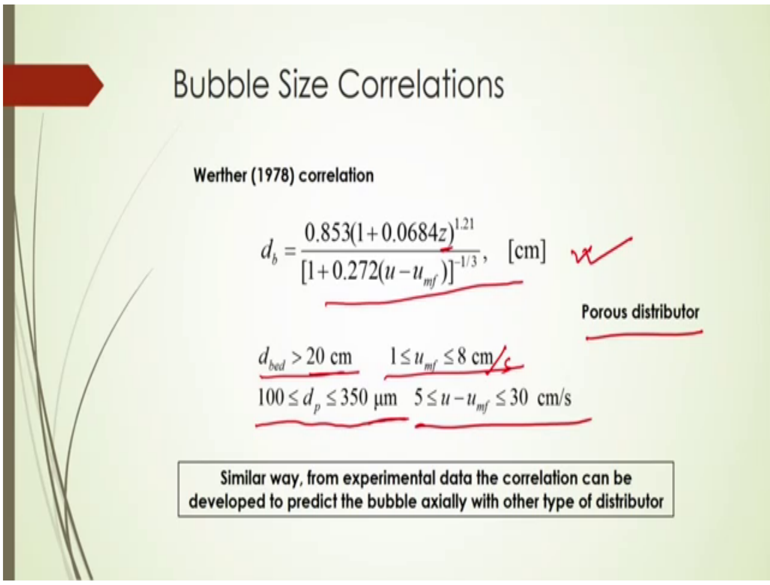

So, another correlations are 1978 Werther he has developed another correlations to predict the bubble size here for the porous distributor as d b is equal to 0.853 into 1 plus 0.0684 z to the power 1.21 by 1 plus 0.272 into u minus u mf to the power 1 by 3. From this correlations again you can calculate what should be the bubble diameter at a particular height jet.

So, this correlation is valid only if the bubble, if the fluidized bed is greater than 20 centimeter in diameter and the minimum fluidization velocity has this less than 8 centimeter per second and here the particle diameter will be, particle diameter will be within the range of 100 to 400, 350 micrometer and the effective velocity; that means, here relative velocity of the gas will be within the range of 5 to 30 centimeter per second.

So, similar way from experimental data the correlation can be developed to predict the bubble axially with other type of distributor even in your experimental condition from the experimental data. You can do the experiment in your laboratory, and you find out and take the photograph of your bubble and calculate the mean bubble diameter at different condition, take this snap shot, analyze and have a data and make a correlation based on this concept you will get different type of correlations and exactly you will see how to calculate, how to estimate the bubble diameter without doing experiment at different location. And you see after making a correlations again take the snap shot and see whether it will be exactly the same or may be within a very list error you can obtain what should be the you can check whether your correlation is valid or not.

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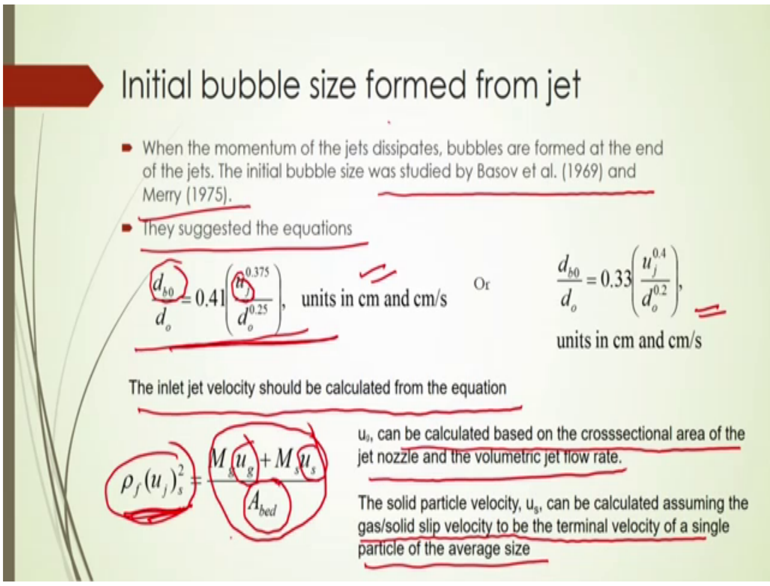

Now, initial bubble size that is formed from the jet when the momentum of the jet dissipated of course, bubbles are formed at the end of the jets. The initial bubble size was studied by Busov et al 1969 and Merry 1975 according to their proposed correlations you can calculate what should be the minimum, what should be the, what should be the initial bubble diameter that you can calculate from this correlations.

So, the inlet jet velocity should be calculated from the equation here because this inlet jet velocity is required to calculate to calculate the initial bubble diameter from this correlation. So, this u j is the jet velocity. So, inlet jet velocity you can calculate from this equation here this is nothing, but the rho f p u j square the energy here. So, this will be nothing, but this here momentum.

Now, u g here can be calculated based on the cross sectional area of the jet nozzle and the volumetric jet flowrate. The solid particle velocity u s here can be calculated assuming the gas solid slip velocity to the terminal velocity of a single particle of the average size. So, from the gas velocity and the solid velocity inside the bed and also if you know the cross sectional area of the bed you will be able to calculate what should be the jet velocity, in the jet velocity which will give you the initial bubble diameter from this correlation.

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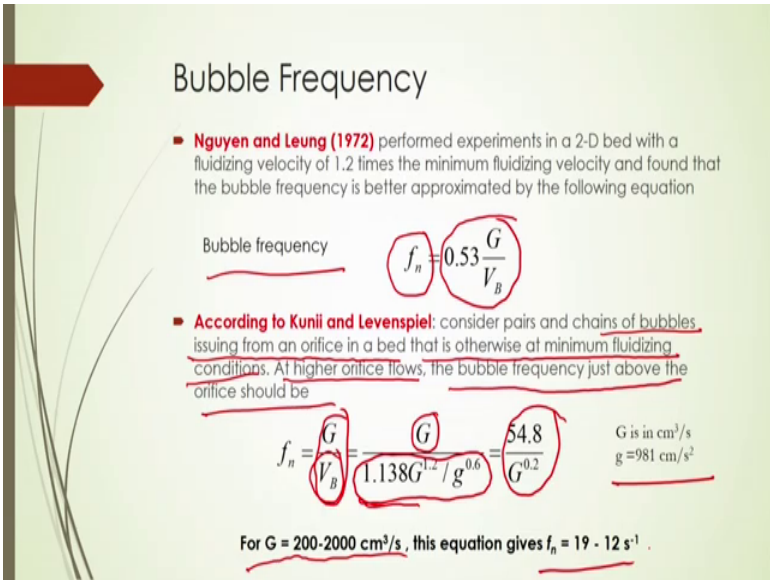

Now, bubble frequency what is that bubble frequency bubble frequency is the how many bubbles will be formed during this operation.

Now, Nguyen and Leung, 1972 performed experiments in a 2-D bed, 2 dimensional bed with a fluidizing velocity of 1.2 times the minimum fluidization velocity and they found that the bubble frequency is better approximated by the following equation. This bubble frequency represented by f n that will be is equal to 0.53 into G by V B. What is G? G is the gas volumetric flowrate.

According to the Kunii and Levenspiel it is seen that the, if you consider the pairs and chains of bubbles issuing from an orifice in a bed that is otherwise at minimum fluidization conditions you will see at higher orifice flow bubble frequency just above the orifice should be is equal to G by V B. This G by V B is nothing, but the volume of the bubble that is formed from the orifice or from the distributor. So, this will be calculated here this V B that already given by given in earlier slides that V B will be is equal to 1.138 into G to the power 1.2 by g to the power 0.6 from which you will be able to calculate what would be the frequency of the bubble. So, G in here centimeter cube per second and small g is 981 centimeter per second square.

For gas volumetric flowrate within a range of 200 to 2000 centimeter per second this equation gives the frequency of 19 to 12 number per second. So, this is very important how to calculate the bubble frequency inside the bed for a particular gas flowrate.

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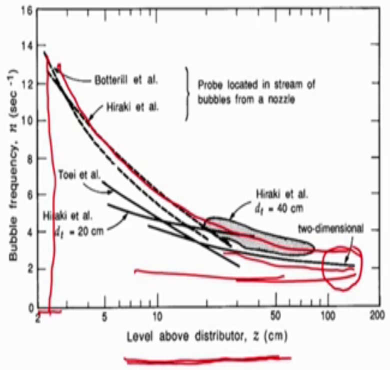

Frequency of bubbles passing a point in a fluidized bed at various gas flow rates; from Kunii and Levenspiel (1991).

Now, how this frequency of the bubbles passing a point in a fluidized bed at various gas flowrates. You will see bubble frequency at different level how it will be changing. The bubble frequency you will see will be lowest at you will see at the top of the fluidized bed because they are whatever bubbles are forming at the distributor that will be maximum and whenever it will be going up all those bubbles are coming to each other and make a coalescence and they form the bigger bubbles and because of which the number of bubbles; that means, frequency of the bubbles will reduced.

And it will be actually exponentially decreasing along the height of the fluidized bed. You will here see in this figure different investigators they have represented the bubble frequency at different level of the distributor, level above the distributor.

Now, here you will see very near about this bubble the frequency is maximum whereas, if you come to the distance that is for above this distributor you will see the bubble frequency will be lowest. So, here it is seen that this almost exponentially decreasing this bubble frequency as a function of level above the distributor.

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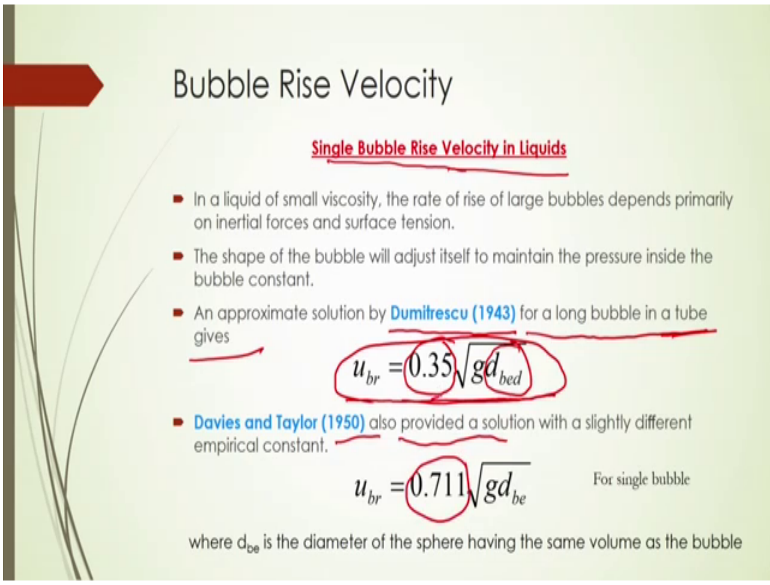

Now, what should be the bubble rise velocity? Once you know the bubble size and also once you know the bed effective bubble size or you can say the equivalent bubble diameter and also bed diameter, how to calculate the bubble rise velocity there.

Now, if we consider the single bubble rise velocity in liquids, in a liquid of small viscosity the rate of rise of large bubbles depends primarily on the inertial forces and surface tension. The shape of the bubble will adjust itself to maintain the pressure inside the bubble and it will be remain constant so that the shape of the bubbles will be optimized.

And approximate solution by Dumitrescu 1943 for a long bubble in a tube they have given this bubble rise velocity correlation as this. So, they have developed this bubble rise velocity and they stated that in this bubble rise velocity will be directly related to this bed diameter because they have actually used that they have done the experiment in a tube that is why they are they are considering this bubble rise velocity as a function of tube diameter.

Now, Davies and Taylor, 1950, they have done some experiment with solution with a significally different empirical constant here. So, they got this empirical constant this 0.71 instead of 0.35 whereas, they have taken this diameter as a bubble, not diameter of a bubble not diameter of a bed or tube. So, this Davies and Taylor they have correlated they have made a correlation for estimate the bubble rise velocity has a function of equivalent bubble diameter. If you know the equivalent diameter then you just substitute here you will be able to calculate what should be the bubble rise velocity. Of course, this is for single bubble and here this bubble rise velocity may injured or may be changed if there are more than one bubbles, and if there is a interaction between bubbles then of course, there will be a change of bubble rise velocity there.

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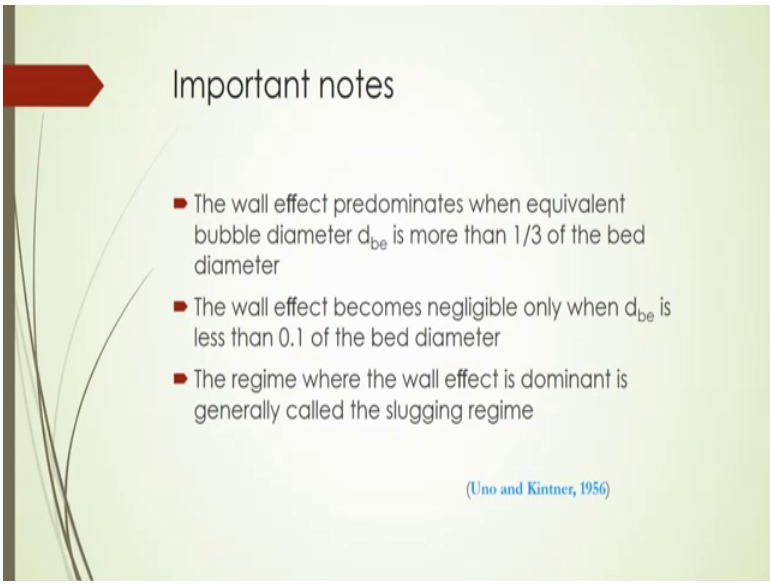

Now, the wall effect predominates when equivalent bubble diameter d be is more than one, one-third of the bed diameter the wall effect becomes negligible; when equivalent biometer is less than, less than 10 percent of the bed diameter. Even the regime where the wall effect is dominant is generally called the slugging regime. So, very important that this bubble rise velocity that depends on if is there any interaction of this bubble diameter to other wall or not, if there is no disturbance on the single bubble is rising in a medium then you can use this correlation to estimate the bubble rise velocity.

Whereas, if is there any interaction this interaction may be wall bubble interaction, there may be wall effect wall, wall, wall and what is that particle and bubble interaction there. So, there will be some condition whether this bubbles will be bigger or smaller or there will be decrease or coalescence and because of which is there any slugging formation or not. So, that depends on.

So, there may be some effect on that. So, wall effect sometimes predominant, so when equivalent bubble diameter is more than one-third of this bed diameter and also wall effect will be negligible if there is the bubble diameter is 10 percent of the bed diameter and of course, this wall effect will dominate generally if any regime which is called the slugging regime.

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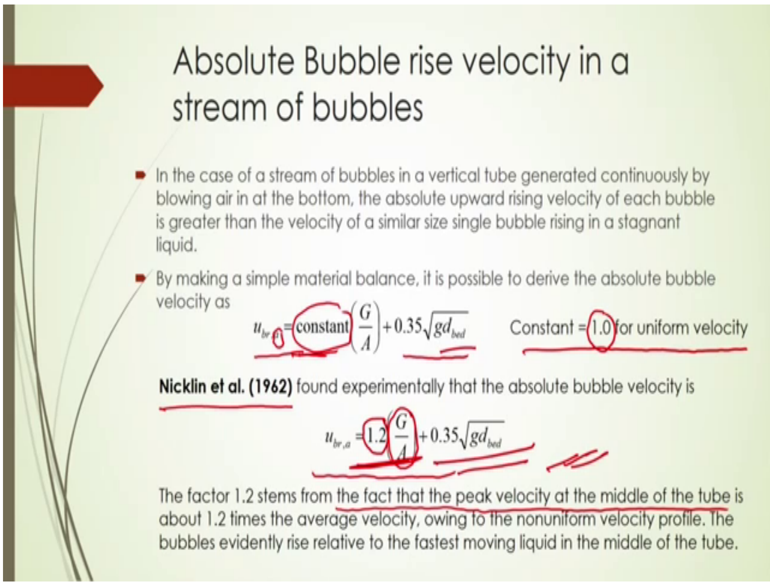

So, absolute bubble rise in a stream of bubbles then if there is more than one bubbles there will be interaction of bubbles and for which what should be the absolute bubble rise velocity.

In the case of stream of bubbles in a vertical tube that is generated continuously by blowing air in at the bottom the absolute upward rising velocity of each bubbles will be greater than the velocity of a similar size single bubble rising in a stagnant liquid. So, by making a simple material balance it is possible to derive the absolute bubble velocity as here this absolute bubble velocity a for here absolute will be noted here. So, absolute bubble rise velocity is a function of this is superficial gas velocity and the bubble bed diameter. So, here that will be is equal to constant into G by A plus 0.35 into root over gd bed. This constant is equal to 1 for uniform velocity.

Whereas, Nicklin et al 1962 they proposed another correlations based on their experimental result and they have suggested the suggested that the absolute bubble rise velocity will be is equal to 1.2 times of superficial gas velocity plus this 0.35 into root over gd bed. So, here this constants will be 1.2 instead of 1 here. So, this absolute bubble rise velocity as per Nicklin et al 1962 model this will be used to calculate this will be more appropriate to calculate the bubble rise velocity.

The factor 1.2 here stems from the fact that the peak velocity at the middle of the tube is about 1.2 times the average velocity. And this owing to the non uniform velocity profile actually. The bubbles evidently rise relative to the fastest moving liquid in the middle of the tube. And what should be the absolute rise velocity if it is there is a swarm of bubbles present inside the bed? For a swarm of bubbles, the same concept you can apply here you can just, you can just apply that concept of the bubble rise velocity as a summation of gas velocity and this bubble rise velocity of the single bubble.

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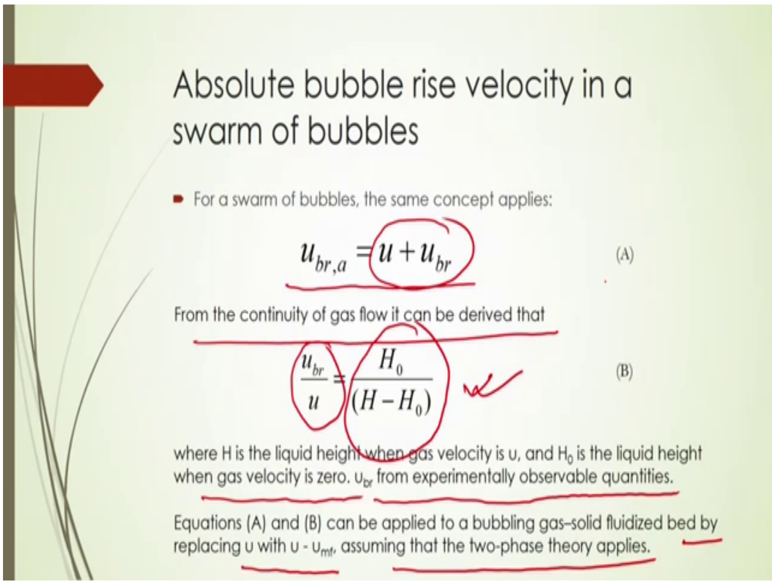

So, from the continuity of the gas flow it can be derived that this u br by u that will be is equal to H 0 by H minus H 0. What is this H? H is the liquid height when the gas velocity is u and H 0 is the liquid height when gas velocity is 0; and u br from the u br from experimentally observable quantities. So, this is very important in the liquid medium how to calculate the bubble rise velocity in a swarm of bubbles here.

Now, from equation A and B you can obtain the bubble gas bubbling the bubble rise velocity in a bubbling gas-solid fluidized bed by replacing, if I replacing u with u minus u mf, assuming that the two phase theory applies here. So, in swarm of bubbles the bubble rise velocity can be calculated from this correlations.

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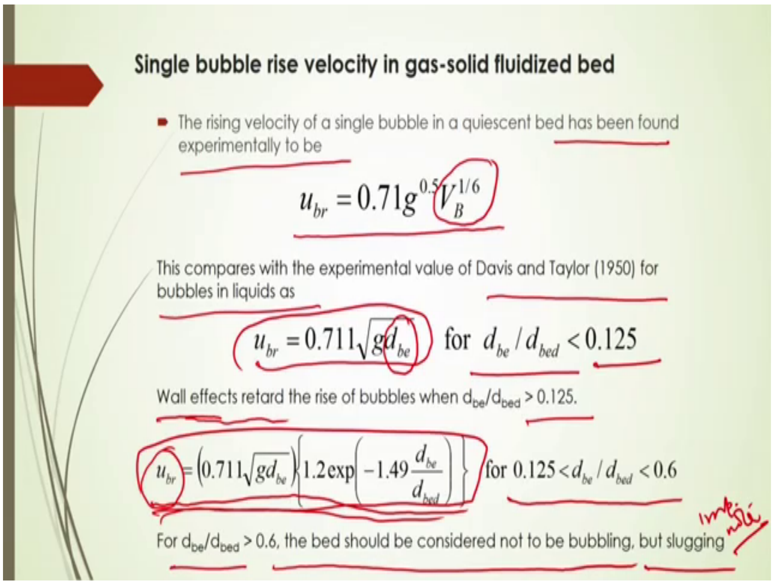

Now, single bubble rise velocity in a gas solid fluidized bed the rising velocity of a single bubble in a quiescent bed that has been found experimentally to be this 0.71 g to the power 0.5 into V B to the power 1 by 6. This is in terms of bubble volume. If you know the bubble volume what should be the bubble rise velocity. Of course, higher volume of the bubbles will have the higher diameter of course, equivalent diameter it will give you the more rise velocity.

This compares to the experimental value of Davis and Taylor for bubbles in a liquid. Bubbles in a liquid will be is equal to this, this bubble rise velocity can be calculated in the liquid medium that is equal to 0.711 into gd be, here in this case the bubble equivalent bubble diameter. In this case this equivalent bubble diameter relative to this bed diameter should be less than 0.125.

If there is a wall effects then this wall effects retarded the rise of the bubbles when d be is by d bed is greater than 0.125. So, from this condition you can calculate what should be the bubble rise velocity. So, u br can be calculated from this equation for the ratio of equivalent bubble diameter to the bed diameter if it lies within the range of 0.125 to 0.6 and from which you will be able to calculate this bubble rise velocity.

For this ratio the equivalent bubble diameter to this bed diameter it is greater than 0.6 the bed should be considered not to be bubbling, but slugging here. This is very important note, important note here to be remember that if equivalent bubble diameter is 60 percent of the bed diameter, is greater than 60 percent of the bed diameter then you can say there will be no bubbling it will be slugging instead.

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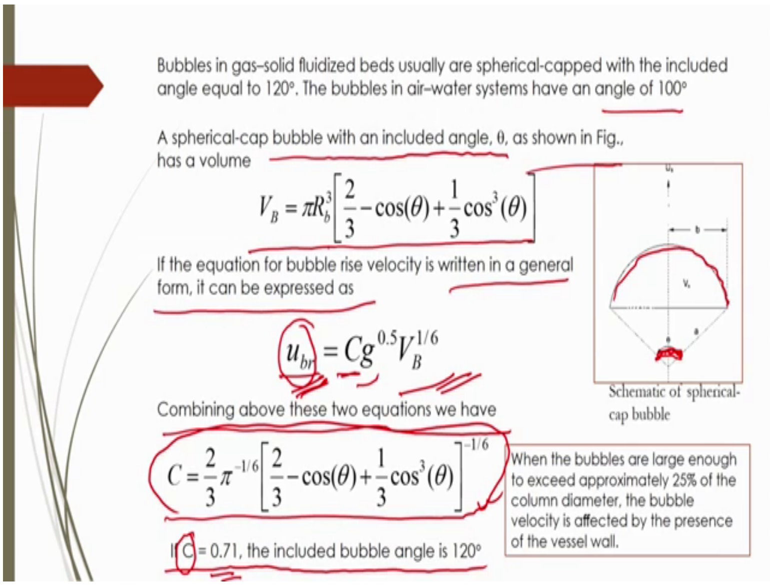

Now, bubbles in gas solid fluidized bed generally you will see different shape of bubbles are formed sometimes the spherical cap bubbles will form, and which may include the different angle which may be equal to 120 degree, the bubbles in air water system have an angle of 100 degree centigrade.

So, a spherical cap bubble with an included angle of theta as shown in figure here this is theta, this is theta, this is the spherical cap bubble. So, at this theta what should be the bubble volume? This bubble volume will be calculated, here this phi R b, R b is nothing but the radius of the bubble and here it will be into 2 by 3 minus cos theta plus 1 by 3 cos theta here. So, if the equation for bubble rise velocity is written in a general form it can be expressed as u br is equal to some constant of g to the power 0.5 V B to the power 1 by 6.

Now, combining above these two equations then you can generalize for the constant as C in terms of this spherical cap orientation. So, this C will be, C will be a function of this theta. So, if you increase the theta decrease the theta you will see corresponding value of C you can obtain from this correlation. Now, this if C is equal to 0.71 the included bubble angle will be 120 degree. So, generally in gas solid fluidized bed this spherical bubble cap is formed with this included angle of theta is equal to 120 degree. So, from which you can say that C will be is equal to 0.71 and from this 0.71 this bubble rise velocity will be is equal to 0.71 into g the power 0.5 into V B to the power 1 by 6. So, from this correlation you will be able to calculate what should be the bubble rise velocity for spherical cap size bubble in gas solid fluidized bed, even in air water system or gas water system. For gas water system theta will be is equal to 100 degree.

So, when the bubbles are large enough to exceed this approximately 25 percent of the column diameter or bed diameter the bubble velocity is affected by the presence of this vessel wall that is why.

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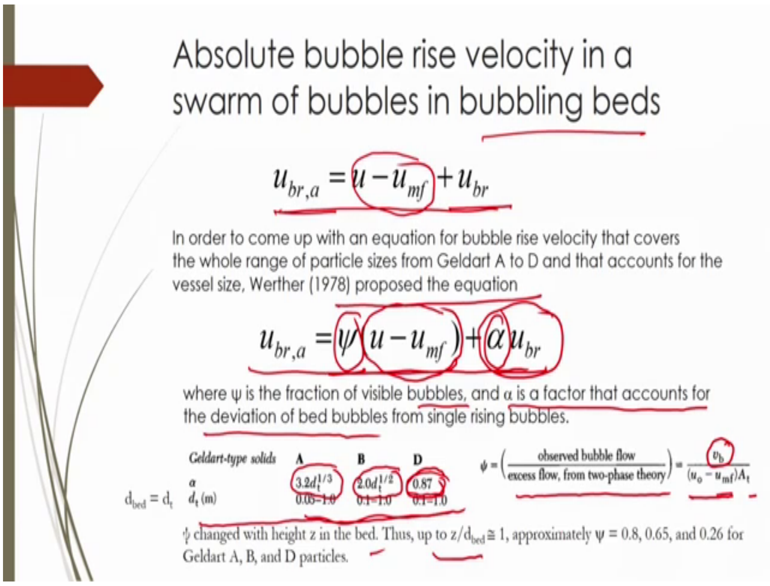

Now, absolute bubble rise velocity in a swarm of bubbles in bubbling beds. In the bubbling beds you will see for gas solid operation see this u br absolute bubble rise that will be is equal to relative velocity of the gas plus single bubble rise velocity. In order to come up with an equation for bubble rise velocity that covers the whole range of particle size from this Geldart A to D particles and that accounts for the vessel size then Werther 1978 proposed this correlations to calculate the bubble rise velocity at in this absolute condition, that should be is equal to function of what is that relative velocity of the gas plus this bubble rise velocity.

This psi and alpha is the characteristics factor or parameter which governs like this psi is the fraction of visible bubbles and alpha is a factor that accounts for the deviation of bed bubbles from single rising bubbles.

Now, for different type of particles this alpha value will be different. This alpha will be changing with respect to this bed diameter or tube diameter for this A type and B type and D type particles. This A and B type particles it is seen that this A alpha, this alpha parameter it changing with tube diameter whereas, for D type particles it does not change with tube diameter or bed diameter it is fixed at 0.87 whereas, of course, this correlations should be valid within a range of certain bed diameter here as shown here.

What is psi here? Psi is the fraction of visible bubbles here. How it is divined here? This psi is defined as this observable bubble flow by excess flow from two phase theory here. So, this will be is equal to V B by what is that; u 0 minus u mf into 80, u 0 is the gas velocity and u mf is the minimum fluidization velocity. And this psi of course, changed with height z in the bed thus up to z by bed diameter if is approximately is equal to 1; that means, z is equal to bed diameter then psi values will be is equals to 0.8 and 0.6 5 and 0.26 for Geldart A, B and D particles.

So, from which will be able to this is the general correlations for absolute bubble rise velocity in a swarm of bubbles in bubbling fluidized bed. So, this only this psi and alpha is required to calculate this absolute bubble rise velocity and this psi and alpha of course, will be obtained from this different ranges of bubble diameter.

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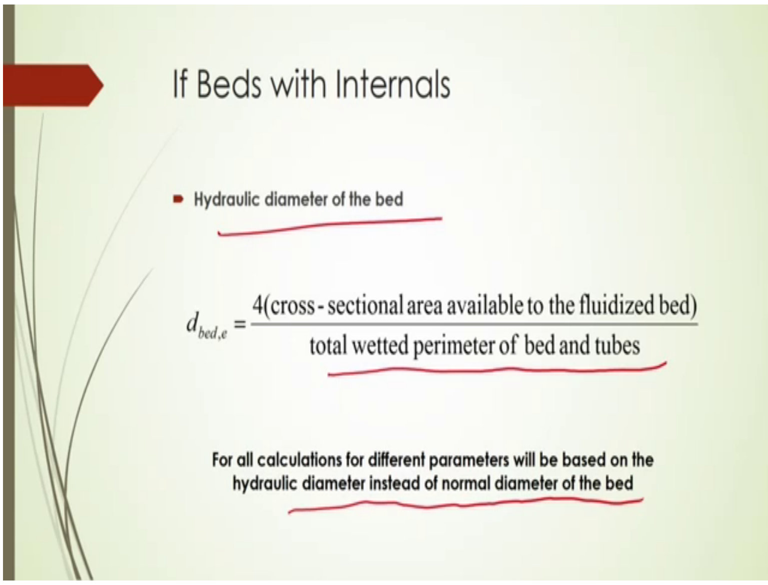

If beds with internals, then what will happen; you have to consider the hydraulic diameter of the bed. This hydraulic diameter of the bed of course, will be defined this,

this, this 4 into cross sectional area available to the fluidized bed and total wetted perimeter of the bed and tubes. For all calculations for different parameters will be based on the hydraulic diameter instead of normal diameter of the bed. So, for different beds you can calculate what should be the bubble rise velocity based on that earlier relations.

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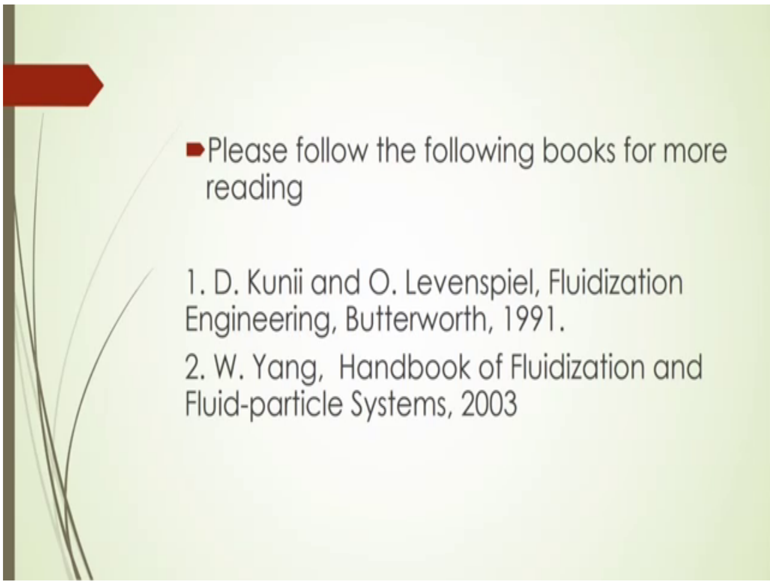

Now, for details you can further read these two books all these – Yang, this handbook of fluidization and fluid particle systems and Kunii and Levenspiel.

So, thanks for all today's lecture. From this lecture we can then have how to calculate the bubble size? What should be the maximum bubble size? How to estimate the bubble size at different location of the fluidized bed and also what should be the bubble rise velocity? What should be the single bubble rise velocity? How to calculate the bubble rise velocity at different location also?

What should be the bubble rise velocity in swarm of bubbles in fluidized bed form of general correlations, from the correlations how to calculate the bubble rise velocity; once you know the bed diameter as well as the equivalent bubble diameter. Also how to calculate the equivalent bubble diameter just we have discussed in this lecture. So, I think it will be very useful for your this bubble characteristics in this bubbling fluidizer.

Next, lecture will be provided the bubble characteristics even some other part of this bubbling fluidized bed.

Thank you.